A Unified Probabilistic Approach for Predicting the Structural Response of Oriented Strandboard

by

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“I’m not singing for the future  
I’m not dreaming of the past  
I’m not talking of the first time  
I never think about the last”

Quotation from “A Rainy Night in Soho” by
Shane MacGowen
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Abstract

Oriented strandboard (OSB) is a wood-based composite manufactured from elongated wood-strands coated in a resin binder that are oriented and arranged in layers, cross-laminated and hot pressed to form large panels. OSB is a highly complex material that requires a large number of parameters to fully define its internal structure and mechanical behaviour. The variability of the defining parameters further adds to the complexity. Current design and production practices rely on highly-simplified, deterministic methods where many of the defining parameters and their variability are omitted and replaced with high safety factors. Reliability methods offer significant potential for improved efficiency in the OSB industry. However, such methods require knowledge of the stochastic properties, mechanical behaviour and relationships between parameters as well as appropriate modelling and analysis tools.

In this thesis, a new approach to predicting the mechanical behaviour and associated variability of OSB/3 panels using a stochastic finite element model is developed. As part of the work, a large-scale experimental programme was undertaken that included over 2,780 tests to evaluate 45 different physical and mechanical properties for commercial OSB/3 and single-layer OSB panels. This provided the necessary information to evaluate the stochastic properties, mechanical behaviour and correlations between parameters. The Anderson-Darling method was used to establish suitable probabilistic models to describe the variability of each parameter. The Pearson’s correlation coefficient was used to describe relationships between the parameters. Using regression analysis, suitable mathematical models to accurately represent the orthotropic, non-linear mechanical behaviour of OSB subjected to tension, compression, bending and panel-shear loading were developed. New normalised non-linear constitutive relationships for OSB were implemented in 3-D finite element models. A stochastic analysis based on the Monte Carlo method accurately reproduced the variability of the defining parameters found in the experiments. This approach is suitable for implementation in reliability-based structural design.
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Glossary of Symbols

\( \hat{a}_{c,x} \) Normalised Longitudinal Compressive Behaviour Coefficient
\( \hat{a}_{c,y} \) Normalised Lateral Compressive Behaviour Coefficient
\( \hat{a}_{s,xy} \) Normalised Panel-Shear Behaviour Coefficient
\( \hat{a}_{t,x} \) Normalised Longitudinal Tensile Behaviour Coefficient
\( \hat{a}_{t,y} \) Normalised Lateral Tensile Behaviour Coefficient
\( \hat{b}_{c,x} \) Normalised Longitudinal Compressive Behaviour Coefficient
\( \hat{b}_{c,y} \) Normalised Lateral Compressive Behaviour Coefficient
\( \hat{b}_{s,xy} \) Normalised Panel-Shear Behaviour Coefficient
\( \hat{b}_{t,x} \) Normalised Longitudinal Tensile Behaviour Coefficient
\( \hat{b}_{t,y} \) Normalised Lateral Tensile Behaviour Coefficient
\( \hat{c}_{c,x} \) Normalised Longitudinal Compressive Behaviour Coefficient
\( \hat{c}_{c,y} \) Normalised Lateral Compressive Behaviour Coefficient
\( A^2 \) Anderson-Darling Statistic
\( E_{b,g,x} \) Longitudinal Bending Global Elastic Modulus
\( E_{b,g,y} \) Lateral Bending Global Elastic Modulus
\( E_{b,l,x} \) Longitudinal Bending Local Elastic Modulus
\( E_{b,l,y} \) Lateral Bending Local Elastic Modulus
\( E_{c,g,x} \) Longitudinal Compressive Global Elastic Modulus
\( E_{c,g,y} \) Lateral Compressive Global Elastic Modulus
\( E_{c,l,x} \) Longitudinal Compressive Local Elastic Modulus
\( E_{c,l,y} \) Lateral Compressive Local Elastic Modulus
\( E_{c,z} \) Bearing Elastic Modulus
\( E_{c,z} \) Bearing Elastic Modulus
\( E_{t,x} \) Longitudinal Tensile Elastic Modulus
\( E_{t,y} \) Lateral Tensile Elastic Modulus
\( E_{t,z} \) Internal Bond Elastic Modulus
\( E_{t,z} \) Internal Bond Elastic Modulus
\( F_{\text{max}} \) Failure Load
\( G_{s,xy} \) Panel-Shear Modulus
\( G_{s,xz} \) Plate-Shear Modulus
\( G_{s,yz} \) Planar-Shear Modulus
\( H_0 \) Null Hypothesis
\( T_{c,x} \) Longitudinal Compressive Tangent Modulus
\( T_{c,y} \) Lateral Compressive Tangent Modulus
\( l_1 \) Gauge Length
\( r^2 \) Coefficient of Determination
\( t_c \) Core Layer Thickness
\( t_{dam,l} \) Left Surface Damage Layer Thickness
\( t_{dam,r} \) Right Surface Damage Layer Thickness
\( t_{s,l} \) Left Surface Layer Thickness
\( t_{s,r} \) Right Surface Layer Thickness
\( \bar{x} \) Sample Mean
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$\gamma_{u,s,xy}$</td>
<td>Panel-Shear Ultimate Strain</td>
</tr>
<tr>
<td>$\gamma_{u,s,xz}$</td>
<td>Plate-Shear Ultimate Strain</td>
</tr>
<tr>
<td>$\gamma_{u,s,yz}$</td>
<td>Planar-Shear Ultimate Strain</td>
</tr>
<tr>
<td>$\varepsilon_{u,b,x}$</td>
<td>Longitudinal Bending Ultimate Strain</td>
</tr>
<tr>
<td>$\varepsilon_{u,b,y}$</td>
<td>Lateral Bending Ultimate Strain</td>
</tr>
<tr>
<td>$\varepsilon_{u,c,x}$</td>
<td>Longitudinal Compressive Ultimate Strain</td>
</tr>
<tr>
<td>$\varepsilon_{u,c,y}$</td>
<td>Lateral Compressive Ultimate Strain</td>
</tr>
<tr>
<td>$\varepsilon_{u,c,z}$</td>
<td>Bearing Ultimate Strain</td>
</tr>
<tr>
<td>$\varepsilon_{u,t,x}$</td>
<td>Longitudinal Tensile Ultimate Strain</td>
</tr>
<tr>
<td>$\varepsilon_{u,t,y}$</td>
<td>Lateral Tensile Ultimate Strain</td>
</tr>
<tr>
<td>$\varepsilon_{u,t,z}$</td>
<td>Internal Bond Ultimate Strain</td>
</tr>
<tr>
<td>$\varepsilon_{y,c,x}$</td>
<td>Longitudinal Compressive Yield Strain</td>
</tr>
<tr>
<td>$\varepsilon_{y,c,y}$</td>
<td>Lateral Compressive Yield Strain</td>
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<tr>
<td>$\rho_c$</td>
<td>Core Layer Density</td>
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<tr>
<td>$\rho_{dam,l}$</td>
<td>Left Surface Damage Layer Density</td>
</tr>
<tr>
<td>$\rho_{dam,r}$</td>
<td>Right Surface Damage Layer Density</td>
</tr>
<tr>
<td>$\rho_{s,l}$</td>
<td>Left Surface Layer Density</td>
</tr>
<tr>
<td>$\rho_{s,r}$</td>
<td>Right Surface Damage Density</td>
</tr>
<tr>
<td>$\sigma_{u,b,x}$</td>
<td>Longitudinal Bending Ultimate Strength</td>
</tr>
<tr>
<td>$\sigma_{u,b,y}$</td>
<td>Lateral Bending Ultimate Strength</td>
</tr>
<tr>
<td>$\sigma_{u,c,x}$</td>
<td>Longitudinal Compressive Ultimate Strength</td>
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<td>$\sigma_{u,c,y}$</td>
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<tr>
<td>$\sigma_{u,c,z}$</td>
<td>Bearing Ultimate Strength</td>
</tr>
<tr>
<td>$\sigma_{u,t,x}$</td>
<td>Longitudinal Tensile Ultimate Strength</td>
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<tr>
<td>$\sigma_{u,t,y}$</td>
<td>Lateral Tensile Ultimate Strength</td>
</tr>
<tr>
<td>$\sigma_{u,t,z}$</td>
<td>Internal Bond Ultimate Strength</td>
</tr>
<tr>
<td>$\sigma_{y,c,x}$</td>
<td>Longitudinal Compressive Yield Strength</td>
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<tr>
<td>$\sigma_{y,c,y}$</td>
<td>Lateral Compressive Yield Strength</td>
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<tr>
<td>$\tau_{u,s,xy}$</td>
<td>Panel-Shear Ultimate Strength</td>
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<td>$\tau_{u,s,xz}$</td>
<td>Plate-Shear Ultimate Strength</td>
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<td>$\tau_{u,s,yz}$</td>
<td>Planar-Shear Ultimate Strength</td>
</tr>
<tr>
<td>$H$</td>
<td>Moisture Content</td>
</tr>
<tr>
<td>$h$</td>
<td>Test Specimen Height</td>
</tr>
<tr>
<td>$T$</td>
<td>Test Time</td>
</tr>
<tr>
<td>$W$</td>
<td>Section Elastic Modulus</td>
</tr>
<tr>
<td>$A$</td>
<td>Cross-Sectional Area</td>
</tr>
<tr>
<td>$I$</td>
<td>Second Moment of Area</td>
</tr>
<tr>
<td>$L$</td>
<td>Total Span</td>
</tr>
<tr>
<td>$N$</td>
<td>Population Size</td>
</tr>
<tr>
<td>$U$</td>
<td>Strain Energy</td>
</tr>
<tr>
<td>$b$</td>
<td>Section Width</td>
</tr>
<tr>
<td>$n$</td>
<td>Sample Size</td>
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<tr>
<td>$o$</td>
<td>Degree-of-Orthotropy</td>
</tr>
<tr>
<td>$p$</td>
<td>Probability of Occurrence</td>
</tr>
<tr>
<td>$r$</td>
<td>Pearson’s Correlation Coefficient</td>
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<td>Symbol</td>
<td>Description</td>
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<td>--------</td>
<td>-----------------------------</td>
</tr>
<tr>
<td>$s$</td>
<td>Sample Standard Deviation</td>
</tr>
<tr>
<td>$t$</td>
<td>Specimen Thickness</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Level of Significance</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Population Mean</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Global Density</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Population Standard Deviation</td>
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### Glossary of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Full Form</th>
</tr>
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<tbody>
<tr>
<td>ANSI</td>
<td>American National Standards Institute</td>
</tr>
<tr>
<td>APDL</td>
<td>ANSYS Parametric Design Language</td>
</tr>
<tr>
<td>ASTM</td>
<td>American Society for Testing and Materials</td>
</tr>
<tr>
<td>BSI</td>
<td>British Standards Institution</td>
</tr>
<tr>
<td>CDF</td>
<td>Cumulative Distribution Function</td>
</tr>
<tr>
<td>CEN</td>
<td>European Committee for Standardisation</td>
</tr>
<tr>
<td>CNC</td>
<td>Computer Numerically Controlled</td>
</tr>
<tr>
<td>COV</td>
<td>Coefficient of Variation</td>
</tr>
<tr>
<td>CSA</td>
<td>Canadian Standards Authority</td>
</tr>
<tr>
<td>EDF</td>
<td>Empirical Distribution Function</td>
</tr>
<tr>
<td>FPL</td>
<td>Forest Products Laboratory</td>
</tr>
<tr>
<td>HDD</td>
<td>Horizontal Density Distribution</td>
</tr>
<tr>
<td>LVDT</td>
<td>Linearly-Varying Differential Transducer</td>
</tr>
<tr>
<td>LVL</td>
<td>Laminated Veneer Lumber</td>
</tr>
<tr>
<td>MDI</td>
<td>Methylene Diphenyl di-Isocyanate</td>
</tr>
<tr>
<td>MOE</td>
<td>Modulus of Elasticity</td>
</tr>
<tr>
<td>MOR</td>
<td>Modulus of Rupture</td>
</tr>
<tr>
<td>MUF</td>
<td>Melamine Fortified Urea</td>
</tr>
<tr>
<td>MUPF</td>
<td>Melamine Urea Phenol Formaldehyde</td>
</tr>
<tr>
<td>OSB</td>
<td>Oriented Strandboard</td>
</tr>
<tr>
<td>PF</td>
<td>Phenol Formaldehyde</td>
</tr>
<tr>
<td>PMDI</td>
<td>Polymeric Di-Phenyl Methane Di-Isocyanate</td>
</tr>
<tr>
<td>PRF</td>
<td>Phenol Resorcinol Formaldehyde</td>
</tr>
<tr>
<td>PSL</td>
<td>Parallel Strand Lumber</td>
</tr>
<tr>
<td>PVA</td>
<td>Poly-Vinyl Acetate</td>
</tr>
<tr>
<td>RH</td>
<td>Relative Humidity</td>
</tr>
<tr>
<td>SBA</td>
<td>Structural Board Association</td>
</tr>
<tr>
<td>UF</td>
<td>Urea Formaldehyde</td>
</tr>
<tr>
<td>USDA</td>
<td>United States Department of Agriculture</td>
</tr>
<tr>
<td>VBA</td>
<td>Visual Basic for Applications</td>
</tr>
<tr>
<td>VDP</td>
<td>Vertical Density Profile</td>
</tr>
</tbody>
</table>


1 Introduction

1.1 Introduction

The global threat posed by climate change has prompted the construction industry to begin seeking alternative materials to replace materials such as steel and concrete with more eco-friendly materials for use in domestic construction. Timber construction had largely fallen out of favour in many parts of Europe due to a multitude of factors. Dwindling supplies, problems with biological attack and increasingly strict fire and sound proofing regulations contributed in the past to timber falling out of favour in domestic construction and being replaced by carbon-intensive materials such as concrete and masonry.

The drive to reduce carbon output has prompted the construction industry to re-examine the potential for reintroducing timber as the primary structural material for use in domestic construction. Recent developments in sustainable forest management and new innovative structural wood-based materials have improved the quality and supply of raw timber. Timber also has the added benefit of being a carbon-neutral material which adds to its attractiveness as an environmentally-friendly building material. Despite these improvements, the biggest obstacles that prevent the wider application of timber in the construction industry are the uncertainty of supply of quality timber and the variability of its mechanical properties. Engineered wood products offer significant potential to overcome many of the problems associated with solid wood.

This chapter is subdivided into several sections to give the reader a brief background to the problems addressed by this thesis and the approaches used to address them. The first section of this chapter discusses the background to engineered wood products, the motivations for developing them and the unique challenges they pose from production and design perspectives. This chapter moves on to introduce the engineered wood-based panel product Oriented Strand Board (OSB) in terms of internal structure, raw materials and current design and production practice. Finally, this chapter finishes with a problem statement and outline of how the current work addressed these problems.
1.2 Engineered Wood Products

1.2.1 Motivations for Development

Engineered wood products first appeared in the early 1940s. The primary motivations to the development of such products were to address the uncertainty in supply and variability in mechanical properties of sawn timber. Engineered timber products can be made from raw materials that are unsuitable for making traditional sawn lumber or laminated wood products thereby greatly enhancing the availability of supply. Engineered wood products minimise the impact of the variability that inherently exists in solid lumber by ensuring a more uniform dispersion of natural defects throughout structural members. The rediscovery of timber in the domestic construction market has resulted in the development of dozens of new engineered wood products. Products such as glulam, oriented strandboard, laminated veneer lumber, composite timber I-joists, cross-laminated lumber and structural insulated panels are considered by industry experts to be the future of domestic timber construction.

The downside of engineered timber products is that they take a material that already has an extremely complex internal structure and make it even more complex. Solid timber is often treated as a two-phase material made from cellulose micro-fibrils bound with a naturally-occurring organic polymer known as lignin. Engineered wood products add to this complexity of solid wood by introducing additional material phases in the form of synthetic adhesives and reinforcing materials (2009, Raftery and Harte, 2009, 2011). Additionally, most engineered wood products involve intensive processing to convert the raw material into a useable product, introducing an additional source of variability into the system. Furthermore, the raw materials used in engineered wood products are often of poor quality and they are generally more variable than the raw materials used to produce solid timber products.

1.2.2 Current Industry Practices

The current practice to product development in the engineered wood products industry is often trial and error based. Sample batches of products are manufactured and tested. The results of testing trial batches form the basis for
determining production parameters. Quality assurance is maintained by extensive in-process quality control testing. These empirical approaches are extremely time-consuming and expensive. The end result is a product that is known to be capable of performing its required function. However, it does not have a sound scientific basis for design and production, and it is still highly variable when compared to competing materials such as steel and concrete.

The time, cost and uncertainty of the outcome of product development programs discourages manufacturers from making the necessary investment in terms of time and money to improve existing products and develop new product lines. Furthermore, design codes define characteristic values for material properties as either the mean (elastic moduli) or 5th percentile (strength) values which are divided by high partial safety factors to obtain design values. The aim of this approach is to eliminate the impact of the variability in material performance on structures by restricting the design values of material properties to a fraction of the actual strength of the materials. Although this approach produces a safe design, it significantly detracts from the true capabilities of engineered wood materials.

1.2.3 Need for Improvement

The engineered wood industry is seeking to address many of these problems by gaining a better understanding of their products and building a scientific basis for their production and structural design. Such an approach would eliminate much of the uncertainty and significantly reduce the time and cost of developing new products. One such approach that offers significant potential for improvement in the engineered wood products industry is the move to probabilistic or reliability based design.

Current design codes in Europe use a deterministic approach and variability or uncertainty in loading and materials is accounted for simply by using a 95th percentile value for the loading and a 5th percentile value for the material strength properties. There is a move internationally to develop reliability-based design codes. Reliability-based design is based around the principle where a failure function is defined that treats the loads and material properties as random
variables. The output from a reliability-based design is a series of numbers with values ranging from zero to one which represent the probabilities of failure not occurring under each design scenario considered. Probabilistic design approaches have not been widely adopted for use in structural timber design due to the combination of the large number of parameters required to define its behaviour and the lack of established probabilistic models to describe the variability of these parameters. This will be addressed in the current work.

1.3 Oriented Strand Board (OSB)

The present research is focused primarily on oriented strandboard (OSB). OSB is an engineered wood-based panel product manufactured from three layers of elongated wood strands coated in resin and hot pressed together. The wood strands are chopped from logs with their longer dimension aligned approximately parallel with the grain of the log. The term “oriented” comes from the fact that the wood strands on the surface-layers of OSB panels are orientated with their longer dimension parallel to the longer dimension of the panel while those in the centre layer are either randomly distributed or are orientated with their longer dimension perpendicular to the longer dimension of the panel. Figure 1-1 below demonstrates the two most common OSB panel lay-ups.

![OSB Panel Layups – Oriented Core vs Random Core](image)

**Figure 1-1 – OSB Panel Layups – Oriented Core vs Random Core (SBA, 2004a)**
1.3.1 Raw Materials

OSB is traditionally manufactured in North America from under-utilised timber species such as aspen pine, yellow poplar and southern pine as well as small diameter logs from thinnings and tops from more traditional commercial species. North American OSB producers tend to use Phenol-Formaldehyde (PF) and Methylene Diphenyl di-Isocyanate (MDI) as binders in their OSB products (Thelandersson and Larsen, 2003).

European OSB producers generally use thinnings and tops from more traditional commercial species such as Sitka spruce, Scots pine or Douglas fir. Typical binders used by European OSB producers include Phenol Resorcinol-Formaldehyde (PRF), Melamine Fortified Urea (MUF) and Methylene di-Phenyl di-Isocyanate (MDI) (Whelan, 2008, O'Toole, 2006, SmartPly, 2008).

![Figure 1-2 – Logs for OSB Production (Courtesy of SmartPly)](image)

1.3.2 Manufacturing Process

The OSB manufacturing process is summarised in Figure 1-3 below. Logs are debarked and fed into the strand cutter where they are sliced tangentially to produce elongated wood strands. The longitudinal axis of the wood strands is approximately aligned parallel to the grain direction of the log. The average
strand dimensions range from between 9 mm to 15 mm in length and are typically 30 mm in width (Whelan, 2008). The wood strands are sorted, dried, blended with the resin binder and stored in hoppers that feed the orienters.

Three different mats of resin-coated wood strands are formed laid on top of each other. They are passed to the hot press where they are heated under pressure,
causing the resin to cure, producing panels. The strand mats can be pressed either in a batch press as is common practice in North America or in a continuous as is common practice in Europe. The panels as they emerge from the press are considerably larger size than those sold commercially. They are typically cut to form smaller 2400 x 1200 mm panels before being packaged and dispatched.

1.3.3 Properties of OSB

The alignment of the wood strands in OSB panels results in a material that exhibits orthotropic properties similar to solid timber and plywood. The mechanical properties are enhanced under selected loading conditions when load is applied parallel to the longer dimension of the panel. This is one of the primary features of OSB that gives it a competitive advantage over other panel products that use a random strand orientation such as waferbord, particle board or MDF. OSB is the main competitor to plywood in the structural wood-based panel market. The mechanical performance of OSB tends to be slightly poorer than plywood when loaded in tension, compression and bending. However, OSB exhibits significantly better performance than plywood when loaded in shear. OSB also tends to be less variable than plywood because the internal structure of OSB panels results in a more uniform dispersion of natural defects.

1.3.4 European OSB Production and Design Codes

1.3.4.1 Regulating Bodies and Codes

OSB panels manufactured in Europe must comply with the European Committee for Standardisation (CEN) BS EN 300 (BSI, 2006). A set of characteristic values for the main mechanical properties has been published in BS EN 12369-1 (BSI, 2001) for structural use OSB panels.

1.3.4.2 Classification and Grading System

BS EN 300: 2006 (BSI, 2006) defines four different OSB panel classifications. The classifications are based upon the environmental exposure conditions and loading levels the board will be subjected to in service. Two sets of criteria are set by BS EN 300 before it can be certified. Table 1-1 below presents the
dimensional tolerance, moisture content and formaldehyde release requirements that OSB panels must conform to for all classifications.

<table>
<thead>
<tr>
<th>No.</th>
<th>Property</th>
<th>Test Method</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>Tolerance on Nominal Dimensions:</td>
<td>BS EN 324-1</td>
<td>± 0.3 mm</td>
</tr>
<tr>
<td></td>
<td>Thickness (Sanded within and between Boards)</td>
<td>(BSI, 1993e)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Thickness (Un-sanded within and between boards)</td>
<td></td>
<td>± 0.8 mm</td>
</tr>
<tr>
<td></td>
<td>Length and Width</td>
<td></td>
<td>± 3.0 mm</td>
</tr>
<tr>
<td>2a</td>
<td>Edge straightness tolerance</td>
<td>BS EN 324-2</td>
<td>1.5 mm/m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(BSI, 1993f)</td>
<td></td>
</tr>
<tr>
<td>3a</td>
<td>Squareness tolerance</td>
<td>BS EN 324-2</td>
<td>2.0 mm/m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(BSI, 1993f)</td>
<td></td>
</tr>
<tr>
<td>4a</td>
<td>Moisture content</td>
<td>BS EN 322</td>
<td>2% to 12%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(BSI, 1993c)</td>
<td></td>
</tr>
<tr>
<td>5b</td>
<td>Tolerance on mean density within a board</td>
<td>BS EN 323</td>
<td>± 15%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(BSI, 1993d)</td>
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<tr>
<td>6a</td>
<td>Formaldehyde release according to BS EN 13986</td>
<td>BS EN 120</td>
<td>Content ≤ 8 mg/100 g</td>
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<tr>
<td></td>
<td></td>
<td>(BSI, 1992a)</td>
<td>oven-dry board</td>
</tr>
<tr>
<td></td>
<td>- Class E1</td>
<td>BS EN 717-1</td>
<td>Release ≤ 0.124 mg/m³</td>
</tr>
<tr>
<td></td>
<td>Perforator valuef</td>
<td>(BSI, 2004a)</td>
<td>air</td>
</tr>
<tr>
<td></td>
<td>Steady-state emission valuec</td>
<td>BS EN 120</td>
<td>Content &gt; 8 mg/100 g</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(BSI, 1992a)</td>
<td>oven-dry board</td>
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<td>- Class E2</td>
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<td>(BSI, 2004a)</td>
<td>air</td>
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<tr>
<td></td>
<td>Steady-state emission value</td>
<td>BS EN 717-1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(BSI, 2004a)</td>
<td></td>
</tr>
</tbody>
</table>

(a) Certain users of OSB can require other tolerances (see separate performance standards, e.g. BS EN 12871)
(b) These values are characterised by a moisture-content in the material corresponding to a relative humidity of 65% and a temperature of 20°C.
(c) Experience has shown that to ensure compliance with the limit for class E1 the rolling average of the BS EN 120 values found from the factory production control over a period of six months should not exceed 6.5 mg formaldehyde 100 g panel mass for OSB.
(d) Initial type testing may be carried out for formaldehyde class E1 (established products only) on the basis of existing data with either BS EN 120 or per BS EN 717-1testing, either from factory production control or from external inspection, see BS EN 13986.
(e) For more detail concerning the formaldehyde classes and requirements, see BS EN 13986.
(f) The perforator values apply to boards with moisture content H of 6.5%. In the case of boards with different moisture content (in the range of 3% ≤ H ≤ 10%) the perforator value shall be multiplied by a factor P which can be calculated from the following equation: P = - 0.133 H + 1.86.

Table 1-1 – BS EN 300 General Requirements, all OSB Grades
The four different European OSB classifications are:

- **OSB/1** for non-load bearing interior use
- **OSB/2** for load bearing applications in permanently dry conditions
- **OSB/3** for load bearing applications in humid conditions
- **OSB/4** for heavy-duty load bearing applications in humid conditions

Table 1-2 below presents the mechanical performance criteria for OSB panels.

<table>
<thead>
<tr>
<th>Property</th>
<th>Test Method</th>
<th>Requirement Thickness Range (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>6 to 10</td>
</tr>
<tr>
<td>Major bending strength (N/mm²)</td>
<td>EN 310</td>
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</tr>
<tr>
<td>Minor bending strength (N/mm²)</td>
<td>EN 310</td>
<td>10</td>
</tr>
<tr>
<td>Major bending MOE (N/mm³)</td>
<td>EN 310</td>
<td>2500</td>
</tr>
<tr>
<td>Minor bending MOE (N/mm³)</td>
<td>EN 310</td>
<td>1200</td>
</tr>
<tr>
<td>Internal bond (N/mm³)</td>
<td>EN 319</td>
<td>0.30</td>
</tr>
<tr>
<td>24 h immersion swell (%)</td>
<td>EN 317</td>
<td>25</td>
</tr>
</tbody>
</table>

**OSB/2**

<table>
<thead>
<tr>
<th>Property</th>
<th>Test Method</th>
<th>Requirement Thickness Range (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>6 to 10</td>
</tr>
<tr>
<td>Major bending strength (N/mm²)</td>
<td>EN 310</td>
<td>22</td>
</tr>
<tr>
<td>Minor bending strength (N/mm²)</td>
<td>EN 310</td>
<td>11</td>
</tr>
<tr>
<td>Major bending MOE (N/mm³)</td>
<td>EN 310</td>
<td>3500</td>
</tr>
<tr>
<td>Minor bending MOE (N/mm³)</td>
<td>EN 310</td>
<td>1400</td>
</tr>
<tr>
<td>Internal bond (N/mm³)</td>
<td>EN 319</td>
<td>0.34</td>
</tr>
<tr>
<td>24 h immersion swell (%)</td>
<td>EN 317</td>
<td>20</td>
</tr>
</tbody>
</table>

**OSB/3**

<table>
<thead>
<tr>
<th>Property</th>
<th>Test Method</th>
<th>Requirement Thickness Range (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>6 to 10</td>
</tr>
<tr>
<td>Major bending strength (N/mm²)</td>
<td>EN 310</td>
<td>22</td>
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<tr>
<td>Minor bending strength (N/mm²)</td>
<td>EN 310</td>
<td>11</td>
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<tr>
<td>Major bending MOE (N/mm³)</td>
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<td>3500</td>
</tr>
<tr>
<td>Minor bending MOE (N/mm³)</td>
<td>EN 310</td>
<td>1400</td>
</tr>
<tr>
<td>Internal bond (N/mm³)</td>
<td>EN 319</td>
<td>0.34</td>
</tr>
<tr>
<td>24 h immersion swell (%)</td>
<td>EN 317</td>
<td>15</td>
</tr>
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</table>

**OSB/4**

<table>
<thead>
<tr>
<th>Property</th>
<th>Test Method</th>
<th>Requirement Thickness Range (mm)</th>
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<tr>
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<td>6 to 10</td>
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<td>Major bending strength (N/mm²)</td>
<td>EN 310</td>
<td>30</td>
</tr>
<tr>
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<td>EN 310</td>
<td>16</td>
</tr>
<tr>
<td>Major bending MOE (N/mm³)</td>
<td>EN 310</td>
<td>4800</td>
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<tr>
<td>Minor bending MOE (N/mm³)</td>
<td>EN 310</td>
<td>1900</td>
</tr>
<tr>
<td>Internal bond (N/mm³)</td>
<td>EN 319</td>
<td>0.50</td>
</tr>
<tr>
<td>24 h immersion swell (%)</td>
<td>EN 317</td>
<td>12</td>
</tr>
</tbody>
</table>

Table 1-2 – BS EN 300 Strength and Stiffness Requirements, all OSB Grades

After gaining initial certification, OSB manufacturers must demonstrate continued conformance to BS EN 300 using quality assurance testing programs.
BS EN 326 (BSI, 1994, BSI, 2000, BSI, 2003) outlines specific requirements that quality control testing programs must conform to. Manufacturers are required by BS EN 300 to obtain certification from an approved third-party organisation for all BS EN 300 compliant products prior to introducing them to the market.

1.4 Problem Statement

Despite their potential in terms of being sustainable, renewable, environmentally-friendly, economically viable building materials, engineered wood products are lagging behind other construction materials. This is largely due to outdated practices used in the development, production and use of these materials.

The aim of this research is to develop a unified approach that will address many of the outdated practices currently in use in OSB production and design. The first stage will be to comprehensively evaluate current commercially-available OSB/3 products and identify the key physical parameters that govern the mechanical behaviour. The results of experimental testing will be subjected to a series of statistical analyses with the aims of:

- Identifying suitable probability distribution models that can accurately represent the random nature in which these parameters vary so that they could be used, for example, in reliability-based design,
- Establishing relationships between physical and mechanical behaviour parameters,
- Establishing empirical relationships that can accurately describe mechanical behaviour of the material up to failure.

The final phase of the research includes a stochastic finite element model that can accurately reproduce the results obtained from the experimental testing program. This model will have the ability not only to represent the mechanical behaviour of the material but will have the ability to represent the random variability in the physical and mechanical behaviour parameters. This will enable the impact of the variability on the overall performance of the material to be accurately assessed.
1.5 Thesis Outline

This thesis is divided into a total of six chapters. These chapters are summarised as follows:

Chapter 1: Introduction

Provides a background to the research including development, current design and production control practice for OSB and concludes with a problem statement.

Chapter 2: Literature Review

Comprehensive review of previously published research on OSB focusing on experimental studies to evaluate the mechanical properties and on modelling studies using statistical models to predict strength properties of wood-based composites.

Chapter 3: Experimental Testing

Details of materials used, preparation of test specimens, testing arrangements, instrumentation, experimental procedures, discussion of results and conclusions.

Chapter 4: Statistical Analysis

Details of the statistical analysis of experimental data, statistical methods, development of customised computer software developed specifically for this study, discussion of results and conclusions.

Chapter 5: Numerical Modelling

Details of the material models used, implementation of finite element and Monte-Carlo simulation method, model validation through reproduction experimental observation, parameter studies, results discussion and conclusions.

Chapter 6: Conclusions

Review of the conclusions presented in each Chapter, commentary on the effectiveness of current study and proposals for further research.
2 Literature Review

2.1 Introduction

This chapter presents a review of the previously published research on evaluating and modelling the properties of wood-based composite materials. The review covers past research on topics relevant to this study including:

- Experimental and modelling studies of the mechanical behaviour and failure properties of wood-based composite materials,
- Experimental and modelling studies of the physical properties of wood-based composite materials,
- Statistical studies examining relationships between physical and mechanical properties, mathematical modelling of mechanical behaviour and determining probabilistic models to describe the variability of wood-based composite materials.

The end of the chapter summarises the findings of the literature review, identifies the gaps in the current knowledge and explains how the current research will go about addressing some of the gaps in the current knowledge.

2.2 Non-Aligned Wood Strand Composites

2.2.1 Background

The first wood-based composite materials were less sophisticated than modern wood-based composite materials. Materials including waferboard, particleboard and hardboard were not manufactured using specially prepared wood strands of a particular shape and size aligned in particular directions but of randomly aligned wood strands of varying shapes and sizes. The random nature of the internal structure of these materials sacrificed many of the benefits of solid timber such as enhanced mechanical properties in the parallel-to-grain direction. These materials bear little or no resemblance in terms of mechanical performance to modern wood-based composite materials. However parts of the manufacturing processes and many of the testing methods developed for traditional wood-based composites are still used today. One key feature shared by modern and traditional
wood-based composites is the presence of a vertical density profile. The shape of the vertical density profile can be controlled by the pressing cycle, which in turn influences the mechanical performance of the material. Therefore, many of the design and production techniques originally developed for the traditional wood-based composite materials are relevant to the current research.

2.2.2 Bending and Internal Bond Behaviour

2.2.2.1 Influence of Particle Geometry and Resin Content

Turner (1954) conducted one of the earliest studies on the potential use of wood-based composites made from wood strands and particles in structural applications. He concluded that wood-based composite materials had to offer mechanical performance that compared favourably with accepted wood materials using a resin content low enough to make them economically viable. Turner performed bending tests on a wide variety of laboratory-produced panels using different particle shapes and sizes, different resin contents and pressing cycles. Turner used phenol-formaldehyde resin and particles from a variety of sources and species including residues from sawmills and laboratory-produced wood particles. He also tested a set of laboratory-produced 7-ply Sitka-spruce plywood panels for comparison purposes.

Figure 2-1 – Variation of MOR and Resin Content with Particle Size (Turner, 1954)
Turner summarised his results in a chart (see Figure 2-1 above). The results show that long thin wood strands offer the best bending performance at the lowest possible resin content. Additionally, Turner discovered that the bending performance improved with increasing specific gravity and resin content but the level of enhancement was not as significant as increasing the strand length. Smaller strands offered improved dimensional stability when compared to panels comprising of long strands.

### 2.2.2.2 Influence of Vertical Density Profile

Early studies recognised that wood-based composites differed significantly from plywood or solid wood in that the density varies across the thickness of the panel. These studies adopted the term “vertical density profile” to describe this unique characteristic of wood-based composites. The vertical density profile of a typical panel is characterised by regions of relatively high density near the surfaces of the panel with a region of relatively low density towards the middle of the panel.

The vertical density profile has been shown to be dependent on the moisture content of the particle mat prior to pressing and the press cycle parameters. Carroll (1963) briefly discussed the influence of the core density on internal bond characteristics of wood-based composites as part of a wider study into the efficiency of different resins for use in particleboard manufacture. A previous study by Strickler (1959) concluded that the vertical density profile influenced the bending performance during his study into the effect of pressing and the wood-strand mat moisture content on the properties of particleboard.

Shen and Carroll (1969, 1970) performed one of the first studies focusing primarily on examining the influence of the vertical density profile on the mechanical properties of particleboards. They developed a new torsion-shear test for evaluating the planar-shear strength of particleboard (Shen and Carroll, 1969). They used the method to measure the shear strength at different depths of a variety of commercially-produced particleboards and generated a strength profile. Shen and Carroll performed regression analyses between layer density and planar-shear strength.
Figure 2-2 – Planar-Shear Strength Profile (Shen and Carroll, 1970)

Figure 2-2 above shows a plot of planar-shear verses depth published by Shen and Carroll. The results show that the planar-shear strength profile follows a similar “U” shape to that observed for the density profile. The results clearly show a deterioration of planar-shear strength with increasing distance from the panel surface and with decreasing density.

Nearn (1968) developed a new non-destructive method for assessing the continuous vertical density profiles of wood-based composites by adopting X-ray scanning technology originally developed by the metals industry. Studies by Woodson (1976, 1977) employed this new technology to evaluate the density profile of particleboard and fibreboard and examine its influence on bending, internal bond and screw withdrawal performance.

Figure 2-3 – Typical Vertical Density Profile for Particleboard (Woodson, 1976)

Figure 2-3 above presents a typical vertical density profile for particleboard evaluated using X-ray scanning technology. Woodson demonstrated that the panels with a high surface density and low core density exhibited superior
bending performance when compared to those with low surface or uniform density across the panel thickness. The results showed that panels with uniform density had superior internal bond and screw withdrawal performance.

2.2.3 Tension, Compression and Shear Behaviour

The USDA Forest Products Laboratory (FPL) commissioned the first extensive study to assess the mechanical behaviour of wood-based composites under a variety of loading condition. McNatt (1973) studied the strength and elastic properties of nine commercially-available particleboard products as well as a standard FPL Douglas-fir UF bound particleboard subjected to tension, compression, bending and shear. McNatt evaluated these properties in three mutually orthogonal directions (i.e. parallel and perpendicular to longer dimension of the panel and perpendicular to the panel surface).

McNatt developed cutting patterns similar to the one shown in Figure 2-4 below.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Property</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>Static Bending</td>
</tr>
<tr>
<td>C</td>
<td>Compression parallel-to-surface</td>
</tr>
<tr>
<td>$G_{pl}$</td>
<td>Plate-Shear</td>
</tr>
<tr>
<td>$S_c$</td>
<td>Edgewise Shear</td>
</tr>
<tr>
<td>$S_i$</td>
<td>Interlaminar Shear</td>
</tr>
<tr>
<td>T</td>
<td>Tension parallel-to-surface</td>
</tr>
<tr>
<td>IB</td>
<td>Internal Bond</td>
</tr>
</tbody>
</table>

Figure 2-4 – Typical Cutting Patterns (McNatt, 1973)

McNatt presented descriptive statistics for each property for each particleboard. He used regression analyses to investigate relationships between different
strength and mechanical properties. He concluded that linear relationships existed between:

- Interlaminar shear strength and internal bond strength,
- Plate-shear modulus and bending modulus of elasticity (MOE),
- Tension parallel-to-surface strength and modulus of rupture (MOR),
- Edgewise shear strength and tension parallel-to-surface strength.

McNatt did not state any conclusions regarding variations in mechanical performance between material directions. This study formed the basis for the publication of characteristic values for wood-based composite materials produced in accordance with USDA regulations. The methodology used in this study is still a standard format used in studies to evaluate the mechanical performance of wood-based composites (including the present study).

Hunt (1975) explored the possibility of using wood-based products to construct webs of composite structural timber I-joists. Hunt performed panel-shear tests on commercially-available particleboard panels and compared the results against commercially-available Structural I Sheathing grade plywood of similar thickness. He demonstrated that the particleboard had far superior panel-shear performance and offered an excellent opportunity to improve performance of structural timber I-joists.

2.2.4 Modelling of Non-Aligned Wood-Based Composites

2.2.4.1 Mechanical Properties

Hunt (1974) conducted one of the earliest attempts to model wood-based composites using the then new finite element method. He developed a computer model that combined the finite element method and Monte Carlo simulation to predict the elastic tension and shear properties of a homogenous particleboard. Hunt used simple regular framework of beam elements and 2-D plate elements. The beam elements represented the resin binder while the plate elements represented the wood strands (see Figure 2-5 below). Hunt’s model used the Monte Carlo method to represent the random grain orientation of each wood flake in the model based on a uniform probability distribution. The input for
Hunt’s model consisted of a database of experimentally-determined elastic properties for UF resin and for Douglas fir (Pseudotsuga menziesii) and Aspen (*populus*) wood flakes in three directions.

Hunt validated his model by comparing predictions against experimental results conducted on laboratory-produced particleboard panels. The results showed good agreement between the predicted and measured mechanical properties in tension with the model underestimating the tension modulus of elasticity (MOE) by 2% for Aspen flakes and by 3% for Douglas fir (Pseudotsuga menziesii) flakes. The model overestimated the shear modulus of elasticity by 15% and 20% for the Aspen and Douglas fir (Pseudotsuga menziesii) flakes respectively.

### 2.3 Experimental Studies of Aligned Wood-Strand Composites

#### 2.3.1 Introduction

Although still commercially-produced, the use of non-aligned wood-based composites such as particleboard, flakeboard, waferboard, fibreboard and particleboard in structural applications has largely ceased. They have largely been replaced by more sophisticated materials that are made using specially prepared wood strands that are aligned in particular directions. Aligned wood-
strand composites have been designed to retain the positive aspects of solid wood such as enhanced mechanical properties in one direction while still reducing the impact of the negative aspects such as knots and other defects. Modern aligned-strand wood composites include parallel strand lumber (PSL), oriented strandboard (OSB) and laminated veneer lumber (LVL).

The earliest attempts to create wood-based composite panels with orthotropic properties consisted of applying veneers to the surface of randomly-oriented wood composite materials to improve their performance (Fujii, 1958, McKeen et al., 1975, Batey et al., 1975). This approach produced composite materials that behaved in an orthotropic fashion similar to sawn lumber, plywood and glued-laminated timber. Although they offered a more efficient use of veneer stocks, these materials were difficult and expensive to produce. Researchers began to move away from single-layer, randomly aligned wood-strand mats and began to explore the potential offered by multi-layered wood-based composites materials manufactured from aligned wood strands.

2.4 **Experimental Research on OSB**

2.4.1 **Mechanical Properties of Oriented Strandboard**

Biblis (1985) conducted one of the earliest studies to evaluate the properties of OSB. He performed bending tests (parallel and perpendicular to face particle direction), plate-shear, panel-shear, internal bond, planar-shear and dimension stability tests on commercially-produced oriented strandboard. He compared the performance of the OSB panels against published design values for southern plywood and Aspen (Populus) waferboard. Biblis tested the panels after exposure to the following conditions:

- Conditioned to equilibrium moisture content at 72°F, 65% RH,
- Pressure-soaked for 48 hours,
- Pressure soaked for 48 hours then reconditioned to equilibrium at 72 °F. 65% RH.

The results showed that the OSB panels were inferior to the published values for Southern plywood in bending but were superior in all other mechanical
properties. The results also showed that the OSB was superior to Aspen (popluss) waferboard in most cases. Biblis concluded that southern hardwoods could be used to produce OSB that was an acceptable alternative to more traditional plywood and waferboard. Biblis (1989) followed up his research by testing panels from two other mills producing OSB from 100% Southern pine (*Pinus taeda* L.). Although the results showed good shear performance for all panels tested, the bending performance varied widely between the panels. He recommended that more detailed evaluation of the structural properties of OSB for uses other than sheathing in housing applications.

Lee (1988) conducted a study to evaluate and compare the shear properties of seven different wood-based composites (MDF, hardboard, two thicknesses of waferboard, OSB, particleboard and plywood). The aim of the study was to investigate the suitability of these materials for use as a web material for composite timber I-joists. He performed panel-shear and interlaminar shear tests on these materials at 50% and 85% RH with a constant temperature of 72°F. He concluded that hardboard had the best panel-shear properties at both humidity conditions while particleboard had the poorest panel-shear properties. MDF had the best planar-shear properties while the thicker waferboard panels had the poorest planar-shear properties. The results also showed that both MDF and OSB had better shear properties at both humidity levels that the plywood.

Thomas (2001) conducted one of the few studies on Poisson’s ratios for OSB. He evaluated the in-plane Poisson’s ratios of standard European OSB produced in accordance with BS EN 300 (BSI, 2006) from tension tests in accordance with BS EN 789 (BSI, 2004b). Thomas measured the surface strains over a gauge length of 101.6 mm at three locations in the middle of the tension test specimen (see Figure 2-6 below). He plotted the applied load verses the average strain in both directions for all test specimens (see Figure 2-7 below). The results suggested that the mean short-term in-plane Poisson’s ratios for OSB were 0.23 and 0.16. Moarcas (1999) previously investigated the Poisson’s ratios of particleboard using a four-point bending arrangement. He reported an average in-plane Poisson’s ratio of 0.2.
2.4.2 Design Values for Oriented Strandboard

One of the earliest codes to publish design values for strength and elastic modulus of OSB was the 1994 edition of CSA O86.1 (CSA, 1994) based on the results from a study commissioned by the Structural Board Association (SBA) and carried out by Forintek in Canada. The results of the study were summarised in detail by Karacabeyli (1996). The study involved extensive testing of Canadian waferboard and OSB panel products produced in accordance with CSA O325 (CSA, 2007). The results showed that in spite of being produced in accordance with the same standard, the properties varied widely between
products from different mills. The results of this study formed the basis for a new code CSA O452 (CSA, 2001b).

BS EN 12369-1 (BSI, 2001) gives characteristic values for all grades of OSB products produced in accordance with BS EN 300. The design values presented in BS EN 12369-1 are based on a study commissioned by the CEC and carried out by the Building Research Establishment in the UK, the Centre Technique du Bois et de l’Ameublement in France and the University of Surrey by Wickens and Griffiths (1995). A paper by Thomas (2001) contains some of the data obtained from this study through his participation in the University of Surrey test program. He presented the results of tension, compression, bending, planar-shear, panel-shear and punching shear tests in both directions on several thicknesses of OSB ranging from 9.0 to 19.5 mm produced by a single manufacturer. Thomas reported that OSB exhibited orthotropic behaviour when loaded in tension, compression and bending but not when loaded in panel-shear, planar-shear or punching shear.

![Figure 2-8 – Mechanical Properties for European OSB (Thomas, 2001)](image)

2.5 Modelling Research of Aligned-Strand Wood Composites

2.5.1 Empirical Modelling

models used regression analyses to fit mathematical expressions to experimental data. Shaler and Blankenhorn (1990) developed a theoretical model to predict the bending modulus of elasticity of oriented flakeboard using the rule of mixtures and the Halpin-Tsai equations. The variables included in the model were:

- Elastic moduli of the wood species,
- Elastic moduli of the resin,
- Geometry of the flakes,
- Alignment of the flakes,
- Volume fraction of the wood, the resin and air.

The model did not include the influence of the vertical density profile, inhomogeneities in the wood or the compatibility of the resin.

Figure 2-9 – Predicted vs Measured Bending MOE (Shaler and Blankenhorn, 1990)

Shaler and Blankenhorn (1990) validated their model by comparing predictions against bending test results conducted on laboratory-produced orientated flakeboard panels made from Aspen and red maple flakes bound with PF resin. They generated plots of predicted versus measured values for the bending
modulus of elasticity and concluded that the model underestimated the bending MOE by approximately 25%.

Suchsland (1989, 1991) developed a theoretical model to simulate the influence of the horizontal and vertical density distributions on the dimensional stability and internal bond performance cross aligned flakeboard. A computer program randomly generated flakeboard mat by varying the void space, number of flakes and number of overlaps at discrete locations within the mat. The computer program stored the mat structure in a matrix form (see Figure 2-10 below).

Suchsland validated his model by comparing predicted results against dimensional-stability and internal bond tests conducted on laboratory-produced flakeboard panels made from yellow-poplar strands bound with PF resin. The results showed excellent agreement between predicted and experimental values.

al., 2006b, 2006a). Although good agreement was observed between predicted and experimental values, most of these models were only validated against laboratory-produced panels where strict control could be executed over the manufacturing variables. Real manufacturing conditions are much more variable and much harder to control. Consequentially, most of the analytical models are of limited practical use and so are not discussed in any great detail.

2.5.2 Numerical Modelling

A much more promising approach to predicting the performance of aligned wood-based strand composites is the stochastic finite element method. A review by Taylor (1995) highlighted the potential usefulness of the stochastic finite element model in the wood engineering industry. However, relatively few examples of this approach are present in the literature.

Triche and Hunt (1988, 1989, 1993) developed one of the earliest 3-D finite element models for predicting properties of parallel aligned wood strand composites. Their model predicted the tension strength and stiffness properties of laboratory-produced, parallel-aligned yellow poplar wood composites bound with PF resin. The model treated the composite board as a three-phase material:

- The wood-strands,
- The resin,
- The wood-strand/resin interface.

The input consisted of the orthotropic tension strength and stiffness properties of the yellow-poplar strands, the properties of the resin and properties of the wood-strand/resin interface. Hunt and Triche performed an extensive laboratory testing program using individual and small assemblies of strands to collect data of the behaviour of individual strands and the strand/wood interface. The model used a typical three-dimensional 8-noded brick element with three degrees of freedom at each of the 8-nodes. Triche and Hunt explored the suitability of a variety of failure theories developed by the reinforced polymer industry including:

- Maximum Stress Theory (Schoutens and Kaman, 1982),
• American Institute of Timber Construction Interaction Equation (AITC, 1985),
• Tsai-Hill Interaction Equation (Schoutens and Kaman, 1982),
• Norris Interaction Equation (Norris, 1962),
• Tsai-Wu Tensor Polynomial Theory (Tsai and Wu, 1971).

They validated their model by experimentally testing small-scale laboratory-produced parallel-aligned wood strand boards. The model predicted the tensile elastic modulus properties of the laboratory-produced boards with excellent accuracy. However, Triche and Hunt reported mixed findings for tension strength prediction. They noted in their results that the AITC, Tsai-Hill, Norris and Tsai-Wu all calculated similar values for failure load and suggested that interaction-type theories were more suitable for predicting strength of wood-based composites.

Wang and Lam (1998b) conducted one of the earliest studies that took advantage of the stochastic finite element method to model simple parallel-aligned wood-based strand composites. They developed a 3-D non-linear stochastic finite element model to predict the probability distribution of the tension strength of parallel-aligned wood-based strand composites. The model also incorporated a size effect adjustment procedure based on the Weibull (1939) weakest link theory. Prior to developing the model, Wang and Lam conducted an extensive experimental test program to evaluate the tension strength and modulus of elasticity properties of single and multiple-ply Douglas fir wood strands. They used the results from the test program to:

• Establish suitability probability distributions to describe the natural variability in the strength and stiffness of the wood strands, and
• Evaluate the strength of the relationship (if any) between the strength, stiffness and volume of the wood-strands.

Wang and Lam validated their model by using it to predict the probability distribution for the failure load of three; four and six-ply wood strand assemblies
of two different lengths made from the same Douglas-fir used in the experimental test program (see Figure 2-11 below).

![Figure 2-11 – Predicted Probability Distribution for Strength (Wang and Lam, 1998b)](image)

The results show excellent agreement between the predicted and measured probability distributions.

The most extensive research published to date on stochastic finite element modelling of wood-based strand composites was conducted by Clouston and Lam (1995, 1998b, 1998a, 2001, 2001, 2002). This study was an extension of the work conducted by Wang and Lam reviewed above. Clouston extended the model's capabilities to include:
- Multiple-ply composites with strands of varying sizes, degrees-of-alignment and orientations,
- The ability to model compression and ultimately bending behaviour.

Clouston and Lam developed a simplified, idealised tri-linear stress-strain relationship to model the mechanical behaviour of Douglas-fir wood-strands (see Figure 2-12 below).

![Figure 2-12 – Idealized Stress-Strain Curve (Clouston and Lam, 2001)](image)

The model used the properties the wood-strands combined with Monte Carlo simulation to accurately predict the probability distributions for ultimate strength of multi-ply, cross-laminated parallel-aligned wood strand composites. The model used the Tsai-Wu failure criteria to model the failure behaviour. Clouston compared the predicted empirical distribution function (EDF) plots for ultimate strength against those obtained from experimental test results conducted on laboratory-produced panels.

Figure 2-13 below shows a comparison of the EDF plots predicted by Clouston’s model for multi-ply cross-laminated parallel-aligned wood strand composites stacked in $[\pm 15]_s$ and $[\pm 30]_s$ loaded in tension and compression. The results show that Clouston’s model predicted the correct probability distribution for the ultimate strength in tension and compression with a high degree of accuracy. Clouston expanded the capabilities of the model by using it to predict the probability distribution of ultimate bending strength.
2.6 Concluding Remarks

The preceding literature review discusses relevant past research conducted to investigate the mechanical behaviour of wood-based composite materials using a variety of empirical and numerical approaches. The results show that a considerable body of knowledge exists regarding the properties of OSB. However, most of the papers reviewed above do not provide any information regarding the probability distributions each property follows.

The stochastic finite element method as used by Hunt and Clouston seems to be the most effective approach for modelling the two key aspects of wood-based composite materials:

- The mechanical behaviour of wood-based composites under a variety of loading conditions, and
- The random variability of the parameters that define the material’s physical and mechanical properties.
The model developed by Clouston and Lam is the most extensive body of work conducted in this field to date. This model is capable of representing size effects and the degree-of-alignment of the wood strands on the mechanical performance but does not include the effects of other physical properties such as the vertical density profile. Clouston’s model also has not been tested for use with commercial OSB products.

The current research aims to generate the data necessary to determine the random variability of a range of physical and mechanical properties of commercial OSB/3 panels. The data will be generated through an extensive experimental testing program. The results from the experimental testing program will be supplemented by the development of a numerical model capable of predicting the mechanical behaviour of commercial OSB/3 panels based on the internal panel structure.
3 Experimental Testing

3.1 Introduction

This chapter provides the details of an experimental testing program where commercially available, three-layered OSB/3 panels were subjected to tension, compression, bending and panel-shear loading. The loads were applied both parallel and perpendicular to the longer dimension of the panels. Tests were also carried out to determine the moisture content and density properties of the panels. A total of five commercial OSB/3 panels in a variety of thicknesses from three different manufacturers were used. The commercial materials tested were manufactured in accordance with BS EN 300 (BSI, 2006).

All load-test procedures were designed in accordance with the requirements of BS EN 789 (BSI, 2004b). The moisture content test was conducted in accordance with BS EN 322 (BSI, 1993c). The density profile test was conducted in accordance with BS EN 323 (BSI, 1993d). The summary statistics presented here were calculated based on the assumption that samples come from populations that follow normal distributions. This was done in order to facilitate direct comparisons between results from different samples and to compare experimental results with characteristic values presented in the design code. Sample results are discussed in the context of mean values, 5<sup>th</sup> percentile values and their coefficients of variability.

In addition to testing commercial OSB/3 panels, a custom-produced batch of single-layer OSB panels fabricated from commercial OSB/3 panels was subjected to the same series of tests. The objective of testing single-layer OSB panels was to evaluate the physical properties and the mechanical performance of the individual plies that constitute commercially available OSB/3 panels. This is based on the approach used by the fibre reinforced polymers industry where the resultant properties of multi-ply, cross-laminated materials can be predicted based on the material lay-up and the properties of individual plies. The results from single-layer testing formed the input to a stochastic finite element model to predict the structural response of commercial OSB/3 panels subject to a variety
of loading conditions based on the panel lay-up and vertical density profile. This is discussed in detail in Chapter 5.

3.2 **Objectives of Experimental Testing Program**

The objectives of the experimentally testing commercial OSB/3 panels were to:

- Determine the physical properties and mechanical behaviour under a variety of loading conditions of a selection of commercial OSB/3 panels produced in accordance with BS EN 300 (BSI, 2006),
- Investigate the effect of loading angle relative to the longer dimension of the panel on the mechanical performance,
- Compare the characteristic values for mechanical properties achieved by the panels with those specified by BS EN 12369-1 (BSI, 2001),
- Study the mechanical behaviour and failure mechanisms of commercial OSB/3 under a variety of loading conditions.

The objectives of the experimentally testing single-layer OSB/3 panels were to:

- Determine the physical properties and mechanical behaviour under a variety of loading conditions of the layers that constitute commercial OSB/3 panels currently in production,
- Form the basis of an understanding of the effects that the strand-orientation, stacking sequence and through-the-thickness density variations have on the behaviour of commercial OSB/3 panels,

Additionally, experimental testing of commercial OSB/3 and single-layer OSB panels provided the necessary data required for:

- Identifying correlations between the physical properties, the mechanical properties and the mechanical behaviour (covered in Chapter 4).
- Advanced statistical analysis aimed at fitting suitable probability distribution models that could be used to represent the variability of the physical and mechanical properties in a stochastic finite element model (covered in Chapter 4).
- Validate predictions made by stochastic finite element models (Covered in Chapter 5).

### 3.3 Materials

The experimental test program used OSB/3 products produced by three different manufacturers and produced in accordance with BS EN 300 (BSI, 2006) using a variety of raw materials and processing technologies.

#### 3.3.1 Manufacturer A

Three different thicknesses (11 mm, 15 mm and 18 mm) of OSB/3 produced by Manufacturer A were tested. The panels produced by Manufacturer A were made using a mixture of Sitka spruce and Scots pine wood strands bound with Methylene Diphenyl Di-Isocyanate (MDI) resin pressed in a daylight press. The panels used to produce the single-layer OSB panels were 18 mm thick OSB/3 panels produced by Manufacturer A.

#### 3.3.2 Manufacturer B

One thickness (15 mm) of OSB/3 produced by Manufacturer B was tested. The panels produced by Manufacturer B were made using Scots pine and Lodgepole pine wood strands bound with Melamine Urea Phenol Formaldehyde (MUPF) resin in the surface-layers and Polymeric Di-Phenyl Methane Di-Isocynate (PMDI) in the core-layer pressed in a daylight press.

#### 3.3.3 Manufacturer C

One nominal thickness (15 mm) of OSB/3 produced by Manufacturer C was tested. The panels produced by Manufacturer C were made using pine wood strands bound with polymeric PMDI resin in the core-layer and MUPF resin in the surface-layers pressed in a continuous press.

### 3.4 Sampling

#### 3.4.1 Cutting Plans

A total of 32 cutting plans were prepared in prior to specimen preparation for each panel type. The cutting plans used in this test program were based on the
sample cutting plans presented in BS EN 789 (BSI, 2004b). Cutting plans were prepared using AutoCAD 2007 drafting software. Figure 3-1 below shows a sample cutting plan. A full set of cutting plans is presented in Appendix A.
3.4.2 Cutting

3.4.2.1 Manual Cutting

The first batch of test specimens was prepared using 11 mm, 15 mm and 18 mm panels produced by Manufacturer A. Fifteen cutting plans were selected at random and marked out on randomly selected panels for each nominal thickness. The specimen name, its orientation relative to the longer dimension of the panel and the lower left-hand corner were marked on each specimen prior to cutting for future reference. Figure 3-2 below shows a marked out panel prior to cutting.

![Figure 3-2 – Marked Out Panels](image)

The panels were cut to for the rough shape of the test specimens using a circular saw and cut to their final dimensions using a table-mounted panel saw. The curved sections of the tension and panel-shear test specimens were marked out using an MDF template and cut to their final shape using a band saw.

3.4.2.2 CNC Cutting

The computer numerically controlled (CNC) machine used was a SCM Record 100 NT located at the SIP Energy Ireland factory in Athenry, Co Galway controlled by SCM Group PanelMac software. This included a module that automatically generated the CNC code to cut each pattern from the AutoCAD file. The machine bed was sufficiently large to accommodate full-sized panels.

The test specimens were cut in two passes of the machine. The first pass cut the outline of the specimens to a depth 5 mm above the machine bed. The specimens
were labelled and screwed to the machine bed. The outline generated by the first pass ensured the screws were safely placed in locations that were not in the path of the cutting head. Two screws were used per test specimen and were located on diagonally-opposite corners of the test specimens where the resulting holes would not had any significant impact on test results. Figure 3-3 below shows a photograph of a 15 mm thick panel produced by Manufacturer C after the first pass of the CNC machine with the waste still in place.

Figure 3-3 – OSB Panel after First Pass of CNC Machine

A second pass of the CNC cut the specimens to their full depth. The waste was removed leaving the test specimens. Figure 3-4 below shows a photograph of a 15 mm thick panel produced by Manufacturer C after the second pass of the CNC machine with the waste removed.

Figure 3-4 – OSB Panel after Second Pass of CNC Machine (Waste Removed)
3.4.3 Single-Layer Panel Production

3.4.3.1 Aims

The aim of fabricating single-layer OSB panels was to determine the structural response of single-plies of OSB to facilitate the application of laminated plate theory to OSB. Laminated plate theory allows the resultant structural response of a laminated plate to be calculated as a function of the panel lay-up and the structural response of a single lamina of the material.

3.4.3.2 Raw Materials

The single-layer OSB was custom made for this project using 18 mm thick OSB/3 panels with a sanded finish supplied by Manufacturer A. Two different types of single-layer OSB panels were produced:

- Single-layer OSB panels consisting of surface-layer material,
- Single-layer OSB consisting of core-layer material.

3.4.3.3 Gluing

All single-layer panels were manufactured from two standard 18 mm thick OSB/3 panels glued together using a two-component structural sandwich panel adhesive (SikaForce-7710 L35 base and SikaForce-7020 hardener) (Sika, 2008). They were pressed overnight in a vacuum press located at the SIP Energy Ireland factory in Athenry, Co Galway. Figure 3-5 below shows the vacuum press loaded with a set of standard 18 mm thick OSB/3 panels after gluing.

![Figure 3-5 – Panels in Gluing Press after Gluing](image-url)
3.4.3.4 Milling

Single-layer OSB panels made from surface-layer material were made from two 18 mm thick panels glued together. The total thickness of the glued panels was approximately 37 mm (2 × 18 mm thick panels + 1 mm thick glue line). From trial runs, it was determined that the target thickness of the finished single-layer OSB panels should be approximately 11 mm. The panel was reduced to 11 mm with two passes of the CNC machine using a 25 mm diameter cutting head. The first pass reduced the panel thickness by 13 mm after which the panel was flipped over and reduced by the same amount on the other side. This process produced in a single-layer surface-layer material panel 11 mm thick (2 × 5 mm thick surface-layers + 1 mm thick glue line). This is demonstrated in Figure 3-6 below while Figure 3-7 and Figure 3-8 below show photographs of pass 1 and pass 2 of the milling process respectively.

![Figure 3-6 – Single-Layer OSB Production Stages (Surface Layer)](image)

![Figure 3-7 – Single-Layer OSB Production – Pass 1 (Surface Layer Material)](image)
Figure 3-8 – Single-Layer OSB Production – Pass 2 (Surface Layer Material)

Figure 3-9 below demonstrates the manufacturing process involved in producing single-layer panels produced from core-layer material.

Figure 3-9 – Single-Layer OSB Production Stages (Core Layer)
Milling 7.5 mm from one surface of two commercial OSB/3 panels removed in the high-density surface material from one face of the panels, resulting in low-density core layer material being exposed on the milled surfaces. The milled surfaces of two panels were glued together to produce a compound panel with a total thickness of 21 mm (2 × [18 - 7.5] mm thick panels + 1 mm thick glue line). The panel was reduced to 11 mm with two further passes of the CNC machine using a 25 mm diameter cutting head. The first pass reduced the panel thickness by 5 mm, removing the high-density surface layer material from one face of the compound panel. The compound panel was flipped over and reduced by a further 5 mm, removing the remaining high-density surface material. This resulted in a single-layer core-material panel 11 mm thick (2 × 5 mm thick single-layer OSB lamina + 1 mm thick glue line).

Figure 3-10 and Figure 3-11 below show photographs of pass 1 and pass 2 of the milling process respectively.
3.4.4 Specimen Naming

3.4.4.1 Standard OSB Panels

A five part labelling system was developed to keep track of the test specimens during this experimental testing program. The labelling system for test specimens cut from commercial OSB/3 test specimens followed the format:

Manufacturer – Cutting Pattern – Thickness – Load Condition – Direction

A test specimen labelled A-1-11-TENS-LONG means that it was produced by Manufacturer A, was cut according to Cutting Pattern 1, has a nominal thickness of 11 mm, and is loaded in tension parallel to the longer panel dimension. A summary of the abbreviations used for the different loading conditions and panel directions is given below in Table 3-1 and Table 3-2 respectively.

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Load Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>TENS</td>
<td>Tension</td>
</tr>
<tr>
<td>COMP</td>
<td>Compression</td>
</tr>
<tr>
<td>BEND</td>
<td>Bending</td>
</tr>
<tr>
<td>S(PANEL)</td>
<td>Panel-Shear</td>
</tr>
<tr>
<td>S(PLANE)</td>
<td>Planar-Shear</td>
</tr>
<tr>
<td>BEAR</td>
<td>Bearing</td>
</tr>
</tbody>
</table>

Table 3-1 – Abbreviations for Load Condition

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>LONG</td>
<td>Parallel to Longer Panel Side</td>
</tr>
<tr>
<td>LAT</td>
<td>Perpendicular to Longer Panel Side</td>
</tr>
</tbody>
</table>

Table 3-2 – Abbreviations for Orientation

3.4.4.2 Single-Layer OSB Panels

Test specimens from single-layer OSB panels were named using a slightly modified version of the naming system described above. The labelling system for commercial OSB/3 test specimens is of the following format:

Manufacturer – Cutting Pattern – Layer – Load Condition – Direction

For example, a test specimen labelled A-1-SURF-TENS-LONG indicates it was produced by Manufacturer A, was cut according to cutting Pattern 1, is made
from surface-layer material, is used for a tension test and is aligned parallel to the longer panel direction. A summary of the abbreviations used to identify which layer the single-layer panel is made from is given in Table 3-3 below.

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>SURF</td>
<td>Made using Surface Layer Material</td>
</tr>
<tr>
<td>CORE</td>
<td>Made using Core Layer Material</td>
</tr>
</tbody>
</table>

Table 3-3 – Abbreviations for Identifying Material

3.5 Mechanical Testing:

All mechanical testing used in this study was conducted in accordance with BS EN 789 (BSI, 2004b). All test specimens were conditioned to equilibrium moisture content at 20ºC (± 2ºC) and 65% (± 5%) relative humidity prior to testing. Test pieces were weighted prior to entry into the chamber and weighed intermittently at minimum intervals of 24 hours. Equilibrium mass was said to had been attained when the results of two successive weighing operations did not differ by more than 1%. All weighing operations were performed to an accuracy of 0.1 g.

Test specimens were loaded in “displacement control” mode i.e. loaded at a constant rate of strain as opposed to a constant rate of stress. This was to ensure that the instrumentation could accurately capture the data, particularly at or near specimen failure. Load and displacement measurements were continuously monitored using a National Instruments NI CDAQ-9172 modular data acquisition system and LabVIEW 8.2 signal processing software.

3.5.1 Tensile Testing:

3.5.1.1 Test Piece Details:

The test specimen used followed the same basic profile as the one described in BS EN 789 (BSI, 2004b) with slightly modified dimension as used by Chui (2001) and O’Toole (2006). Like most materials, varying the test specimen size has been shown to influence the results of tension tests performed on wood-based composites (Schwab et al., 2007). Past research shows that the mean tensile strength of brittle materials tends to decrease as the volume of the material
increases. This has been attributed to the increased probability of the presence of a strength-reducing flaw in the material with increasing volume. Adopting the same dimensions enabled the results from the study conducted by O’Toole to be incorporated into the results of this study without having to allow for size effects. All tension test specimens were cut to a tolerance of ±5 mm using either the manual cutting method described in Section 3.4.2.1 above or the CNC cutting method described in Section 3.4.2.2 above.

![Figure 3-12 – Modified Tensile Test Piece (O’Toole, 2006, Chui, 2001)](image)

The finished dimensions, thickness and gauge length of the test specimens were measured and recorded using an electronic calliper with an accuracy of 0.02 mm. The dimensions and thickness reported in the results section is taken as the average of the readings taken at the locations indicated in Figure 3-13 below.

![Figure 3-13 – Tensile Test Piece (Recorded Dimensions)](image)

### 3.5.1.2 Testing arrangement

Figure 3-14 below demonstrates the tension testing arrangement. The test specimen was gripped by the end tabs using hydraulic grips of a Dartec 250 kN universal hydraulic testing machine. The gripping pressure varied according to the thickness of the material being tested. The displacement was measured by mounting two MPE type HS full bridge linearly varying differential transducers (LVDTs) with a ram length of 5 mm. Displacement was recorded over a gauge...
length of 120 mm. The LVDTs were mounted to the test specimen using specially fabricated mounting blocks that were bolted together through the test specimen using M3 bolts with as 5 mm diameter contact area between the mounting blocks.

![Figure 3-14 – Tension Testing Arrangement](image)

### 3.5.1.3 Loading Rates

Loading rates were determined to ensure the test specimen failed within 300 ± 120 s. Loading rates were estimated using Equation 3.1 below and the code of practice values for tension strength and elastic modulus presented in BS EN 12369-1:2001 (BSI, 2001).

\[
\delta h_{\text{est}} = \frac{f_{t,\text{est}} L_G}{E_{t,\text{est}} T}
\]

where: \( \delta h_{\text{est}} \) = estimated crosshead movement rate; \( f_{t,\text{est}} \) = estimated tensile ultimate strength; \( L_G \) = distance between machine grips; \( E_{t,\text{est}} \) = estimated tensile elastic modulus; \( T \) = average test time

The loading rates were adjusted as necessary following the first few test runs. The adjusted loading rates for each panel type, thickness and direction were summarised in Table 3-4 below.
### 3.5.1.4 Sample Size

Initially, fifteen 11 mm, 15 mm and 18 mm thick OSB/3 panels produced by Manufacturer A were manually cut as described in Section 3.4.2.1 above and tested using the arrangement described in Section 3.5.1.2 above. Based on the results from the first batch of tests, eight additional 11 mm thick panels were CNC cut as described in Section 3.4.2.2 above to produce additional tension test specimens. The eight additional panels were cut to make tension test specimens only, i.e. no test specimens were produced for any other loading conditions. Fifteen 15 mm thick OSB/3 panels produced by Manufacturers B and C were CNC cut as described in Section 3.4.2.2 above. Twenty surface-layer (fifteen of which were tested) and four core-layer panels were CNC cut as described in Section 3.4.2.2 above.

Table 3-5 and Table 3-6 below present the final number of tension test replications performed for each panel type, thickness and direction.

<table>
<thead>
<tr>
<th>Manufacturer A</th>
<th>Manufacturer B</th>
<th>Manufacturer C</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Thickness</strong></td>
<td>LONG (mm/s)</td>
<td>LAT (mm/s)</td>
</tr>
<tr>
<td>11 mm</td>
<td>0.008</td>
<td>0.008</td>
</tr>
<tr>
<td>15 mm</td>
<td>0.010</td>
<td>0.010</td>
</tr>
<tr>
<td>18 mm</td>
<td>0.012</td>
<td>0.008</td>
</tr>
</tbody>
</table>

**Table 3-4 – Tensile Test Loading Rates**

<table>
<thead>
<tr>
<th>Manufacturer A</th>
<th>Manufacturer B</th>
<th>Manufacturer C</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Thickness</strong></td>
<td>LONG</td>
<td>LAT</td>
</tr>
<tr>
<td>11 mm</td>
<td>65(^1)</td>
<td>49</td>
</tr>
<tr>
<td>15 mm</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>18 mm</td>
<td>15</td>
<td>15</td>
</tr>
</tbody>
</table>

\(^1\) Includes 15 tests conducted as part of previous study (O'Toole, 2006)

**Table 3-5 – Tensile Test Repetitions (Commercial OSB/3 Panels)**

<table>
<thead>
<tr>
<th>Manufacturer A</th>
<th>Manufacturer B</th>
<th>Manufacturer C</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Material</strong></td>
<td>LONG</td>
<td>LAT</td>
</tr>
<tr>
<td>SURF</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>CORE</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

**Table 3-6 – Tensile Test Repetitions (Single-Layer OSB)**
3.5.1.5 Results

3.5.1.5.1 Material Properties

The material properties were calculated using the methods described in BS EN 789 (BSI, 2004b). The tensile ultimate strength was calculated using Equation 3.2 below.

\[
\sigma_{u,t} = \frac{F_{\text{max}}}{A}
\]  

(3.2)

where: \( \sigma_{u,t} \) = tensile ultimate strength; \( F_{\text{max}} \) = maximum load; \( A \) = cross-sectional area at failure location

The tensile ultimate strain was calculated using Equation 3.3 below.

\[
\varepsilon_{u,t} = \frac{u_{\text{max}}}{l_1}
\]  

(3.3)

where: \( \varepsilon_{u,t} \) = tensile ultimate strain; \( u_{\text{max}} \) = displacement corresponding to maximum load; \( l_1 \) = gauge length

The tensile elastic modulus was calculated using the section of the load-displacement curve falling between \( 0.1F_{\text{max}} \) and \( 0.4F_{\text{max}} \) (see Figure 3-16 below) using Equation 3.4 below.

\[
E_t = \frac{(F_2 - F_1) l_1}{(u_2 - u_1) A}
\]  

(3.4)

where: \( E_t \) = tensile elastic modulus; \( F_1 = 0.1F_{\text{max}} \); \( F_2 = 0.4F_{\text{max}} \); \( u_1 \) = displacement corresponding to \( F_1 \); \( u_2 \) = displacement corresponding to \( F_2 \); \( l_1 \) = gauge length; \( A \) = cross-sectional area of necked section

A custom-developed computer program used Equations 3.2 to 3.4 to automatically calculate the tensile ultimate strength, tensile ultimate strain and tensile elastic modulus from the raw experimental data. The computer program was developed using Microsoft Visual Basic for Applications (VBA) and embedded into a Microsoft Excel 2003 template. This will be discussed in more detail in Chapter 4 below.

Table 3-7 and Table 3-8 below present a summary of the results for tensile ultimate strength, ultimate strain and elastic modulus for the commercial OSB/3 and single-layer panels respectively.
### Table 3-7 – Tension Test Results Summary (Commercial OSB/3 Panels)

<table>
<thead>
<tr>
<th>Panel Type</th>
<th>Ultimate Strength</th>
<th>Ultimate Strain</th>
<th>Elastic Modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (N/mm²)</td>
<td>CoV (%)</td>
<td>Mean (×10³)</td>
</tr>
<tr>
<td>Long</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-11mm</td>
<td>11.07</td>
<td>19.91</td>
<td>3.13</td>
</tr>
<tr>
<td>A-15mm</td>
<td>13.19</td>
<td>15.44</td>
<td>3.55</td>
</tr>
<tr>
<td>A-18mm</td>
<td>10.86</td>
<td>15.51</td>
<td>3.51</td>
</tr>
<tr>
<td>B-15mm</td>
<td>10.32</td>
<td>11.10</td>
<td>3.33</td>
</tr>
<tr>
<td>C-15mm</td>
<td>10.57</td>
<td>18.78</td>
<td>2.89</td>
</tr>
<tr>
<td>Lat</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-11mm</td>
<td>9.48</td>
<td>19.46</td>
<td>3.22</td>
</tr>
<tr>
<td>A-15mm</td>
<td>10.51</td>
<td>8.43</td>
<td>3.90</td>
</tr>
<tr>
<td>A-18mm</td>
<td>8.94</td>
<td>20.21</td>
<td>3.25</td>
</tr>
<tr>
<td>B-15mm</td>
<td>8.94</td>
<td>9.98</td>
<td>3.27</td>
</tr>
<tr>
<td>C-15mm</td>
<td>6.76</td>
<td>12.64</td>
<td>3.18</td>
</tr>
</tbody>
</table>

1) Includes 15 tests conducted as part of previous study (O'Toole, 2006)

### Table 3-8 – Tension Test Results Summary (Single-Layer OSB Panels)

<table>
<thead>
<tr>
<th>Panel Type</th>
<th>Ultimate Strength</th>
<th>Ultimate Strain</th>
<th>Elastic Modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (N/mm²)</td>
<td>CoV (%)</td>
<td>Mean (×10³)</td>
</tr>
<tr>
<td>Long</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-SURF</td>
<td>20.08</td>
<td>14.82</td>
<td>4.08</td>
</tr>
<tr>
<td>A-CORE</td>
<td>3.56</td>
<td>10.04</td>
<td>3.13</td>
</tr>
<tr>
<td>Lat</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-SURF</td>
<td>9.90</td>
<td>9.93</td>
<td>4.07</td>
</tr>
<tr>
<td>A-CORE</td>
<td>6.91</td>
<td>46.55</td>
<td>2.63</td>
</tr>
</tbody>
</table>

1) Calculated using a sample size of 4 assuming a normal distribution

A detailed discussion of test results is presented below in Section 3.5.1.6 below while details of more rigorous statistical analyses were presented in Chapter 4.

#### 3.5.1.5.2 Mechanical Behaviour

Figure 3-15 below shows a typical load vs displacement curve observed for an 11 mm thick OSB/3 panel produced by Manufacturer A loaded in longitudinal tension. Figure 3-16 below shows a typical stress vs strain curve observed for an 11 mm thick OSB/3 panel produced by Manufacturer A loaded in longitudinal tension. A more comprehensive set of results is presented in Appendix B. Note that the red section shown in Figure 3-16 below represents the section of the stress-strain curve over which the tensile elastic modulus was calculated.
The load-displacement and stress-strain curves in Figure 3-15 and Figure 3-16 above respectively demonstrate that the mechanical behaviour is non-linear at high strains. The tension test specimens failed in a brittle mode with little or no
warning of the onset of failure. This is reflected by the abrupt end to the load-displacement and stress-strain curves shown above in Figure 3-15 and Figure 3-16 above. Inspection of the failure surface showed that the failure mechanism consisted of a combination of strand failure and bond failure. Figure 3-17 below shows a tension failure surface for a lateral tension test conducted on a 15 mm thick OSB/3 panel produced by Manufacturer C.

Figure 3-17 – Tension Failure Surface

Figure 3-17 above indicates that some of the wood strands that transverse the failure surface were fractured while others were still intact but had debonded from the wood strands at the opposite side of the failure surface.

3.5.1.6 Discussion

3.5.1.6.1 Tensile Ultimate Strength

Figure 3-18 below compares the mean and 5th percentile tensile ultimate strength results in both material directions for the materials tested.
Figure 3-18 – Tensile Ultimate Strength

The A-SURF panels had the overall highest mean (20.04 N/mm$^2$) and 5th percentile (15.26 N/mm$^2$) tensile ultimate strength while the A-CORE panels had the overall lowest mean (3.56 N/mm$^2$) and 5th percentile (3.10 N/mm$^2$) tensile ultimate strength in the longitudinal direction. This reflects the fact that:

- The A-SURF-TENS-LONG test specimens consisted of high-density wood strands aligned parallel to the direction of loading,
- The A-CORE-TENS-LONG test specimens consisted of low-density wood strands aligned perpendicular to the loading direction.

Note also that A-SURF panels had a mean (9.90 N/mm$^2$) and 5th percentile (8.69 N/mm$^2$) tensile ultimate strength in the lateral direction. This is comparable to the results obtained for tensile ultimate strength in the lateral direction despite the fact that in the case of the A-SURF panels, the tensile load is resisted entirely by wood strands orientated at 90º to the loading direction. This suggests that the increasing the density of the wood strands enhances the mechanical performance in both parallel and perpendicular to the wood strand orientation.
The A-CORE panels had a higher mean (8.86 N/mm²) and 5th percentile (8.07 N/mm²) tensile ultimate strength in the lateral direction than in the longitudinal direction. This reflects the fact that:

- The A-CORE-TENS-LAT test specimens consisted of low-density wood-strands aligned parallel to the loading direction,
- The A-CORE-TENS-LONG test specimens consisted of low-density wood strands aligned perpendicular to the loading direction.

When loaded parallel to the wood strand direction, the results from the A-CORE-TENS-LAT test specimens show the low-density A-CORE panels achieved a mean (8.86 N/mm²) and 5th percentile (8.07 N/mm²) tensile ultimate strength. This is comparable to the tensile ultimate strength of standard commercial OSB/3 panels loaded in the lateral direction and A-SURF panels in loaded a right angles to the wood strand direction. This demonstrates that:

- The direction of loading relative to the orientation of the wood strands in individual layers of commercial OSB/3 panels has a significant influence on the tensile ultimate strength of the layers.
- The density of the constituent layers that comprise commercial OSB/3 panels has a significant influence on the strength of the layers.
- The stacking sequence and layer density of commercial OSB/3 panels has a significant influence on the performance of commercial OSB/3 panels.

Of the commercial OSB/3 panels, the A-15mm panels had the highest mean (13.19 N/mm²) and 5th percentile (9.67 N/mm²) tensile ultimate strength in the longitudinal direction. The B-15mm panels had the lowest mean (10.32 N/mm²) tensile ultimate strength in the longitudinal direction. The C-15mm panels had the lowest 5th percentile (7.12 N/mm²) tensile ultimate strength in the longitudinal direction. This is likely due to the greater variability of the C-15mm panels (CoV = 18.78%) when compared to the B-15mm panels (CoV = 11.10%). This means that the B-15mm panels had a higher characteristic tensile ultimate
strength despite the fact that the mean tensile ultimate strength of the C-15mm panels is greater than that for the B-15mm panels. This demonstrates that:

- Characteristic values for material strengths were generally taken as 5\textsuperscript{th} percentile values rather than mean values because the mean values do not accurately reflect the degree of variability of the material,
- Reducing the variability of the material strength offers significant scope for increasing the characteristic material strength values.

In the lateral direction, the A-15mm panels had the highest mean (10.51 N/mm\textsuperscript{2}) and 5\textsuperscript{th} percentile (9.35 N/mm\textsuperscript{2}) tensile ultimate strength values. The C-15mm panels had the lowest mean (6.76 N/mm\textsuperscript{2}) and 5\textsuperscript{th} percentile (5.60 N/mm\textsuperscript{2}) tensile ultimate strength in the lateral direction.

### 3.5.1.6.2 Tensile Ultimate Strain

Figure 3-19 below compares the mean and 5\textsuperscript{th} percentile tensile ultimate strain results in both material directions for the materials tested.

![Tensile Ultimate Strain](image)

The results show that the A-SURF panels had the highest mean (4.08×10\textsuperscript{-3}) and 5\textsuperscript{th} percentile (3.12×10\textsuperscript{-3}) tensile ultimate strain in the longitudinal direction. The
A-SURF panels had the highest mean \( (4.07 \times 10^{-3}) \) and 5\(^{th}\) percentile \( (3.40 \times 10^{-3}) \) tensile ultimate strain in the lateral direction. The A-CORE panels had the lowest mean \( (2.63 \times 10^{-3}) \) tensile ultimate strain in the lateral direction.

Of the commercial OSB/3 panels, the B-15mm panels had the highest mean \( (3.33 \times 10^{-3}) \) and 5\(^{th}\) percentile \( (2.95 \times 10^{-3}) \) tensile ultimate strain in the longitudinal direction. The C-15mm panels had the lowest mean \( (2.89 \times 10^{-3}) \) and 5\(^{th}\) percentile \( (2.24 \times 10^{-3}) \) tensile ultimate strain in the longitudinal direction. The A-15mm panels had the highest mean \( (3.90 \times 10^{-3}) \) and 5\(^{th}\) percentile \( (3.27 \times 10^{-3}) \) tensile ultimate strain in the lateral direction. The C-15mm panels had the lowest mean \( (3.18 \times 10^{-3}) \) tensile ultimate strain in the lateral direction. The A-11mm panels had the lowest 5\(^{th}\) percentile \( (2.20 \times 10^{-3}) \) tensile ultimate strain in the lateral direction. This is likely due to the increased variability of the tensile ultimate strain results for the A-11mm panels \( (CoV = 17.91\%) \) when compared to the C-15mm panels \( (CoV = 12.57\%) \).

3.5.1.6.3 Tensile Elastic Modulus

Figure 3-20 below compares the mean and 5\(^{th}\) percentile tensile elastic modulus results in both material directions for the materials tested.
As was the case with tensile ultimate strength, the A-SURF panels had the highest mean (5538 N/mm²) and 5th percentile (4907 N/mm²) tensile elastic modulus in the longitudinal direction. The A-CORE panels had the lowest mean (1355 N/mm²) and 5th percentile (1176 N/mm²) tensile elastic modulus in the longitudinal direction. The reasons for this were the same as described for tensile ultimate strength in 3.5.1.6.1 above.

The A-CORE panels achieved a mean (3863 N/mm²) and 5th percentile (3624 N/mm²) tensile elastic modulus when loaded parallel to the wood strands. This is lower than for A-SURF panels loaded parallel to the wood strands, is greater than A-SURF wood strands loaded perpendicular to the wood strands and is comparable to commercial OSB/3 panels loaded in the lateral direction. The significance of these findings in terms of assessing the performance of commercial OSB/3 panels is:

- When loaded in the longitudinal direction, the surface-layers of OSB/3 panels will carry a significantly greater proportion of the load than the core-layer. This implies that it is likely that the surface-layers will reach their tensile ultimate strength before the core-layers. This means that the failure of commercial OSB/3 panels loaded in tension in the longitudinal direction would be initiated by failure of the surface-layers followed by redistribution of load to the core-layer rapidly followed by failure of the core-layer.

- When loaded in the lateral direction, the core-layer of commercial OSB/3 panels will take a slightly greater proportion of the load than the surface-layers. This implies that it is likely that the core-layer will reach its tensile ultimate strength before the surface-layers. This means that failure of a commercial OSB/3 panels loaded in tension in the lateral direction would be initiated by failure of the core-layer followed redistribution of the load to the surface-layers. It is likely that the surface-layers had significant reserve load carrying capacity post the core failure due to their lower elastic modulus and greater tensile ultimate strength. Therefore, core failure of a commercial OSB/3 panel subject to lateral tension may not
result in a global failure but will result in a significant increase in deformation as load is transferred from the core to the surface-layers.

Of the commercial OSB/3 panels, the A-15mm panels had the highest mean (4458 N/mm²) and 5th percentile (3904 N/mm²) tensile elastic modulus in the longitudinal direction. The B-15mm panels had the lowest mean (3684 N/mm²) tensile elastic modulus. The A-18mm panels had the lowest 5th percentile (3147 N/mm²) tensile elastic modulus in the longitudinal direction. As was the case with the tensile ultimate strength described in 3.5.1.6.1 above, this is likely due to the greater variability of the longitudinal tensile elastic modulus of the A-18mm panels ($CoV = 11.47\%$) when compared to the B-15mm panels ($CoV = 10.02\%$).

It is worth highlighting the clear downward trend in the mean longitudinal tensile elastic modulus with increasing panel thickness for panels produced by Manufacturer A. This is not reflected by the 5th percentile longitudinal tensile elastic modulus values with the value for the A-15mm panels (3904 N/mm²) being greater than for the A-18mm panels (3147 N/mm²) and for the A-11mm panels (3256 N/mm²). This is likely due to the lower variability of the longitudinal tensile elastic modulus for the A-15mm panels ($CoV = 8.72\%$) when compared to the A-11mm panels (15.57%) and the A-18mm panels (11.47%).

In the lateral direction, the A-11mm panels had the highest mean (3526 N/mm²) tensile elastic modulus value. The A-15mm panels had the highest 5th percentile (2825 N/mm²) tensile elastic modulus value in the lateral direction. As stated above, this is likely due to the fact that the lateral tensile elastic modulus of A-11mm panels is more variable ($CoV = 16.31\%$) when compared to the A-15mm panels ($CoV = 10.02\%$) as shown in Table 3-7 above. The C-15mm panels had the lowest mean (2736 N/mm²) and 5th percentile (2335 N/mm²) tensile elastic modulus values in the lateral direction.

Unlike in the longitudinal direction, there were no clear trends in terms of the values of lateral tensile elastic modulus for the panels produced by Manufacturer A. It is possible that increasing the sample size may reveal a similar trend.
3.5.1.7 Degree-of-Orthotropy

The degree-of-orthotropy is a value used to compare the relative performance of orthotropic materials in different material directions. It can be calculated for any material property using Equation 3.5 below.

\[
o = \frac{Material \ Property \ in \ Direction \ 1}{Material \ Property \ in \ Direction \ 2}
\]  \hspace{1cm} (3.5)

The degree-of-orthotropy for isotropic materials has a value of 1 for all material properties (i.e. material property in Direction 1 equals the same material property in Direction 2). A value of \( r \) such that \( 0 \leq o < 1 \) implies that the value of a material property in Direction 1 is less than the value of the same material property in Direction 2. A value of \( o > 1 \) indicates that the value of a material property in Direction 1 is greater than the value of the same material property in Direction 2. Therefore, for an orthotropic material, the closer the value of the degree-of-orthotropy is to 1, the more isotropic the material.

Table 3-9 below presents the degree-of-orthotropy for the tensile properties for each material tested.

<table>
<thead>
<tr>
<th>Panel Type</th>
<th>Mean</th>
<th>5th Percentile</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ultimate Strength</td>
<td>Ultimate Strain</td>
</tr>
<tr>
<td>A-11mm</td>
<td>0.856</td>
<td>1.029</td>
</tr>
<tr>
<td>A-15mm</td>
<td>0.797</td>
<td>1.097</td>
</tr>
<tr>
<td>A-18mm</td>
<td>0.827</td>
<td>0.925</td>
</tr>
<tr>
<td>B-15mm</td>
<td>0.866</td>
<td>0.981</td>
</tr>
<tr>
<td>C-15mm</td>
<td>0.639</td>
<td>1.102</td>
</tr>
<tr>
<td>A-SURF</td>
<td>0.493</td>
<td>0.998</td>
</tr>
<tr>
<td>A-CORE</td>
<td>2.485</td>
<td>0.841</td>
</tr>
</tbody>
</table>

Table 3-9 – Degree-of-Orthotropy Results for Tensile Properties

3.5.1.7.2 Tensile Ultimate Strength

The results indicate that all materials tested exhibit orthotropic behaviour in terms of tensile ultimate strength. This is demonstrated by the fact that the degrees of-orthotropy for all materials tested had values that were less than or greater than a value of 1.
As anticipated, the A-SURF panels were the most orthotropic in terms of their mean (0.493) and 5th percentile (0.568) tensile ultimate strength values, both of which were significantly less than a value of 1. These values indicate that the tensile ultimate strength in the longitudinal direction (i.e. parallel to the wood strands) is approximately twice that in the lateral direction (i.e. perpendicular to the wood strands). The A-CORE panels were orthotropic in the opposite manner in terms of their mean (2.485) and 5th percentile (2.603) tensile ultimate strength values, both of which were significantly greater than a value of 1. These values indicate that the tensile ultimate strength in the lateral direction (i.e. parallel to the wood strands) is approximately twice that in the longitudinal direction (i.e. perpendicular to the wood strands).

Of the commercial OSB/3 panels, the C-15mm panels were the most orthotropic in terms of mean (0.639) tensile ultimate strength. The A-18mm panels were the most orthotropic in terms of 5th percentile (0.715) tensile ultimate strength. The B-15mm panels were the least orthotropic in terms of mean (0.866) and 5th percentile (0.831) tensile ultimate strengths. These results suggest that the longitudinal tensile ultimate strength is in the range of 1.2 to 1.4 times of the lateral tensile ultimate strength thereby showing that the commercial OSB/3 panels exhibit enhanced tensile strength in the direction parallel to the longer dimension of the panel.

The increased orthotropy of the single-layer panels reflects the fact that they consist of wood strands aligned in a single direction only. Therefore the natural orthotropic behaviour exhibited by solid timber is more apparent in the single-layer panels than the multi-layered layered commercial OSB/3 panels. The commercial OSB/3 panels were less orthotropic than the single-layer panels but still behave in an orthotropic manner. This is because the 90º core-layer reduces the natural orthotropic behaviour associated with solid timber. The test results show that the core-layer is significantly weaker when loaded both parallel and perpendicular to the wood strands. This partly explains why the introduction of a layer of wood-strands aligned perpendicular to the surface layer strands does not eliminate the orthotropic behaviour entirely.
3.5.1.7.3 **Tensile Ultimate Strain**

The results presented in Table 3-9 above suggested that no orthotropy exists for both mean and 5th percentile tensile ultimate strain. This is highlighted by the fact that all degree-of-orthotropy values for all materials both in terms of mean and 5th percentile values were approximately equal to a value of 1. This suggests that unlike tensile ultimate strength, tensile ultimate strain does not exhibit orthotropic behaviour.

A Student’s t-test was conducted to determine conclusively if the longitudinal and lateral tensile ultimate strains were equal. The Student’s t-test is a statistical hypothesis test based on the Student’s t-distribution. It is used to determine if two samples come from the same population i.e. test if the two samples had the same mean. The test statistic used in the Student’s t-test is calculated from Equation 3.6 below.

\[
t = \frac{|\bar{x}_1 + \bar{x}_2|}{\sqrt{AB}}
\]

(3.6)

where: \(\bar{x}_1\) = sample mean from sample 1; \(\bar{x}_2\) = sample mean from sample 2; 
\(A = (n_1 + n_2)/n_1n_2\); \(n_1\) = sample size for sample 1; \(n_2\) = sample size for sample 2; 
\(B = [(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2]/[n_1 + n_2 - 2]; s_1 = sample standard deviation for sample 1; s_2 = sample standard deviation for sample 2.

The test statistic is used to calculate a probability that the null hypothesis is correct based on the Student’s t-distribution and the number of degrees-of-freedom in the system which is calculated using Equation 3.7 below.

\[
df = (n_1 + n_2) - 2
\]

(3.7)

Probability tables had been published by Gossett (1908) (under the name Student) for different values of \(t\) for different degrees of freedom. For the purpose of this study, the probabilities associated with \(t\) were calculated using Microsoft Excel. A level of significance of \(\alpha = 0.05\) was used throughout this study. If the value of \(p\) for any value of \(t\) is less than the chosen significance level \(\alpha\), the null hypothesis is immediately rejected i.e. the two samples do not come from the same population. Table 3-10 below presents the results of t-tests.
conducted to determine if the mean longitudinal and mean lateral tensile ultimate strains were equal.

<table>
<thead>
<tr>
<th>Material</th>
<th>Sample A Size</th>
<th>Sample B Size</th>
<th>t-Value</th>
<th>p-Value</th>
<th>Accept/Reject</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-11mm</td>
<td>65</td>
<td>49</td>
<td>0.837</td>
<td>0.404</td>
<td>Accept</td>
</tr>
<tr>
<td>A-15mm</td>
<td>15</td>
<td>15</td>
<td>1.804</td>
<td>0.082</td>
<td>Accept</td>
</tr>
<tr>
<td>A-18mm</td>
<td>15</td>
<td>15</td>
<td>1.274</td>
<td>0.213</td>
<td>Accept</td>
</tr>
<tr>
<td>B-15mm</td>
<td>15</td>
<td>15</td>
<td>0.451</td>
<td>0.656</td>
<td>Accept</td>
</tr>
<tr>
<td>C-15mm</td>
<td>15</td>
<td>15</td>
<td>1.896</td>
<td>0.068</td>
<td>Accept</td>
</tr>
<tr>
<td>A-SURF</td>
<td>15</td>
<td>15</td>
<td>0.046</td>
<td>0.964</td>
<td>Accept</td>
</tr>
<tr>
<td>A-CORE</td>
<td>4</td>
<td>4</td>
<td>2.381</td>
<td>0.055</td>
<td>Accept</td>
</tr>
</tbody>
</table>

1) \( H_0: \) The longitudinal and lateral tensile ultimate strains had the same mean
2) \( \alpha \) level of significance of \( \alpha = 0.05 \) has been used

Table 3-10 – Student’s \( t \)-Test Results for Tensile Ultimate Strains

The results from the \( t \)-tests confirm that there is no significant difference between the longitudinal and lateral tensile ultimate strains. This is consistent with the degree-of-orthotropy values approximately equal to 1 for tensile ultimate strain presented in Table 3-9 above. This confirms that the materials tested do not exhibit orthotropic behaviour in terms of tensile ultimate strain.

3.5.1.7.4 Tensile Elastic Modulus

The results presented in Table 3-9 above suggest that similar to tensile ultimate strength as discussed in Section 3.5.1.7.2 above, all materials exhibit orthotropic behaviour in terms of tensile elastic modulus. This is suggested by the fact that all materials had a degrees-of-orthotropy for mean and 5\(^{th}\) percentile values that were less than or greater than a value of 1.

As expected, the A-SURF panels were the most orthotropic in terms of mean (0.555) and 5\(^{th}\) percentile (0.548) tensile elastic modulus. The A-CORE panels were orthotropic in the opposite manner in terms of mean (2.33) and 5\(^{th}\) percentile (3.082) tensile elastic modulus. This is consistent with the results for tensile ultimate strength discussed in 3.5.1.7.2 above.

Of the commercial OSB/3 panels, the C-15mm panels were the most orthotropic in terms of mean (0.625) and 5\(^{th}\) percentile (0.654) tensile elastic modulus. This
is consistent with the results for tensile ultimate strength discussed in Section 3.5.1.6.1 above. The B-15mm panels were the least orthotropic in terms of mean (0.929) and 5th percentile (0.852) tensile elastic modulus.

As was the case with tensile ultimate strength discussed in 3.5.1.7.2 above, the commercial OSB/3 panels were generally less orthotropic than the single-layer panels. This reflects the fact that the 90º core-layer reduces the natural orthotropic behaviour associated with solid timber without eliminating it entirely.

### 3.5.1.8 Comparison with Code

Table 3-11 below presents the characteristic values for tensile ultimate strength and elastic modulus as presented in BS EN 12369-1 (BSI, 2001).

<table>
<thead>
<tr>
<th>Thickness Range</th>
<th>Longitudinal</th>
<th>Lateral</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ultimate Strength (N/mm²)</td>
<td>Elastic Modulus (N/mm²)</td>
</tr>
<tr>
<td>10-18 mm</td>
<td>9.4¹</td>
<td>3800²</td>
</tr>
</tbody>
</table>

¹) Code values for characteristic tensile ultimate strength were 5th percentile values  
²) Code values for characteristic tensile elastic modulus were mean values

Table 3-11 – Codes Values for Tensile Ultimate Strength and Elastic Modulus

Of the materials tested, only the A-15mm and A-SURF panels achieved a characteristic longitudinal tensile ultimate strength exceeding the code value. In the lateral direction, the A-15mm, the B-15mm and the A-SURF panels exceeded the characteristic tensile ultimate strength specified in the code. The A-11mm, the A-15mm, the C-15mm and the A-SURF panels all achieved mean longitudinal tensile elastic moduli that exceeded the code value. All materials except the C-15mm panels achieved mean tensile elastic moduli exceeding the code value in the lateral direction.

### 3.5.2 Compression Testing

#### 3.5.2.1 Test Piece Details:

The test specimen were prepared according to the guidelines given in Appendix A of BS EN 789:2004 (BSI, 2004b). Figure 3-21 below gives details of the compression test specimens.
Figure 3-21 – OSB Compression Test Piece Details

The test specimens consisted of strips of OSB glued together to make test specimens stocky enough to prevent out of plane buckling. The width, height and
finished thickness of the test specimens were functions of the panel thickness. Rectangular sections of panel were marked out and cut before being cut into strips. The strips were glued together using a Poly Vinyl Acetate (PVA) wood adhesive. Test pieces were glued slightly longer than needed so they could be trimmed to the correct length after gluing, ensuring smooth ends that were parallel to each other. Figure 3-22 below shows details of the gluing arrangement and shows a typical finished compression test specimen.

A summary of the original and finished dimensions for the compression test specimens for each panel thickness is given in Table 3-12 below.

<table>
<thead>
<tr>
<th>Thickness (mm)</th>
<th>Initial Size</th>
<th>Number of Strips</th>
<th>Thickness (mm)</th>
<th>Width (mm)</th>
<th>Height (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11 mm</td>
<td>230 mm × 260 mm</td>
<td>4</td>
<td>44</td>
<td>50</td>
<td>240</td>
</tr>
<tr>
<td>15 mm</td>
<td>220 mm × 300 mm</td>
<td>3</td>
<td>45</td>
<td>67</td>
<td>250</td>
</tr>
<tr>
<td>18 mm</td>
<td>220 mm × 300 mm</td>
<td>2</td>
<td>36</td>
<td>100</td>
<td>200</td>
</tr>
</tbody>
</table>

Table 3-12 – Compression Test Piece Dimensions

The finished width, thickness and gauge length for each the test specimen were measured using an electronic calliper with an accuracy of 0.02 mm. The finished height for each the test specimen was measured with a ruler with an accuracy of 0.5 mm. The dimensions for each test specimen were recorded in a Microsoft Excel workbook. The dimensions and thicknesses reported in the results section were taken as the average of the readings taken at the locations indicated in Figure 3-23 below.
3.5.2.2 Testing arrangement

Figure 3-24 below shows a schematic of the compression test setup.

The load was applied through a ball joint as per the requirements of BS EN 789 (BSI, 1992b). The displacement of the machine crosshead was recorded with an
MPE type HS full bridge linearly varying differential transducer (LVDT) with a ram length of 25 mm. The displacement of the test specimen was recorded with two MPE type HS full bridge linearly varying differential transducers with a ram length of 5 mm test specimen using specially fabricated mounting blocks that were bolted together through the test specimen using M3 bolts. The diameter of the contact area between the mounting block and test specimen was 5 mm. The displacement of the test specimen was recorded over a gauge length of 120 mm.

3.5.2.3 Loading Rates

Loading rates for compressive testing were estimated using Equation 3.8 below.

\[ \delta h_{est} = \frac{f_{c,est} h}{E_{c,est} T} \]  

where: \( \delta h_{est} \) = estimated crosshead movement rate, \( f_{c,est} \) = estimated compressive ultimate strength, \( h \) = height of test specimen, \( E_{c,est} \) = estimated compressive elastic modulus, \( T \) = average test time

The values for compression strength and elastic modulus specified in BS EN 12369-1:2001 (BSI, 2001) were used in Equation 3.8 above to estimate the loading rates. The target average failure time specified in BS EN 789 was 300 ± 120 s. The loading rates were adjusted as necessary following the first few test runs. The adjusted loading rates for each panel type, thickness and direction were summarised in Table 3-13 below.

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Manufacturer A</th>
<th>Manufacturer B</th>
<th>Manufacturer C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LONG(mm/min)</td>
<td>LAT(mm/min)</td>
<td>LONG(mm/min)</td>
</tr>
<tr>
<td>11 mm</td>
<td>0.220</td>
<td>0.220</td>
<td>-</td>
</tr>
<tr>
<td>15 mm</td>
<td>0.310</td>
<td>0.310</td>
<td>0.310</td>
</tr>
<tr>
<td>18 mm</td>
<td>0.450</td>
<td>0.450</td>
<td>0.310</td>
</tr>
</tbody>
</table>

| Thickness | Manufacturer C | |
|-----------|----------------|
|           | LAT(mm/min)    |
| 11 mm     | -              |
| 15 mm     | 0.310          |
| 18 mm     | 0.310          |

Table 3-13 – Compression Test Loading Rates

The nature of this test meant that the LVDTs mounted to the test specimen could not be left in place until the piece failed due to the risk of the LVDTs being damaged by a sudden rupture or out of plane buckling failure of the specimen. To overcome this difficulty, the test specimen was loaded to approximately 50% of its capacity. It was unloaded and the LVDTs removed. This was referred to as
the “MOE” test. The test specimen was then reloaded to failure using only the LVDT monitoring the crosshead to record the material behaviour up to the failure point. This was referred to as the “MOR” test. A summary of the MOE stop loads is given in Table 3-14 below.

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Manufacturer A</th>
<th>Manufacturer B</th>
<th>Manufacturer C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LONG (kN)</td>
<td>LAT (kN)</td>
<td>LAT (kN)</td>
</tr>
<tr>
<td>11mm</td>
<td>17</td>
<td>15</td>
<td>-</td>
</tr>
<tr>
<td>15mm</td>
<td>24</td>
<td>20</td>
<td>24</td>
</tr>
<tr>
<td>18mm</td>
<td>28</td>
<td>23</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3-14 – Compression MOE Test Stop Loads

3.5.2.4 Sample Size

Fifteen 11 mm, 15 mm and 18 mm thick OSB/3 panels produced by Manufacturer A were manually cut as described in Section 3.4.2.1 above and tested. Fifteen 15 mm thick OSB/3 panels produced by Manufacturers B and C were CNC cut as described in Section 3.4.2.2 above. Twenty surface-layer (fifteen of which were tested) and four core-layer panels were CNC cut as described in Section 3.4.2.2 above.

Table 3-15 and Table 3-16 below present details of the final number of compression test replications for each panel type, thickness and material directions.

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Manufacturer A</th>
<th>Manufacturer B</th>
<th>Manufacturer C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LONG</td>
<td>LAT</td>
<td>LONG</td>
</tr>
<tr>
<td>11 mm</td>
<td>15</td>
<td>15</td>
<td>-</td>
</tr>
<tr>
<td>15 mm</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
</tbody>
</table>

Table 3-15 – Compression Test Repetitions (Commercial OSB/3 Panels)

<table>
<thead>
<tr>
<th>Material</th>
<th>Manufacturer A</th>
<th>Manufacturer B</th>
<th>Manufacturer C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LONG</td>
<td>LAT</td>
<td>LONG</td>
</tr>
<tr>
<td>SURF</td>
<td>15</td>
<td>15</td>
<td>-</td>
</tr>
<tr>
<td>CORE</td>
<td>4</td>
<td>4</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3-16 – Compression Test Repetitions (Single-Layer OSB)
3.5.2.5 Results:

3.5.2.5.1 Material Properties

The material strength and elastic properties were calculated according to BS EN 789 (BSI, 2004b). The compressive ultimate strength was calculated using Equation 3.9 below.

\[
\sigma_{u,c} = \frac{F_{\text{max}}}{A}
\]  

where: \(\sigma_{u,c}\) = compressive ultimate strength; \(F_{\text{max}}\) = maximum load; \(A\) = cross-sectional area

The compressive local elastic modulus was calculated based on the results from the LVDTs mounted to the test specimen using the portion of the load-displacement curve between 0.1\(F_{\text{max}}\) and 0.4\(F_{\text{max}}\) and Equation 3.11 below.

\[
E_{c,l} = \frac{(F_2 - F_1)l_1}{(u_2 - u_1)A}
\]  

where: \(E_{c,l}\) = compressive local elastic modulus; \(F_1 = 0.1F_{\text{max}}\); \(F_2 = 0.4F_{\text{max}}\); \(u_1\) = displacement corresponding to \(F_1\); \(u_2\) = displacement corresponding to \(F_2\); \(l_1\) = gauge length; \(A\) = cross-sectional area

In addition to the material properties defined in BS EN 789, some additional elastic properties were calculated including:

- Global modulus of elasticity
- Tangent modulus
- Compressive yield stress
- Compressive yield strain
- Compressive ultimate strain

These properties were calculated by applying an idealised tri-linear representation of the mechanical behaviour of OSB in compression to the crosshead displacement readings recorded during the compression testing. The tri-linear approximation was used to simplify the comparison of the failure characteristics of different samples. The tri-linear approximation is defined by a linear-elastic portion, an elasto-plastic portion and a post failure portion.
(Clouston and Lam, 2001, 2001, 2002). This is demonstrated in Figure 2-12 above. The tri-linear model is defined by a yield point and failure point determined such that the strain energy (i.e. area under the curve) of the tri-linear model is equal to that of the experimental curve. The slope of the linear-elastic portion is equal to the global compressive elastic modulus. The slope of the elasto-plastic is referred to as the tangent modulus. The failure point on the tri-linear curve coincides with the ultimate strength and ultimate strain of point on the experimental stress-strain curve.

The global compression elastic modulus was calculated using Equation 3.11 below based on the portion of the load-crosshead displacement curve between $0.1F_{\text{max}}$ and $0.4F_{\text{max}}$.

$$E_{c,g} = \frac{(F_2 - F_1)l_2}{(u_2 - u_1)A}$$

(3.11)

where: $E_{c,g}$ = compressive global elastic modulus; $F_1 = 0.1F_{\text{max}}$; $F_2 = 0.4F_{\text{max}}$; $u_1$ = displacement corresponding to $F_1$; $u_2$ = displacement corresponding to $F_2$; $l_2$ = test specimen length; $A$ = cross-sectional area

The compressive ultimate strain was calculated using Equation 3.12 below.

$$\varepsilon_{u,c} = \frac{u_{\text{max}}}{l_2}$$

(3.12)

where: $\varepsilon_{u,c}$ = compressive ultimate strain; $u_{\text{max}}$ = displacement corresponding to maximum load; $l_2$ = test specimen length

Equation 3.13 below gives the strain energy under the tri-linear approximation.

$$U_{c,\text{mod}} = \frac{1}{2} \left[ \sigma_{y,c} \varepsilon_{y,c} + (\sigma_{u,c} + T_c \varepsilon_y)(\varepsilon_{u,c} - \varepsilon_{y,c}) \right]$$

(3.13)

where: $U_{c,\text{mod}}$ = strain energy for tri-linear approximation; $\sigma_{y,c}$ = compressive yield strength; $\varepsilon_{y,c}$ = compressive yield strain; $\sigma_{u,c}$ = compressive ultimate strength; $\varepsilon_{u,c}$ = compressive ultimate strain; $T_c$ = compressive tangent modulus

The area under the experimental stress-strain curve was determined using the trapezoidal rule given by Equation 3.14 below.
\[ U_{c,\text{exp}} = \frac{1}{2} \sum_{i=1}^{n} [(\sigma_{i-1} + \sigma_i)(\varepsilon_i - \varepsilon_{i-1})] \quad (3.14) \]

where: \( U_{c,\text{exp}} \) = experimental strain energy; \( \sigma_i \) = compressive stress at point \( i \); \( \sigma_{i-1} \) = compressive stress at point \( i - 1 \); \( \varepsilon_i \) = compressive strain at point \( i \); \( \varepsilon_{i-1} \) = compressive strain at point \( i - 1 \); \( n \) = number of data points on experimental stress-strain curve

A custom-developed computer program used Equations 3.9 to 3.14 to automatically calculate the compressive properties from the raw experimental data. The computer program was developed using Microsoft VBA and embedded into a Microsoft Excel 2003 template. The computer program calculated the trilinear approximation by setting \( U_{c,\text{mod}} = U_{c,\text{exp}} \), resulting in an equation with three unknowns (i.e. \( \sigma_{y,c} \), \( \varepsilon_{y,c} \) and \( E_{t,c} \)). This equation must be solved iteratively. This was done using the solver function of Microsoft Excel by setting the initial value of the tangent modulus equal to the global modulus of elasticity calculated from Equation 3.11 above. The solver routine iterated to find values for \( \sigma_{y,c} \), \( \varepsilon_{y,c} \) and \( E_{t,c} \) such that \( U_{c,\text{mod}} = U_{c,\text{exp}} \). This will be discussed in more detail in Chapter 4 below.

Table 3-17 and Table 3-18 below present a summary of the experimental compression test results obtained for the commercial OSB/3 panels tested.

<table>
<thead>
<tr>
<th>Panel Type</th>
<th>Yield Stress</th>
<th>Yield Strain</th>
<th>Local Elastic Modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (N/mm²)</td>
<td>CoV (%)</td>
<td>Mean (×10⁻⁴)</td>
</tr>
<tr>
<td>A-11mm</td>
<td>14.11</td>
<td>17.21</td>
<td>4.69</td>
</tr>
<tr>
<td>A-15mm</td>
<td>13.23</td>
<td>13.30</td>
<td>4.44</td>
</tr>
<tr>
<td>A-18mm</td>
<td>11.80</td>
<td>9.02</td>
<td>4.82</td>
</tr>
<tr>
<td>B-15mm</td>
<td>13.32</td>
<td>10.73</td>
<td>5.68</td>
</tr>
<tr>
<td>C-15mm</td>
<td>11.86</td>
<td>21.52</td>
<td>4.85</td>
</tr>
<tr>
<td>A-11mm</td>
<td>12.01</td>
<td>14.40</td>
<td>4.59</td>
</tr>
<tr>
<td>A-15mm</td>
<td>11.06</td>
<td>14.36</td>
<td>4.59</td>
</tr>
<tr>
<td>A-18mm</td>
<td>10.66</td>
<td>15.05</td>
<td>4.53</td>
</tr>
<tr>
<td>B-15mm</td>
<td>11.28</td>
<td>7.62</td>
<td>5.83</td>
</tr>
<tr>
<td>C-15mm</td>
<td>8.87</td>
<td>13.99</td>
<td>5.36</td>
</tr>
</tbody>
</table>

Table 3-17 – Compression Test Results Summary (Commercial OSB/3 Panels)
Table 3-18 – Compression Test Results Summary (Commercial OSB/3 Panels Continued)

Table 3-19 and Table 3-20 below present a summary of the experimental compression test results obtained for the single-layer OSB panels tested.

<table>
<thead>
<tr>
<th>Panel Type</th>
<th>Ultimate Stress</th>
<th>Ultimate Strain</th>
<th>Global Elastic Modulus</th>
<th>Tangent Modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (N/mm²)</td>
<td>CoV (%)</td>
<td>Mean (×10⁻³)</td>
<td>CoV (%)</td>
</tr>
<tr>
<td>Long</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-11mm</td>
<td>16.35</td>
<td>17.24</td>
<td>7.12</td>
<td>8.39</td>
</tr>
<tr>
<td>A-15mm</td>
<td>15.43</td>
<td>12.10</td>
<td>6.88</td>
<td>9.23</td>
</tr>
<tr>
<td>A-18mm</td>
<td>13.22</td>
<td>10.03</td>
<td>6.69</td>
<td>7.63</td>
</tr>
<tr>
<td>B-15mm</td>
<td>15.26</td>
<td>7.60</td>
<td>7.89</td>
<td>8.49</td>
</tr>
<tr>
<td>C-15mm</td>
<td>13.08</td>
<td>21.43</td>
<td>6.19</td>
<td>8.90</td>
</tr>
<tr>
<td>Lat</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-SURF</td>
<td>14.04</td>
<td>12.54</td>
<td>7.24</td>
<td>8.91</td>
</tr>
<tr>
<td>A-CORE1)</td>
<td>12.75</td>
<td>15.01</td>
<td>6.99</td>
<td>9.55</td>
</tr>
<tr>
<td>A-18mm</td>
<td>12.33</td>
<td>14.64</td>
<td>7.32</td>
<td>11.02</td>
</tr>
<tr>
<td>B-15mm</td>
<td>12.62</td>
<td>7.57</td>
<td>8.09</td>
<td>7.90</td>
</tr>
<tr>
<td>C-15mm</td>
<td>9.92</td>
<td>13.91</td>
<td>7.20</td>
<td>10.90</td>
</tr>
</tbody>
</table>

1) Calculated using a sample size of 4 assuming a normal distribution

Table 3-19 – Compression Test Results Summary (Single-Layer OSB Panels)

<table>
<thead>
<tr>
<th>Panel Type</th>
<th>Yield Stress</th>
<th>Yield Strain</th>
<th>Local Elastic Modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (N/mm²)</td>
<td>CoV (%)</td>
<td>Mean (×10⁻³)</td>
</tr>
<tr>
<td>Long</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-CORE1)</td>
<td>6.31</td>
<td>5.40</td>
<td>8.86</td>
</tr>
<tr>
<td>Lat</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-SURF</td>
<td>15.69</td>
<td>10.27</td>
<td>8.17</td>
</tr>
<tr>
<td>A-CORE1)</td>
<td>12.20</td>
<td>6.87</td>
<td>6.53</td>
</tr>
</tbody>
</table>

1) Calculated using a sample size of 4 assuming a normal distribution

Table 3-20 – Compression Test Results Summary (Single-Layer OSB Panels Continued)

<table>
<thead>
<tr>
<th>Panel Type</th>
<th>Ultimate Stress</th>
<th>Ultimate Strain</th>
<th>Global Elastic Modulus</th>
<th>Tangent Modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (N/mm²)</td>
<td>CoV (%)</td>
<td>Mean (×10⁻³)</td>
<td>CoV (%)</td>
</tr>
<tr>
<td>Long</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-SURF</td>
<td>23.92</td>
<td>8.01</td>
<td>9.27</td>
<td>8.41</td>
</tr>
<tr>
<td>A-CORE1)</td>
<td>6.79</td>
<td>7.55</td>
<td>12.3</td>
<td>13.88</td>
</tr>
<tr>
<td>Lat</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-CORE1)</td>
<td>12.75</td>
<td>6.47</td>
<td>8.15</td>
<td>3.37</td>
</tr>
</tbody>
</table>

1) Calculated using a sample size of 4 assuming a normal distribution
3.5.2.5.2 Mechanical Behaviour

Figure 3-25 and Figure 3-26 below show typical load-deflection and stress-strain curves observed for A-11mm panels loaded in compression respectively.

**Figure 3-25 – Typical Compression Local Load vs Displacement Curve (MOE Results)**

**Figure 3-26 – Typical Compression Local Stress vs Strain Curve (MOE Results)**
Figure 3-27 and Figure 3-28 below show typical load-crosshead displacement and global stress-strain curves observed for A-11mm panels loaded in longitudinal compression respectively. A more comprehensive set of results is presented in Appendix B.
Note the slight non-linearity at low strains as can be seen in Figure 3-27 and Figure 3-28 above. This can be attributed to a combination of settlement of the test specimen into the testing machine and slack in the ball joint of the loading head. This is a common problem with compression testing. It has been corrected by projecting the linear portion of the load-deflection curve such that it intersects the strain axis and then offsetting the whole curve back towards the stress axis by a distance equal to the intercept. This was done by the results processing macro (see Chapter 4) with the same method used by Clouston (2001).

Unlike the tension test specimens, compression test specimens failed gradual pseudo-ductile manner. This is reflected by the shape of the load-displacement and stress-strain curves obtained from the global MOR test which show a linear portion at low strains, a non-linear portion from yield to failure followed by a gradual loss of strength at strains above ultimate strain. Compression failure was generally initiated by debonding of the core-layer as a result of the Poisson’s effect, followed by local buckling of the remaining layers and a gradual loss of strength. Some test specimens did exhibit a certain amount of global buckling but only after local buckling of the surface-layers. Figure 3-29 below shows a typical compression failure.
Figure 3-29 above shows that the core-layer has debonded and that the surface-layers but had buckled locally due to the loss of lateral restraint arising from the debonding of the core.

3.5.2.6 Discussion

3.5.2.6.1 Compressive Yield Strength

Figure 3-30 below compares the mean and 5th percentile compressive yield strength results in both material directions for the materials tested.

![Figure 3-30 – Compressive Yield Strength](image)

As anticipated, the results indicate that the A-SURF panels had the highest mean (21.61 N/mm²) and 5th percentile (19.62 N/mm²) compressive yield strength in the longitudinal direction. The A-CORE panels had the lowest mean (6.31 N/mm²) and 5th percentile (6.00 N/mm²) compressive yield strength in the longitudinal direction. The A-SURF panels had the highest mean (15.69 N/mm²) and 5th percentile (13.60 N/mm²) compressive yield strength in the lateral direction. The A-CORE panels had a greater mean (12.20 N/mm²) and 5th percentile (11.31 N/mm²) compressive yield strength in the lateral direction than
in the longitudinal direction. These results were consistent with those obtained for tensile ultimate strength discussed in Section 3.5.1.6.1 above.

Of the commercial OSB/3 panels, the A-11mm panels had the highest mean (14.11 N/mm²) compressive yield strength in the longitudinal direction. The B-15mm panels had the highest 5th percentile (11.65 N/mm²) compressive yield strength in the longitudinal direction. This is likely due to the greater variability of the compressive yield strength of the A-11mm panels (CoV = 17.21%) when compared to the B-15mm panels (CoV = 10.73%). The A-18mm panels had the lowest mean (11.80 N/mm²) compression yield strength in the longitudinal direction. The C-15mm panels had the lowest 5th percentile (7.68 N/mm²) in the longitudinal direction. This is likely due to the greater variability of the compressive yield strength of the C-15mm panels (CoV = 21.52%) when compared to the A-18mm panels (CoV = 9.02%).

It is worth noting the downward trend in the mean longitudinal compressive yield strength with increasing panel thickness for the panels produced by Manufacturer A. This suggests the possibility that size effects had an influence on compression yield strength of the OSB/3 panels produced by Manufacturer A. Size effects had been observed in past studies for both solid timber and wood-based composite materials (Bohannan, 1966, Barrett, 1974, Madsen and Buchanan, 1986, Barrett et al., 1995, Rosowsky, 1997, Clouston et al., 1998b, Wang and Lam, 1998b, Fan et al., 2006). Size effects were formally recognised in design practice by Eurocode 5 (BSI, 2004c) through the use of a size effect modification factor which reduces the design strength of wood-based materials with increasing member size. This trend is not reflected by the longitudinal tensile ultimate strength as discussed in section 3.5.1.6.1 above nor was it present when comparing 5th percentile longitudinal compressive yield strength. This is likely due to:

- The greater variability in the longitudinal compressive yield strength of the A-11mm panels (CoV = 17.21%) when compared to the A-15mm (CoV = 13.30%) and A-18mm panels (CoV = 9.02%) as shown in Table 3-17 above,
The significantly greater variability in the longitudinal tensile ultimate strength of the A-11mm panels ($CoV = 19.91\%$) when compared to the A-15mm panels ($CoV = 15.44\%$) and the A-18mm panels ($CoV = 15.51\%$) as shown in Table 3-17 above.

The A-11mm panels had the highest mean (12.01 N/mm$^2$) and 5th percentile (9.89 N/mm$^2$) compressive yield strength in the lateral direction. The C-15mm panels had the lowest mean (8.87 N/mm$^2$) and 5th percentile (6.96 N/mm$^2$) compression yield strength in the lateral direction. These results were radically different from those observed for tensile ultimate strength for commercial OSB/3 panels as discussed in 3.5.1.6.1. This suggests that:

- Good performance under one loading condition does not necessarily guarantee good loading performance under another. This is likely due to the radically different stress-strain relationships and failure mechanisms observed for compression and tension loading,
- The variability of the test data has a significant influence on the characteristic values for material properties.

Again it is worth noting the downward trend in the mean lateral compressive yield strength of the Manufacturer A panels with increasing nominal thickness. This trend is not demonstrated by the tensile ultimate strength as discussed in section 3.5.1.6.1 discussed above nor the 5th percentile compressive yield strength in the lateral direction. It is unclear at this time why the trend has not been repeated for the 5th percentile compressive yield strength in the lateral direction. Table 3-17 above shows no significant variability in the test results for the lateral compression yield strength for the three thicknesses. Therefore, it is unlikely that different degrees of variability between samples were contributing to the lack of a downward trend. Further testing is required before definitively stating that size effects influence the strength properties of the materials tested.

3.5.2.6.2 Compressive Yield Strain

Figure 3-31 below compares the mean and 5th percentile compressive yield strain results in both material directions for the materials tested.
The results show that the A-CORE panels had the highest mean \((8.86 \times 10^{-3})\) and 5th percentile \((8.51 \times 10^{-3})\) compressive yield strain values in the longitudinal direction. The A-SURF panels had the highest mean \((8.17 \times 10^{-3})\) and 5th percentile \((7.51 \times 10^{-3})\) compression yield strain values in the lateral direction. Note that both the A-SURF and the A-CORE panels appear to have a higher compressive yield strain in the direction perpendicular to the wood strand orientation. This is significantly different than the results observed for tensile ultimate strain for the A-SURF and A-CORE panels as discussed in section 3.5.1.6.2 above. The Student’s t-tests described in Section 3.5.1.7.3 above showed that no significant orthotropy existed for tensile ultimate strain for all materials tested. This will be investigated further in Section 3.5.2.7.2 below.

Of the commercial OSB/3 panels, the B-15mm panels had the highest mean \((5.68 \times 10^{-3})\) and 5th percentile \((5.21 \times 10^{-3})\) compression yield strain values in the longitudinal direction. The A-15mm panels had the lowest mean \((4.44 \times 10^{-3})\) and 5th percentile \((3.88 \times 10^{-3})\) compression yield strain values in the longitudinal direction. The B-15mm panels had the highest mean \((5.68 \times 10^{-3})\) and 5th percentile \((5.21 \times 10^{-3})\) compressive yield strain in the lateral direction. The A-
11mm and the A-15mm panels both had the lowest mean \( (4.59 \times 10^{-3}) \) compressive yield strain values in the lateral direction. The A-11mm panels had a slightly lower 5th percentile \( (3.99 \times 10^{-3}) \) compressive yield strain in the lateral direction than the A-15mm panels \( (4.08 \times 10^{-3}) \). This is likely due to the slightly greater variability of the lateral compressive yield strain results for the A-11mm panels \( (CoV = 14.40\%) \) when compared with the A-15mm panels \( (CoV = 14.36\%) \). Note that unlike the single-layer OSB panels, the compressive yield strains for the commercial OSB/3 panels appear almost equal in both material directions. This will be investigated further in Section 3.5.2.7.2 below.

3.5.2.6.3 Compressive Ultimate Strength

Figure 3-32 below compares the mean and 5th percentile compressive ultimate strength results in both material directions for the materials tested.

![Figure 3-32 – Compressive Ultimate Strength](image)

The results indicate that the A-SURF panels had the highest mean \( (23.92 \text{ N/mm}^2) \) and 5th percentile \( (21.83 \text{ N/mm}^2) \) compressive ultimate strength values in the longitudinal direction. The A-CORE panels had the lowest mean \( (6.79 \text{ N/mm}^2) \) and 5th percentile \( (6.29 \text{ N/mm}^2) \) compressive ultimate strength values in the longitudinal direction. In the lateral direction, the A-SURF panels had the
highest mean (17.55 N/mm²) and 5th percentile (15.28 N/mm²) compressive ultimate strength. The A-CORE panels had a higher mean (12.94 N/mm²) and 5th percentile (12.21 N/mm²) compressive ultimate strength in the lateral direction (i.e. parallel to the wood strand orientation) than in the longitudinal direction (i.e. perpendicular to the wood strand orientation). These findings were in keeping with those observed for compressive yield strength discussed in section 3.5.2.6.1 above and tensile ultimate strength discussed in section 3.5.1.6.1 above.

Of the commercial OSB/3 panels, the A-11mm panels had the highest mean (16.35 N/mm²) compressive ultimate strength in the longitudinal direction. The B-15mm panels had the highest 5th percentile (13.71 N/mm²) ultimate compression strength in the longitudinal direction. This is likely due to the greater variability of the longitudinal compressive ultimate strength of the A-11mm panels (CoV = 17.24%) when compared to the B-15mm panels (CoV = 7.60%). The C-15mm panels had the lowest mean (13.08 N/mm²) and 5th percentile (8.59 N/mm²) compressive ultimate strength in the longitudinal direction. This is also reflected in the compressive yield strength results discussed in section 3.5.2.6.1 above. During testing, it was observed that the C-15mm panels failed more abruptly and at lower loads in compression than the other panels. This is reflected in the compressive strength results for these panels.

In the lateral direction, the A-11mm panels had the highest mean (14.04 N/mm²) and 5th percentile (11.68 N/mm²) compressive ultimate strength. The C-15mm panels had the lowest mean (9.92 N/mm²) and 5th percentile (8.07 N/mm²) compressive ultimate strength values in the lateral direction. As with the longitudinal direction, observations made during testing indicated that the C-15mm panels failed more abruptly and at lower loads than the other panels tested. This is reflected in the compressive strength results for these panels.

Again it is worth noting the downward trend the mean lateral compressive ultimate strength with increasing nominal thickness for panels produced by Manufacturer A in both material directions. This trend is not demonstrated by the 5th percentile compressive ultimate strength values in both material directions. This is consistent with the findings for both the lateral tensile ultimate strength as
discussed in Section 3.5.1.6.1 above and the lateral compressive yield strength as discussed in Section 3.5.2.6.1 above.

3.5.2.6.4 Compressive Ultimate Strain

Figure 3-33 below compares the mean and 5th percentile compressive ultimate strain results in both material directions for the materials tested.

![Figure 3-33 – Compressive Ultimate Strain](image)

The results indicate that the A-CORE panels had the highest mean (12.3×10⁻³) and 5th percentile (10.8×10⁻³) compressive ultimate strain values in the longitudinal direction. In the lateral direction, the A-SURF panels had the highest mean (12.3×10⁻³) and 5th percentile (11.0×10⁻³) compressive ultimate strain values. Note again that the A-SURF and A-CORE panels appear to have significantly different compressive ultimate strain values in the longitudinal direction than in the lateral direction. This is consistent with the observations made in Section 3.5.2.6.2 above for compression yield strain. This will be investigated further in Section 3.5.2.7.4 below.

Of the commercial OSB/3 panels, the B-15mm panels had the highest mean (7.89×10⁻³) and 5th percentile (6.85×10⁻³) compressive ultimate strain values in
the longitudinal direction. The C-15mm panels had the lowest mean ($6.19 \times 10^{-3}$) and 5th percentile ($5.38 \times 10^{-3}$) compressive ultimate strain values in the longitudinal direction. In the lateral direction, the B-15mm panels had the highest mean ($8.09 \times 10^{-3}$) and 5th percentile ($7.24 \times 10^{-3}$) compressive ultimate strain values. The A-15mm panels had the lowest mean ($6.99 \times 10^{-3}$) compressive ultimate strain value in the lateral direction. The A-11mm and A-15mm both had the lowest 5th percentile ($6.11 \times 10^{-3}$) compressive ultimate strain values in the lateral direction. Note that there appears to be no significant difference between the compressive ultimate strain values in the longitudinal direction than in the lateral direction for the commercial OSB/3 panels. This is consistent with the observations made in Section 3.5.2.6.2 above for compression yield strain. This will be investigated further in Section 3.5.2.7.4 below.

3.5.2.6.5 **Compressive Local Elastic Modulus**

Figure 3-34 below compares the mean and 5th percentile compressive local elastic modulus results in both material directions for the materials tested.

![Local Elastic Modulus](image)

**Figure 3-34 – Compressive Local Elastic Modulus**

The A-SURF panels had the highest mean (5372 N/mm²) and 5th percentile (4612 N/mm²) compressive local elastic modulus in the longitudinal direction.
Similarly, the A-CORE panels had the lowest mean (1189 N/mm\(^2\)) and 5\(^{th}\) percentile (1119 N/mm\(^2\)) compressive local elastic modulus in the longitudinal direction. In the lateral direction, the A-CORE panels had the highest mean (3831 N/mm\(^2\)) and 5\(^{th}\) percentile (3580 N/mm\(^2\)) compressive local elastic modulus values. The A-SURF panels had a lower mean (3075 N/mm\(^2\)) and 5\(^{th}\) percentile (2601 N/mm\(^2\)) compressive local elastic modulus in the lateral direction than the A-CORE panels. This is consistent the tensile elastic modulus results discussed in Section 3.5.1.6.3 above. It is also consistent with the tensile and compressive strength properties discussed in Sections 3.5.1.6.1, 3.5.2.6.1 and 3.5.2.6.3 above.

Of the commercial OSB/3 panels, the A-11mm panels had the highest mean (4265 N/mm\(^2\)) compressive local elastic modulus in the longitudinal direction. The A-15mm panels had the highest 5\(^{th}\) percentile (3701 N/mm\(^2\)) compressive local elastic modulus in the longitudinal direction. This is likely due the greater variability in the longitudinal compressive local elastic modulus of the A-11mm panels (\(CoV = 19.69\%\)) when compared to the A-15mm panels (\(CoV = 7.32\%\)). The B-15mm panels had the lowest mean (3661 N/mm\(^2\)) compressive local elastic modulus in the longitudinal direction. The C-15mm panels had the lowest 5\(^{th}\) percentile (2960 N/mm\(^2\)) compressive local elastic modulus in the longitudinal direction. This is likely due to the greater variability in the longitudinal compressive local elastic modulus of the C-15mm panels (\(CoV = 18.27\%\)) when compared to the C-15mm panels (\(CoV = 10.24\%\)). In the lateral direction, the A-11mm panels had the highest mean (3455 N/mm\(^2\)) and 5\(^{th}\) percentile (2825 N/mm\(^2\)) compressive local elastic modulus values. The C-15mm panels had the lowest mean (2489 N/mm\(^2\)) and 5\(^{th}\) percentile (2090 N/mm\(^2\)) compressive local elastic modulus values in the lateral direction.

Note the downward trend in the mean compressive local elastic moduli in both material directions with increasing nominal thickness for the panels produced by Manufacturer A. This trend is not reflected by the 5\(^{th}\) percentile values. Similar trends had been observed in the discussion on the compressive strength results in
Sections 3.5.2.6.1 and 3.5.2.6.3 above and for the tensile elastic modulus results discussed in Section 3.5.1.6.3 above.

3.5.2.6.6 Compressive Global Elastic Modulus

Figure 3-35 below compares the mean and 5th percentile compressive global elastic modulus results in both material directions for the materials tested.

![Figure 3-35 – Compressive Global Elastic Modulus](image)

In the longitudinal direction, the A-SURF panels had the highest mean (3169 N/mm²) and 5th percentile (2724 N/mm²) compressive global elastic modulus values. The A-CORE panels had the lowest mean (714 N/mm²) and 5th percentile (665 N/mm²) compressive global elastic modulus values in the longitudinal direction. The A-CORE panels had a higher mean (1877 N/mm²) and 5th percentile (1679 N/mm²) compressive global elastic modulus values in the lateral direction than in the longitudinal direction. The A-CORE panels also had a comparable compressive global elastic modulus values in the lateral direction (i.e. parallel to the wood strand orientation) with the A-SURF panels in the lateral direction (i.e. perpendicular to the wood strand orientation). This is consistent the tensile elastic modulus results discussed in Section 3.5.1.6.3 above and with the compressive local elastic modulus discussed in Section 3.5.2.6.5.
above. It is also consistent with the tensile and compressive strength properties discussed in Sections 3.5.1.6.1, 3.5.2.6.1 and 3.5.2.6.3 above.

Of the commercial OSB/3 panels, the A-11mm panels had the highest mean (3026 N/mm$^2$) compressive global elastic modulus value in the longitudinal direction. The A-15mm panels had the highest 5$^{th}$ percentile (2674 N/mm$^2$) compressive global elastic modulus value in the longitudinal direction. This is likely due to the greater variability of the compressive global elastic modulus results for the A-11mm panels ($CoV = 18.85\%$) when compared to the A-15mm panels ($CoV = 8.44\%$) as shown by Table 3-18 above. The B-15mm panels had the lowest mean (2347 N/mm$^2$) compressive global elastic modulus value in the longitudinal direction. The C-15mm panels had the lowest 5$^{th}$ percentile (1850 N/mm$^2$) compressive global elastic modulus value in the longitudinal direction. The discrepancy is likely a result of greater variability of the longitudinal compressive global elastic modulus of the C-15mm panels ($CoV = 14.36\%$) when compared to the B-15mm panels ($CoV = 7.70\%$) as shown by Table 3-18 above. These observations were consistent with those presented in the discussion of the compressive local elastic modulus results in Section 3.5.2.6.5 above. In the lateral direction, the A-11mm panels had the highest mean (2616 N/mm$^2$) and 5$^{th}$ percentile (2154 N/mm$^2$) compressive global elastic modulus values. The C-15mm panels had the lowest mean (1654 N/mm$^2$) and 5$^{th}$ percentile (1336 N/mm$^2$) compressive global elastic modulus values in the lateral direction. These results were consistent with those observed for compressive local elastic modulus discussed in Section 3.5.2.6.5 above.

Note again the downward trend in the mean global compressive elastic modulus values in both material directions with increasing nominal thickness for the panels produced by Manufacturer A. This trend is not reflected by the 5$^{th}$ percentile values. Similar trends had been observed in the discussion on the compressive local elastic modulus results in Section 3.5.2.6.5 above and the tensile elastic modulus results discussed in Section 3.5.1.6.3 above. This trend has also been observed in compressive strength results discussed in Sections 3.5.2.6.1 and 3.5.2.6.3 above.
3.5.2.6.7  **Compressive Tangent Modulus**

Figure 3-36 below compares the mean and 5\textsuperscript{th} percentile global compressive tangent modulus results in both material directions for the materials tested.

![Figure 3-36 – Compressive Tangent Modulus](image)

In the longitudinal direction, the A-SURF panels had the highest mean (960 N/mm\textsuperscript{2}) and 5\textsuperscript{th} percentile (688 N/mm\textsuperscript{2}) compressive tangent modulus values. The A-CORE panels had the lowest mean (140 N/mm\textsuperscript{2}) and 5\textsuperscript{th} percentile (107 N/mm\textsuperscript{2}) compressive tangent modulus values in the longitudinal direction. The A-CORE panels had higher mean (440 N/mm\textsuperscript{2}) and 5\textsuperscript{th} percentile (338 N/mm\textsuperscript{2}) compressive tangent modulus values in the lateral direction (i.e. parallel to the wood strand orientation) than they do in the longitudinal direction (i.e. perpendicular to the wood strand orientation). These results were consistent with those observed for compressive local elastic modulus results discussed in Section 3.5.2.6.5 above, the compressive global elastic modulus results discussed in Section 3.5.2.6.6 above and the tensile elastic modulus results discussed in Section 3.5.1.7.4 above.

Of the commercial OSB/3 panels, the A-11mm panels had the highest mean (940 N/mm\textsuperscript{2}) compressive tangent modulus values in the longitudinal direction. The
A-15mm panels had the highest 5th percentile (684 N/mm²) longitudinal compressive tangent modulus values in the longitudinal direction. The results in Table 3-20 above show that the longitudinal compressive tangent modulus results for the A-11mm panels had a CoV of 20.61% while the longitudinal compressive tangent modulus results for the A-15mm panels had a CoV of 22.11%. This discrepancy therefore cannot be attributed to the longitudinal compressive tangent modulus results for the A-11mm panels being more variable than for the A-15mm panels. The A-18mm panels had the lowest mean (756 N/mm²) and 5th percentile (436 N/mm²) compressive tangent modulus values in the longitudinal direction. In the lateral direction, the A-11mm panels had the highest mean (797 N/mm²) compressive tangent modulus value. The A-18mm panels had the highest 5th percentile (517 N/mm²) compressive tangent modulus value in the lateral direction. Table 3-20 above shows that there is no significant difference in the variability of the lateral compressive tangent modulus between the A-11mm panels (CoV = 34.91%) and the A-15mm panels (CoV = 32.73%). Therefore, it is likely that this discrepancy is not entirely a result of the difference in variability between the materials.

Note again the downward trend in the mean compressive tangent modulus in both directions with increasing nominal thickness for the panels produced by Manufacturer A. This trend is not reflected by the 5th percentile values. Similar trends had been observed in the discussion on the compressive local elastic modulus results in Section 3.5.2.6.5 above, the compressive global elastic modulus results in Section 3.5.2.6.6 above and the tensile elastic modulus results discussed in Section 3.5.1.6.3 above. This trend has also been observed in compressive strength results discussed in Sections 3.5.2.6.1 and 3.5.2.6.3 above.

### 3.5.2.7 Degree-of-Orthotropy

Table 3-21 below presents the degree-of-orthotropy results for the elastic compression properties for the materials tested. Table 3-22 below presents the degree-of-orthotropy results for the compressive failure properties for the materials tested. The degree-of-orthotropy results were calculated using the method described in Section 3.5.1.7 above.

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3.5.2.7.1  Compressive Yield Strength

The results presented in Table 3-21 above show that all panels exhibit orthotropic behaviour in terms of compressive yield strength both in terms of mean and 5th percentile values. This is demonstrated by the fact that the degree-of-orthotropy values for all panels tested had values that were greater or less than a value of 1.

As anticipated, the single-layer panels were the most orthotropic. This is shown by the fact that the degree-of-orthotropy values for the single-layer panels were further from a value of 1 than the commercial OSB/3 panels. The A-SURF panels had mean (0.726) and 5th percentile (0.693) degree-of-orthotropy values that were less than a value of 1. The A-CORE panels had mean (1.934) and 5th percentile (1.887) degree-of-orthotropy values that were greater than 1. This demonstrates that both panels had enhanced compressive yield strength values in the direction parallel to the wood strand orientation. This is consistent with the
results obtained for the tensile ultimate strength as discussed in Section 3.5.1.7.2 above.

Of the commercial OSB/3 panels, Table 3-21 above shows that the C-15mm panels were the most orthotropic in terms of their mean (0.784) compressive yield strength value. The A-15mm panels were the most orthotropic in terms of their 5th percentile (0.816) value. The A-18mm panels were the least orthotropic in terms of their mean (0.903) compressive yield strength value. The A-11mm panels were the least orthotropic in terms of their 5th percentile (1.061) compressive yield strength value. This result indicates that the A-11mm panels exhibit enhanced yield strength in the lateral direction which goes against the general trend observed for all properties for commercial OSB/3 panels discussed. Table 3-17 above shows that the $CoV$ for the longitudinal yield strength is 17.31% compared to the $CoV$ for the lateral yield strength is 14.40% for the A-11mm panels. Inspection of the results indicates that the longitudinal yield strength for A-28-11-COMP-LONG is just 8.35 N/mm$^2$ while the longitudinal yield strength for A-14-11-COMP-LONG is just 9.84 N/mm$^2$. Both of these results were significantly lower than the remaining results which fall in the range of 13-18 N/mm$^2$. It is likely that these two results were disproportionally influencing the overall results for the A-11mm panels due to the relatively small sample size involved. Of the remaining commercial OSB/3 panels, the C-15mm panels were the least orthotropic in terms of their 5th percentile (0.906) value.

The results show that the single-layer panels were slightly more orthotropic than the three-layered commercial OSB/3 panels. However, the degree to which the single-layer panels were more orthotropic than the three-layered commercial OSB/3 panels is not as noticeable as for the tension ultimate strength discussed in Section 3.5.1.7.2 above. The same can also be said for the commercial OSB/3 panels.

It is likely that this can be partly attributed to the failure mechanism associated with the compression test specimens. As described in Section 3.5.1.5.2 above, compression failure was initiated by a debonding in the core-layer of the test specimens. This debonding was as a result of an internal bond failure of the inner
layers. Therefore, it is likely that the internal bond strength of the panels has a significant influence on the compression strength of OSB. Internal bond strength is assessed in accordance with BS EN 319 (BSI, 1993b). It is a measure of the tensile strength of the panel perpendicular to the surface. Internal bond is therefore not influenced by the orientation of the wood strands in the same way as the in-plane strength properties but by the strength of the bond between the resin and the wood strands. This means that the internal bond strength will be equal in both in-plane material directions. Therefore, it is likely that the full longitudinal compressive strength of the single-layer OSB panels cannot be fully capitalised on because the test specimens delaminate before the wood strands reach their full compressive yield strength. The lateral test specimens were not affected as much as the longitudinal specimens because the cross-grain compressive yield strength is significantly less than the parallel-to-grain compressive yield strength.

Increasing the internal bond strength is likely offer a moderate improvement in the lateral compressive yield strength and a significant improvement in longitudinal yield strength producing a material that is more orthotropic than those tested.

3.5.2.7.2 Compressive Yield Strain

The results for degree-of-orthotropy for compressive yield strain presented in Table 3-21 above do not show the same consistency as the degree-of-orthotropy for tensile ultimate strain as shown in Table 3-9 above. The degree-of-orthotropy results for mean and 5th percentile compressive yield strain values for the A-11mm, A-15mm, A-18mm and B-15mm panels all had values that were approximately equal to a value of 1. However, the degree-of-orthotropy for the mean and 5th percentile compressive yield strain values for the C-15mm, A-SURF and A-CORE panels all had values that were clearly not equal to a value of 1. Table 3-23 below presents the results of Student’s t-tests conducted to investigate if the mean longitudinal and mean lateral yield strains were equal. The Student’s t-tests were conducted using the same method described in Section 3.5.1.7.3 above.
Table 3-23 – Student’s t-Test Results for Compressive Yield Strains

| Material | Sample A Size | Sample B Size | t-Value | p-Value | Accept/Reject  
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A-11mm</td>
<td>14</td>
<td>14</td>
<td>0.787</td>
<td>0.438</td>
<td>Accept</td>
</tr>
<tr>
<td>A-15mm</td>
<td>14</td>
<td>14</td>
<td>0.964</td>
<td>0.344</td>
<td>Accept</td>
</tr>
<tr>
<td>A-18mm</td>
<td>15</td>
<td>15</td>
<td>0.818</td>
<td>0.420</td>
<td>Accept</td>
</tr>
<tr>
<td>B-15mm</td>
<td>15</td>
<td>15</td>
<td>0.994</td>
<td>0.329</td>
<td>Accept</td>
</tr>
<tr>
<td>C-15mm</td>
<td>15</td>
<td>15</td>
<td>2.872</td>
<td>0.008</td>
<td>Reject</td>
</tr>
<tr>
<td>A-SURF</td>
<td>15</td>
<td>15</td>
<td>5.515</td>
<td>0.000</td>
<td>Reject</td>
</tr>
<tr>
<td>A-CORE</td>
<td>4</td>
<td>4</td>
<td>5.733</td>
<td>0.001</td>
<td>Reject</td>
</tr>
</tbody>
</table>

1) $H_0$: The longitudinal and lateral compressive yield strains had the same mean
2) A level of significance of $\alpha = 0.05$ has been used

The results confirm the initial observation that there is no significant evidence that the compressive yield strain exhibits orthotropic behaviour for the A-11mm, A-15mm, A-18mm and B-15mm panels. This means that compressive yield strain is independent of material directions for these four materials. This is consistent with the results obtained for tensile ultimate strain as discussed in Section 3.5.1.7.3 above. However, the results presented in Table 3-23 above suggest that there is significant evidence that the compressive yield strain for the C-15mm, the A-SURF and the A-CORE panels does exhibit orthotropic behaviour. This means that compressive yield strain is not independent of material directions for these three materials. This is in contradiction to the results obtained for the tensile ultimate strain for these materials discussed in Section 3.5.1.7.3 above. It is likely that the influence of internal bond as discussed in Section 3.5.2.6.1 above may be responsible for this discrepancy.

3.5.2.7.3 Compressive Ultimate Strength

The results presented in Table 3-22 above show that all panels exhibit orthotropic behaviour in terms of compressive ultimate strength both in terms of mean and 5th percentile values. This is demonstrated by the fact that the degree-of-orthotropy values for all panels tested had values that were greater or less than a value of 1.

The results presented in Table 3-22 above show that single-layer panels were the most orthotropic. This is reflected by degree-of-orthotropy values that furthest
from a value of 1. The results also demonstrate that both the A-SURF and A-CORE panels had enhanced compressive ultimate strength properties when loaded parallel to the wood strand orientation. These results were consistent with results for compressive yield strength discussed in Section 3.5.2.6.1 above and with the results for tensile ultimate strength discussed in Section 3.5.1.6.1 above.

Of the commercial OSB/3 panels, the results presented in Table 3-22 above show that the C-15mm panels were the most orthotropic in terms of their mean (0.754) compressive ultimate strength value. The A-15mm panels were the most orthotropic in terms of their 5th percentile (0.765) compressive ultimate strength value. The A-18mm panels were the least orthotropic in terms of their mean (0.933) compressive ultimate strength value. The A-11mm panels were the least orthotropic in terms of their 5th percentile (1.074) compressive ultimate strength value. This suggests that the A-11mm panels exhibit enhanced ultimate compressive strength in the longitudinal direction. Of the remaining commercial OSB/3 panels, the C-15mm panels were the least orthotropic in terms of their 5th percentile (0.906) value. These findings were all consistent with the results for the compressive yield strength discussed in Section 3.5.2.7.1 above.

As was the case with the compressive yield strength results discussed in Section 3.5.2.7.1 above, these results show that the single-layer panels were slightly more orthotropic than the three-layered commercial OSB/3 panels. However, the degree to which the single-layer panels were more orthotropic than the three-layered commercial OSB/3 panels is not as noticeable as for the tension ultimate strength discussed in Section 3.5.1.7.2 above. The same can also be said for the commercial OSB/3 panels. The likely reasons for this were explained in the Section 3.5.2.7.1 above.

3.5.2.7.4 Compressive Ultimate Strain

The degree-of-orthotropy for compressive ultimate strain presented in Table 3-22 above suggest that certain panel types do not exhibit orthotropic behaviour whereas other panel types do exhibit orthotropic behaviour. The results show that the A-11mm, the A-15mm, the A-18mm, the B-15mm panels all had degrees-of-orthotropy for both their mean and 5th percentile values that were approximately
equal to a value of 1. This suggests that these panels do not exhibit orthotropic behaviour in terms of their compressive ultimate strain. Similarly, Table 3-22 above shows that the C-15mm, the A-SURF and A-CORE panels all had degrees-of-orthotropy for their mean and 5th percentile compressive ultimate strain values that were clearly not equal to a value of 1. This suggests that these materials exhibit orthotropic behaviour in terms of compressive ultimate strain.

A similar trend was highlighted in Section 3.5.2.7.2 above for compressive yield strain. Table 3-24 below presents the result of Student’s t-tests to determine if compressive ultimate strain is independent of material direction. The Student’s t-tests were conducted using the method described in Section 3.5.1.7.3 above.

<table>
<thead>
<tr>
<th>Material</th>
<th>Sample A Size</th>
<th>Sample B Size</th>
<th>$t$-Value</th>
<th>$p$-Value</th>
<th>Accept/Reject</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-11mm</td>
<td>14</td>
<td>14</td>
<td>0.529</td>
<td>0.606</td>
<td>Accept</td>
</tr>
<tr>
<td>A-15mm</td>
<td>14</td>
<td>14</td>
<td>0.413</td>
<td>0.687</td>
<td>Accept</td>
</tr>
<tr>
<td>A-18mm</td>
<td>15</td>
<td>15</td>
<td>2.697</td>
<td>0.017</td>
<td>Reject</td>
</tr>
<tr>
<td>B-15mm</td>
<td>15</td>
<td>15</td>
<td>0.815</td>
<td>0.429</td>
<td>Accept</td>
</tr>
<tr>
<td>C-15mm</td>
<td>15</td>
<td>15</td>
<td>4.614</td>
<td>0.000</td>
<td>Reject</td>
</tr>
<tr>
<td>A-SURF</td>
<td>15</td>
<td>15</td>
<td>10.425</td>
<td>0.000</td>
<td>Reject</td>
</tr>
<tr>
<td>A-CORE</td>
<td>4</td>
<td>4</td>
<td>5.031</td>
<td>0.015</td>
<td>Reject</td>
</tr>
</tbody>
</table>

1) $H_0$: The longitudinal and lateral compression yield strains had the same mean
2) A level of significance of $\alpha = 0.05$ has been used

Table 3-24 – Results of $t$-Tests for Compressive Ultimate Strains

The results show that there is no significant evidence to suggest the A-11mm, the A-15mm and the B-15mm panels exhibit orthotropic behaviour in terms of compressive ultimate strain. This means that compressive ultimate strain is independent of material directions for these three materials. This is consistent with the results obtained for compressive yield strain for these three materials as discussed in Section 3.5.2.7.2 above. However, the results presented in Table 3-24 above show that there is significant evidence that the A-18mm panels do exhibit orthotropic behaviour in terms of compressive ultimate strain. This means that compressive ultimate strain is not independent of material directions for the A-18mm panels. This is in contradiction to the results obtained for compressive yield strain for this material as discussed in Section 3.5.2.7.2 above. Table 3-24 above shows that there is significant evidence that the C-15mm, the A-SURF an
A-CORE panels do exhibit orthotropic behaviour in terms of compressive ultimate strain. This means that compressive yield strain is not independent of material directions for these three materials. This is consistent with the results obtained for compressive yield strain for these three materials as discussed in Section 3.5.2.7.2 above.

3.5.2.7.5 Compressive Local Elastic Modulus

The results presented in Table 3-21 above show that all materials exhibit orthotropic behaviour in terms of compressive local elastic modulus. This is highlighted by the fact that all materials had degrees-of-orthotropy for their mean and 5th percentile values less than or greater than a value of 1. This is consistent with the results for tensile elastic modulus described in Section 3.5.1.7.4 above.

The single-layer OSB panels were the most orthotropic in terms of both their mean and 5th percentile compressive elastic modulus values. Both the A-SURF and A-CORE panels exhibited enhanced compressive local elastic modulus values in the direction parallel to the wood strand orientation. This is consistent with the compressive strength properties discussed in Sections 3.5.2.6.1 and 3.5.2.6.3 above and the tensile elastic modulus results discussed in Section 3.5.1.7.4 above.

Of the commercial OSB/3 panels, the C-15mm panels were the most orthotropic in terms of mean (0.627) compressive local elastic modulus. This is consistent with the tensile elastic modulus results discussed in Section 3.5.2.6.1 above. The A-15mm panels were the most orthotropic in terms of 5th percentile (0.638) compressive local elastic modulus. The A-18mm panels were the least orthotropic in terms of mean (0.857) compressive local elastic modulus. The A-11mm panels were the least orthotropic in terms of 5th percentile (0.906) compressive elastic modulus. This is not consistent with the tensile elastic modulus results discussed in Section 3.5.2.6.1 above.

Note that the degree-of-orthotropy values for compressive local elastic modulus suggest that the single-layer OSB panels were significantly more orthotropic than the commercial OSB/3 panels. The order of the difference is similar to that
recorded for tensile strength properties as reported in Section 3.5.1.7.2 above and
tensile elastic modulus results as reported in Section 3.5.1.7.4 above. The order
of the difference is significantly greater than that recorded for compressive
strength properties as reported in Sections 3.5.2.7.1 and 3.5.2.7.3 above. The
tension test results shown in Table 3-7 and Table 3-8 above and the compression
test results shown in Table 3-17 and Table 3-19 above show that the elastic
modulus is almost the same in tension and compression in both material
directions for the material tested. This is a fact that is reflected in BS EN 12369
(BSI, 2001) which gives the same characteristic value for elastic modulus in both
tension and compression. Recall also that as described in Section 3.5.2.3 above,
the compressive local elastic modulus was evaluated by loading the specimen to
approximately 50% of its failure load i.e. well before the onset of compressive
failure. This strengthens the claims that the degrees-of-orthotropy of the
compressive strength properties for the single-layer panels discussed in Sections
3.5.2.7.1 and 3.5.2.7.3 above were not as significant as one would expect because
of the failure mechanism involved.

3.5.2.7.6 Compressive Global Elastic Modulus
The results presented in Table 3-21 above show that all materials exhibit
orthotropic behaviour in terms of compressive global elastic modulus. This is
consistent with the results for compressive local elastic modulus discussed in
Section 3.5.2.7.5 above and the tensile elastic modulus results discussed in
Section 3.5.1.7.4 above.

The single-layer OSB panels were the most orthotropic in terms of their mean
and 5th percentile compressive elastic modulus values. Both the A-SURF and A-
CORE panels show enhanced performance when loaded in compression parallel
to the direction of the wood strands. This is consistent with the compressive local
extastic modulus results discussed in Section 3.5.2.6.5 above and the tensile
extastic modulus results discussed in Section 3.5.1.7.4 above.

Of the commercial OSB/3 panels, the C-15mm panels were the most orthotropic
in terms of mean (0.706) compressive global elastic modulus. The A-15mm
panels were the most orthotropic in terms of 5th percentile (0.683) compressive
global elastic modulus. This is consistent with the compressive local elastic modulus results discussed in Section 3.5.2.7.5 above. The A-18mm panels were the least orthotropic in terms of the mean (0.879) and 5th percentile (0.850) compressive global elastic modulus.

The results in Table 3-21 above show that the A-11mm panels had enhanced 5th percentile (1.174) compressive global elastic modulus performance in the lateral direction. This was not reflected by the compressive local elastic modulus results discussed in Section 3.5.2.7.5 above. However, enhanced performance was reported for compressive strength properties in the lateral direction in Sections 3.5.2.7.1 and 3.5.2.7.3 above. Section 3.5.2.7.1 above showed that test specimens A-28-11-COMP-LONG and A-14-11-COMP-LONG reported particularly poor compressive yield strengths when compared to the remaining test specimens. Section 3.5.2.7.3 above showed that this was also true for their compressive ultimate strength results. The results had shown that A-28-11-LONG had a compressive global elastic modulus of 1649 N/mm² and that A-14-11-LONG had a compressive global elastic modulus of 1920 N/mm² in the longitudinal direction. Both these values fall considerably short of the results for the remaining values which fall in the region between 2600 to 3700 N/mm². This strengthens the claim that both these test specimens were defective in some manner and they were not representative of the overall compression performance of the A-11mm panels.

Note that the degree-of-orthotropy values for compressive global elastic modulus suggest that the single-layer OSB panels were significantly more orthotropic than the commercial OSB/3 panels. This was reported in the tensile elastic modulus results discussed in Section 3.5.1.7.4 above and for the compressive local elastic modulus results discussed in Section 3.5.2.7.5 above. This was not reflected in the compressive strength properties discussed in Sections 3.5.2.7.1 and 3.5.2.7.3 above. Section 3.5.2.7.5 above suggested that the failure mechanism for the compression test specimens could be responsible for a relatively poor compressive strength performance when compared to the tensile strength performance for the A-SURF panels in the longitudinal direction. The results...
reported here strengthen the suggestion that the longitudinal compressive strength of the A-SURF panels is limited by the internal bond strength. It suggests that the compressive performance can be enhanced by as much as 50% in the longitudinal direction if internal bond failure was eliminated as a variable.

### 3.5.2.7.7 Compressive Tangent Modulus

The results presented in Table 3-22 above show that all materials exhibit orthotropic behaviour in terms of compressive tangent modulus. This is consistent with the results for compressive elastic properties discussed in Sections 3.5.2.7.5 and 3.5.2.7.6 above and the tensile elastic modulus results discussed in Section 3.5.1.7.4 above.

The single-layer OSB panels were the most orthotropic in terms of their mean and 5th percentile compressive tangent modulus values. Both the A-SURF and A-CORE panels show enhanced performance when loaded in compression parallel to the direction of the wood strands. This is consistent with the compressive elastic modulus results discussed in Sections 3.5.2.6.5 and 3.5.2.7.6 above and the tensile elastic modulus results discussed in Section 3.5.1.7.4 above.

Of the commercial OSB/3 panels, the C-15mm panels were the most orthotropic in terms of mean (0.618) and 5th percentile (0.569) compressive tangent modulus. The A-18mm panels were the least orthotropic in terms of mean (0.944) and 5th percentile (1.185) compressive tangent modulus. The most likely explanation as to why the 5th percentile compressive tangent modulus is enhanced in the lateral direction is that the longitudinal results ($CoV = 28.6\%$) were considerably more variable than the lateral results ($CoV = 21.52\%$). However, it is also possible that the compressive failure of the A-18mm panels is naturally more erratic and harder to evaluate than for the other panels tested. Further testing is required to examine this in more detail.

Again, it is worth noting that the degree-of-orthotropy values for compressive tangent modulus suggest that the single-layer OSB panels were significantly more orthotropic than the commercial OSB/3 panels. This is consistent with the compressive elastic property results discussed in Sections 3.5.2.7.5 and 3.5.2.7.6.
above and with the tension test results discussed in Sections 3.5.1.7.2 and 3.5.1.7.4 above.

3.5.2.8 Comparison with Code

Table 3-25 below presents the characteristic values for compressive ultimate strength and local elastic modulus as presented in BS EN 12369-1 (BSI, 2001)

<table>
<thead>
<tr>
<th>Thickness Range</th>
<th>Longitudinal</th>
<th>Lateral</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ultimate Strength (N/mm²)</td>
<td>Local Elastic Modulus (N/mm²)</td>
</tr>
<tr>
<td>10-18 mm</td>
<td>15.4¹)</td>
<td>3800²)</td>
</tr>
</tbody>
</table>

¹) Code values for characteristic compressive ultimate strength were 5th percentile values
²) Code values for characteristic compressive elastic modulus were mean values

Table 3-25 – Code Values for Compressive Ultimate Strength and Elastic Modulus

In terms of compressive ultimate strength, the results in Table 3-18 and Table 3-20 above demonstrate that only the A-SURF panels achieved a characteristic longitudinal compressive ultimate strength exceeding the code value. None of the commercial OSB/3 panels achieved the characteristic compressive ultimate strength equal to or greater than that specified by the design code in the longitudinal direction. In the lateral direction, only the A-SURF panels achieved a characteristic compressive ultimate strength exceeding the code value. None of the commercial OSB/3 panels achieved the characteristic lateral compressive ultimate strength equal to or greater than that specified by the design code.

In terms of compressive local elastic modulus, the results in Table 3-17 and Table 3-19 above demonstrate that of the materials tested, only the B-15mm panels and the A-CORE panels failed to achieve a mean compressive local elastic modulus exceeding the code value in the longitudinal direction. In the lateral direction, all materials tested achieved a mean compressive local elastic modulus exceeding the code value in the lateral direction.

Since BS EN 12369 does not specify values for compressive yield strength, compressive global elastic modulus or compressive tangent modulus, it is not possible to make any comparisons for these properties.
3.5.3 Bending Testing

3.5.3.1 Test Piece Details

Bending test specimens were prepared in accordance with the guidelines given in BS EN 789 (BSI, 2004b). The test specimen consists of a rectangular piece of material, 300 mm (±5 mm) wide and a thickness equal to the thickness of the panel being tested. The span is a function of the panel thickness. A summary of the spans and test specimen dimensions is provided in Table 3-26 below.

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Span (mm)</th>
<th>Total Length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11 mm</td>
<td>652</td>
<td>730</td>
</tr>
<tr>
<td>15 mm</td>
<td>780</td>
<td>880</td>
</tr>
<tr>
<td>15 mm</td>
<td>876</td>
<td>980</td>
</tr>
</tbody>
</table>

Table 3-26 – Spans/Lengths of Bending Test Pieces

The dimensions and thickness reported in the results section is taken as the average of the readings taken at the locations indicated in Figure 3-37 below.

Figure 3-37 – Bending Test Piece - Recorded Dimensions

The thickness and gauge length of the test specimens were measured and using an electronic calliper with an accuracy of 0.02 mm. The length, width and span of the test specimens were measured with a ruler to an accuracy of 0.5 mm. The
dimensions and thicknesses for each test specimen were recorded in a Microsoft Excel workbook.

3.5.3.2 Sample Size

Fifteen 11 mm, 15 mm and 18 mm thick OSB/3 panels produced by Manufacturer A were manually cut. Fifteen 15 mm thick OSB/3 panels produced by Manufacturers B and C were CNC cut. Twenty surface-layer (fifteen of which were tested) and four core-layer panels were CNC cut. Table 3-31 and Table 3-28 below present the final number of bending test replications conducted for each panel type, thickness and material directions.

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Manufacturer A</th>
<th>Manufacturer B</th>
<th>Manufacturer C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LONG</td>
<td>LAT</td>
<td>LONG</td>
</tr>
<tr>
<td>11 mm</td>
<td>15</td>
<td>15</td>
<td>-</td>
</tr>
<tr>
<td>15 mm</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>18 mm</td>
<td>15</td>
<td>15</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3-27 – Bending Test Repetitions (Commercial OSB/3 Panels)

<table>
<thead>
<tr>
<th>Material</th>
<th>Manufacturer A</th>
<th>Manufacturer B</th>
<th>Manufacturer C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LONG</td>
<td>LAT</td>
<td>LONG</td>
</tr>
<tr>
<td>SURF</td>
<td>20</td>
<td>20</td>
<td>-</td>
</tr>
<tr>
<td>CORE</td>
<td>4</td>
<td>4</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3-28 – Bending Test Repetitions (Single-Layer OSB)

3.5.3.3 Testing arrangement

Testing was conducted in accordance with the method described using an Instron 4466 universal screw press testing machine with a 10 kN load cell on a test rig fabricated in accordance with the specifications of BS EN 789:2004 (BSI, 2004b). The testing arrangement is such that the test specimen is loaded in a “four-point” bending configuration. This induces a state of “pure bending” (i.e. constant bending moment with zero shear force) across the section of test specimen between the two loading heads.

The testing arrangement is demonstrated in Figure 3-38 below. The supports were designed so that they could be easily adjusted depending on the panel thickness being tested. The loading head was connected the crosshead using a
pivot joint. This enabled the loading head to rotate freely, ensuring that equal load was applied through the two loading positions during testing. The local displacement was recorded by two MPE type HS full bridge linearly varying differential transducers (LVDTs) with a ram length of 25 mm mounted to a hanger as shown in Figure 3-38 below. The hanger had a gauge length of 225 mm centred between the loading points. It was fixed to the neutral axis of the test specimen. The global displacement was recorded over the full span of the test specimen using two Solartron 10 V analogue LVDTs with a ram length of 100 mm mounted to the loading frame positioned above the specimen at midspan.

![Figure 3-38 – Bending Test Arrangement](image)

3.5.3.4 Loading Rates

Loading rates were estimated using Equation 3.15 below and the code of practice values for bending strength and stiffness presented in BS EN 12369-1 (BSI, 2001) with a target average failure time of 300 ± 120 s.

$$\delta h_{est} = \frac{l_2 f_{b, est}}{3T E_{b, est} l_2} (3L - 4l_2^3)$$  \hspace{1cm} (3.15)

**where:**  
$\delta h_{est}$ = estimated crosshead movement rate; $f_{b, est}$ = estimated bending ultimate strength; $E_{b, est}$ = estimated bending elastic modulus; $T$ = average test time; $l_2$ = distance from loading points to supports (see Figure 3-38 above); $L$ = total span ($= 2l_2 + l_3$)

The loading rates were adjusted as necessary following the first few test runs. The adjusted loading rates for each panel type, thickness and direction were summarised in Table 3-29 below.
Table 3-29 – Bending Test Loading Rates

The failure mode of this particular test specimen meant that the hanger and LVDTs mounted to it could not be left in place until the piece failed due to the risk of the LVDTs being damaged. To prevent the risk of equipment damage, the test specimen was loaded to approximately 40% of its expected load capacity, after which it was unloaded and the hanger along with the LVDTs was removed (referred to as the “MOE” test). The test specimen was then reloaded to failure using the two analogue LVDTs to record the global behaviour of the test specimen to failure (referred to as the “MOR” test). The estimated load capacity was calculated using the characteristic bending strength values for OSB/3 presented in BS EN 12369-1 (BSI, 2001) and adjusted based on the results of the first few test runs. Table 3-30 below presents the stop loads used for the MOE test for each panel type, thickness and material directions.

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Manufacturer A</th>
<th>Manufacturer B</th>
<th>Manufacturer C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LONG (mm/min)</td>
<td>LAT (mm/min)</td>
<td>LONG (mm/min)</td>
</tr>
<tr>
<td>11 mm</td>
<td>4.6</td>
<td>5.4</td>
<td>-</td>
</tr>
<tr>
<td>15 mm</td>
<td>5.8</td>
<td>8.5</td>
<td>5.8</td>
</tr>
<tr>
<td>18 mm</td>
<td>6.2</td>
<td>7.5</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3-30 – Bending MOE Test Stop Loads

3.5.3.5 Sample Size

Fifteen 11 mm, 15 mm and 18 mm thick OSB/3 panels produced by Manufacturer A were manually cut and tested. Fifteen 15 mm thick OSB/3 panels produced by Manufacturers B and C were CNC cut. Twenty surface-layer and four core-layer panels were CNC cut. Table 3-31 below presents details of the final number of bending test replications for each panel type, thickness and material directions.
Table 3-31 – Bending Test Repetitions (Commercial OSB/3 Panels)

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Manufacturer A</th>
<th>Manufacturer B</th>
<th>Manufacturer C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LONG LAT</td>
<td>LONG LAT</td>
<td>LONG LAT</td>
</tr>
<tr>
<td>11 mm</td>
<td>15 15</td>
<td>- -</td>
<td>- -</td>
</tr>
<tr>
<td>15 mm</td>
<td>15 15</td>
<td>15 15</td>
<td>15 15</td>
</tr>
<tr>
<td>18 mm</td>
<td>15 15</td>
<td>- -</td>
<td>- -</td>
</tr>
</tbody>
</table>

3.5.3.6 Results:

3.5.3.6.1 Material Properties

The bending strength and elastic properties were calculated according to BS EN 789 (BSI, 2004b). Equation 3.16 below gave the bending ultimate strength.

\[
\sigma_{u,b} = \frac{F_{\text{max}}}{2W}
\]  \hspace{1cm} (3.16)

where: \(\sigma_{u,b}\) = bending ultimate strength; \(F_{\text{max}}\) = maximum load; \(l_2\) = distance from loading points to supports (see Figure 3-38 above); \(W\) = elastic modulus of cross-section \((= \frac{bt}{6})\); \(b\) = width of test specimen; \(t\) = thickness of test specimen

The bending ultimate strain was calculated using Equation 3.17 below.

\[
\varepsilon_{u,b} = \frac{12u_{\text{max},g}t}{(3L^2 - 4l_2^2)}
\]  \hspace{1cm} (3.17)

where: \(\varepsilon_{u,b}\) = bending ultimate strain; \(u_{\text{max},g}\) = global displacement corresponding to maximum load; \(t\) = thickness of test specimen; \(l_2\) = distance from loading points to supports (see Figure 3-38 above); \(L\) = total span \((= 2l_2 + l_3)\)

The bending local elastic modulus was calculated based on the results from the LVDTs mounted to the hanger using the portion of the load-displacement curve between \(0.1F_{\text{max}}\) and \(0.4F_{\text{max}}\) and Equation 3.18 below.

\[
E_{b,l} = \frac{(F_2 - F_1)l_2^2l_1}{16(u_2 - u_1)l}
\]  \hspace{1cm} (3.18)

where: \(E_{b,l}\) = bending local elastic modulus; \(F_1 = 0.1F_{\text{max}}\); \(F_2 = 0.4F_{\text{max}}\); \(u_1\) = displacement corresponding to \(F_1\); \(u_2\) = displacement corresponding to \(F_2\); \(l_1\) = gauge length of hanger (see Figure 3-38 above); \(l_2\) = distance from loading points to supports (see Figure 3-38 above); \(I\) = second moment of area of test specimen \((= \frac{bt^3}{12})\)
In addition to the material properties defined in BS EN 789, some additional elastic properties were calculated including:

- Bending global elastic modulus,
- Plate-shear modulus.

The bending elastic modulus as defined in the BS EN 789 is calculated based on the results from the section of the test specimen that is subjected to pure bending only where no shear force is present (i.e. the section between the hanger mounting points). This is to eliminate the effects of shear deflection. The shear deflection component of solid timber and wood-based composite beams and has been the subject of extensive study (Orosz, 1970, Thomas, 2002, Bradtmueller, 1994, CSA, 2001b, CSA, 2006) and has been shown constitute a significant proportion of the total deflection of beams loaded in bending and shear. Therefore, evaluating the bending elastic modulus of wood-based materials subjected pure bending is more accurate.

Despite this, it is acknowledged in many jurisdictions that wood-based structural members were rarely loaded in pure bending and were more often than not loaded in bending and shear. Therefore, they also allow the bending elastic modulus to be evaluated using a three-point bending test as an alternative to a four point bending test (ASTM, 2000, AF&PA/AWC, 2005, CSA, 2001a, CSA, 1994, CSA, 2001b, CSA, 2006, CSA, 2007). The three-point bending arrangement means that the beam is subjected to shear and bending over its full span. Calculating the bending elastic modulus based on the results of the three-point bending test produces a value that is significantly lower than that calculated based on the results on the middle third section of a four-point bending test. This is because the deflections recorded from a three-point test comprise of both moment-induced and shear-induced deflections whereas the deflections recorded from the middle-third of a four-point test comprise of bending-induced deflections only.

The advantage of using the three-point arrangement therefore is that the bending elastic modulus has a built-in allowance for shear deflections. Therefore, it is
generally acceptable to estimate the deflection of a wood-based beam using simple bending theory and the bending elastic modulus evaluated using a three-point bending arrangement. Estimating the deflection of a beam subjected to shear and bending using simple bending theory and the bending elastic modulus evaluated from the a four-point bending arrangement would significantly underestimate the deflection of the beam in service. To obtain a proper estimate, one would have to calculate the bending deflections and shear deflections separately then add them together to get the total deflection of the beam. The other advantage with three-point bending tests is that the testing arrangement is much simpler. It is often used by OSB mills (including those operating to European standards) for quality control testing due to the relative ease at which it can be performed (BSI, 1993a).

For the purposes of this study, it was recognised that measuring the deflections of test specimens subjected to four-point bending over the full span will give deflection readings that include bending-induced and shear-induced components. Therefore, calculating the bending elastic modulus using the deflection readings recorded by the two LVDTs mounted to the machine loading frame at mid-span will give a value similar to that obtained from a three-point bending test. This was done for two purposes:

- To allow direct comparison between the results obtained for bending elastic modulus from this test program with data from quality control testing supplied by Manufacturer A using the three-point bending arrangement according to BS EN 310 (BSI, 1993a),
- To examine the possibility for developing an expression for calculating the plate-shear modulus using the difference between estimated global deflection calculated using the bending local elastic modulus and the global deflection recorded during the test, allowing the plate-shear modulus to be determined from a 4-point bending test, thus eliminating the requirement for a plate-shear modulus test.

To distinguish between the bending elastic moduli, the terms bending local elastic modulus and bending global elastic modulus had been adopted. The term
bending local elastic modulus is used to describe the bending elastic modulus evaluated based on the portion of the test specimen located between the mounting points for the hanger and is calculated using Equation 3.18 above. The term bending global elastic modulus is used to describe the bending elastic modulus evaluated based on the deflections recorded over the full span of the specimen and is calculated using Equation 3.19 below.

\[
E_{b,l} = \frac{(F_2 - F_1)(3l_1^2 - 4l_2^2)l_2}{48(u_2 - u_1)l} \quad (3.19)
\]

where: \( E_{b,l} \) = bending local elastic modulus; \( F_1 = 0.1F_{max} \); \( F_2 = 0.4F_{max} \); \( u_1 = \) displacement corresponding to \( F_1 \); \( u_2 = \) displacement corresponding to \( F_2 \); \( l_1 = \) gauge length of hanger (see Figure 3-38 above); \( l_2 = \) distance from loading points to supports (see Figure 3-38 above); \( l = \) second moment of area of test specimen (= \( bt^3/12 \))

The plate-shear modulus was estimated by using the bending local elastic modulus to calculate the theoretical bending-induced deflection over the full span of the test specimen. The shear-induced deflection was calculated by subtracting the bending-induced deflection from the total deflection recorded at mid-span. The plate-shear modulus was calculated using Equation 3.20 below.

\[
G_{yz} = \frac{6E_{b,l}F_{max}^2l_2}{A[48E_{b,l}tu_{max} - F_{max}l_2(3L^2 - 4l_2^2)]l} \quad (3.20)
\]

where: \( G_{yz} \) = plate-shear modulus; \( E_{b,l} \) = bending local elastic modulus; \( F_{max} \) = failure load; \( u_{max} \) = recorded displacement at failure load; \( l_1 = \) gauge length of hanger (see Figure 3-38 above); \( l_2 = \) distance from loading points to supports (see Figure 3-38 above); \( l = \) second moment of area of test specimen (= \( bt^3/12 \)); \( A = \) cross-sectional area of test specimen; \( L = \) total span (= \( 2l_2 + l_3 \))

A custom-developed computer program used Equations 3.16 to 3.20 to automatically calculate the bending properties from the raw experimental data. The computer program was developed using Microsoft VBA and embedded into a Microsoft Excel 2003 template. This will be discussed in more detail in Chapter 4.

Table 3-32 below presents a summary of the four-point bending strength and elastic material properties.
<table>
<thead>
<tr>
<th>Panel Type</th>
<th>Ultimate Strength</th>
<th>Ultimate Strain</th>
<th>Local Elastic Modulus</th>
<th>Global Elastic Modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (N/mm²)</td>
<td>CoV (%)</td>
<td>Mean (×10⁻³)</td>
<td>CoV (%)</td>
</tr>
<tr>
<td>A-11mm</td>
<td>31.09</td>
<td>13.47</td>
<td>4.57</td>
<td>7.85</td>
</tr>
<tr>
<td>A-15mm</td>
<td>29.44</td>
<td>12.52</td>
<td>4.89</td>
<td>11.35</td>
</tr>
<tr>
<td>A-18mm</td>
<td>25.98</td>
<td>14.16</td>
<td>4.61</td>
<td>9.39</td>
</tr>
<tr>
<td>B-15mm</td>
<td>28.38</td>
<td>8.33</td>
<td>4.82</td>
<td>8.86</td>
</tr>
<tr>
<td>C-15mm</td>
<td>24.59</td>
<td>13.47</td>
<td>3.88</td>
<td>5.78</td>
</tr>
<tr>
<td>A-11mm</td>
<td>21.25</td>
<td>9.04</td>
<td>6.34</td>
<td>10.54</td>
</tr>
<tr>
<td>A-15mm</td>
<td>18.39</td>
<td>13.50</td>
<td>6.55</td>
<td>14.06</td>
</tr>
<tr>
<td>A-18mm</td>
<td>15.26</td>
<td>8.91</td>
<td>6.30</td>
<td>8.54</td>
</tr>
<tr>
<td>B-15mm</td>
<td>18.60</td>
<td>15.40</td>
<td>7.02</td>
<td>10.75</td>
</tr>
<tr>
<td>C-15mm</td>
<td>15.54</td>
<td>14.60</td>
<td>6.18</td>
<td>8.86</td>
</tr>
</tbody>
</table>

Table 3-32 – 4-Point Bending Test Results Summary (Standard OSB Panels)

3.5.3.6.2 Mechanical Behaviour

Figure 3-39 below shows a typical local load vs deflection curve observed during an MOE test for an A-18mm panel loaded in 4-point bending. Figure 3-40 below shows a typical stress vs strain curves observed during an MOE test for an A-18mm panel loaded in 4-point bending. A more comprehensive set of results is presented in Appendix B.
Figure 3-40 – 4-Point Bending Local Stress vs Strain Curve (MOE Results)

Figure 3-41 and Figure 3-42 below show typical global load-deflection and stress-strain curves respectively observed during an MOR test for A-18mm panels loaded in 4-point bending. Note the section highlighted in red on Figure 3-42 below shows the section of the curve over which the global elastic modulus was calculated. A more comprehensive set of results is presented in Appendix B.

Figure 3-41 – 4-Point Bending Global Load vs Displacement Curve (MOR Results)
Figure 3-42 – 4-Point Bending Global Stress vs Strain Curve (MOE and MOR Results)

The global load-displacement and stress-strain curves shown in Figure 3-41 and Figure 3-42 above respectively show that the mechanical behaviour is non-linear at high strains. The bending test specimens failed in a brittle mode with little or no warning of the onset of failure. This is reflected by the abrupt end to the load-displacement and stress-strain curves shown in Figure 3-41 and Figure 3-42 above. Inspection of the failure surface showed that the failure mechanism consisted of a combination of strand failure and bond failure. Figure 3-43 below shows a bending failure surface for a longitudinal tension test conducted on an 18 mm thick OSB/3 panel produced by Manufacturer A.
Note the similarities between the mechanical behaviour and failure mechanisms reported in this section for bending and reported in Section 3.5.1.5.2 above for tension. This suggests that bending behaviour is governed by the behaviour of the tension surface. Inspection of the tension and compression strength results discussed in Sections 3.5.1.5.1 and 3.5.2.5.1 above suggest that all materials tested were stronger in compression than they were in tension. Inspection of the tension and compression elastic properties discussed in Sections 3.5.1.5.1 and 3.5.2.5.1 above also show that all materials tested were generally had the same modulus of elasticity in tension and compression. This means that when loaded in bending, the stresses on the tension face would be almost equal to those on the compression face. The result would be that the tension face will reach its ultimate strength before the compression face.

### 3.5.3.7 Discussion

#### 3.5.3.7.1 Bending Ultimate Strength

Figure 3-44 below compares the mean and 5th percentile bending ultimate strength results in both material directions for the materials tested.

![Figure 3-44 – Bending Ultimate Strength](image.png)
In the longitudinal direction, the A-11mm panels had the highest mean (31.09 N/mm²) and 5th percentile (26.20 N/mm²) bending ultimate strength values. The C-15mm panels had the lowest mean (24.59 N/mm²) and 5th percentile (18.66 N/mm²) bending ultimate strength values in the longitudinal direction. In the lateral direction, the A-11mm panels had the highest mean (21.25 N/mm²) and 5th percentile (18.58 N/mm²) bending ultimate strength. The C-15mm panels had the lowest mean (15.54 N/mm²) and 5th percentile (12.22 N/mm²) bending ultimate strength in the lateral direction. Note the downward trend in mean and 5th percentile bending ultimate strength with increasing nominal thickness in both material directions for the panels produced by Manufacturer A. Similar trends had been observed in Sections 3.5.1.6.3, 3.5.2.6.1, 3.5.2.6.3, 3.5.2.6.5 and 3.5.2.6.7 above for certain tension and compression material properties. This suggests that size effects influence the bending performance of the materials produced by Manufacturer A.

3.5.3.7.2 Bending Ultimate Strain

Figure 3-45 below compares the mean and 5th percentile bending ultimate strain results in both material directions for the materials tested.
In the longitudinal direction, the results indicate that the A-15mm panels had the highest mean \((4.89 \times 10^{-3})\) and 5th percentile \((4.27 \times 10^{-3})\) bending ultimate strain values. The C-15mm panels had the lowest mean \((3.88 \times 10^{-3})\) and 5th percentile \((3.55 \times 10^{-3})\) bending ultimate strain values in the longitudinal direction. In the lateral direction, the B-15mm panels had the highest mean \((7.02 \times 10^{-3})\) and 5th percentile \((5.90 \times 10^{-3})\) bending ultimate strain values. The C-15mm panels had the lowest mean \((6.18 \times 10^{-3})\) bending ultimate strain value in the lateral direction. The A-15mm panels had the lowest 5th percentile \((5.28 \times 10^{-3})\) bending ultimate strain value in the lateral direction. This is likely due to the greater variability of the bending ultimate strain for the A-15mm panels \((CoV = 16.06\%\) when compared to the C-15mm panels \((CoV = 8.86\%\) in the lateral direction as shown in Table 3-32 above. Unlike the results for tensile ultimate strain, compressive yield and ultimate strains discussed in Sections 3.5.1.6.2, 3.5.2.6.2 and 3.5.2.6.4 above, bending ultimate strain exhibits orthotropic behaviour.

### 3.5.3.7.3 Bending Local Elastic Modulus

Figure 3-46 below compares the mean and 5th percentile bending local elastic modulus results in both material directions for the materials tested.
In the longitudinal direction, the A-11mm panels had the highest mean (10325 N/mm²) bending local elastic modulus value. The A-15mm panels had the highest 5th percentile (8271 N/mm²) bending local elastic modulus value in the longitudinal direction. This discrepancy is likely due to the greater variability of the bending local elastic modulus results for the A-11mm panels ($CoV = 16.31\%$) when compared to the A-15mm panels ($CoV = 12.59\%$) in the longitudinal direction as shown in Table 3-32 above. The B-15mm panels had the lowest mean (8635 N/mm²) bending local elastic modulus value in the longitudinal direction. The A-18mm panels had the lowest 5th percentile (7389 N/mm²) bending local elastic modulus value in the longitudinal direction. This discrepancy is likely due to the greater variability of the bending local elastic modulus results for the A-18mm panels ($CoV = 10.32\%$) when compared to the B-15mm panels ($CoV = 9.11\%$) as shown in Table 3-32 above. In the lateral direction, the A-11mm panels had the highest mean (4749 N/mm²) and 5th percentile (4259 N/mm²) bending local elastic modulus values. The A-18mm panels had the lowest mean (3480 N/mm²) and 5th percentile (2784 N/mm²) bending local elastic modulus values in the lateral direction.

Note the downward trend in the mean bending local elastic modulus with increasing nominal thickness in both material directions for panels produced by Manufacturer A. This trend is also reflected for the 5th percentile values for all but the A-15mm panels which had been shown throughout to have a particularly low variability. Similar trends had been observed in Section 3.5.3.8.1 above for bending ultimate strength and Sections 3.5.1.6.3, 3.5.2.6.1, 3.5.2.6.3, 3.5.2.6.5 and 3.5.2.6.7 above for certain tension and compression material properties. This strengthens the claim that size effects were having an impact on the mechanical performance of the materials produced by Manufacturer A. However, further testing using larger samples sizes and a greater variety of panel thicknesses is required to fully investigate size effects.

3.5.3.7.4 Bending Global Elastic Modulus

Figure 3-47 below compares the mean and 5th percentile bending global elastic modulus results in both material directions for the materials tested.
Figure 3-47 – Bending Global Elastic Modulus

In the longitudinal direction, the results demonstrate that the A-11mm panels had the highest mean (7716 N/mm$^2$) and 5th percentile (6718 N/mm$^2$) bending global elastic modulus values. The A-18mm panels had the lowest mean (6440 N/mm$^2$) and lowest 5th percentile (5570 N/mm$^2$) bending global elastic modulus values in the longitudinal direction. In the lateral direction, the A-11mm panels had the highest mean (4066 N/mm$^2$) and 5th percentile (3739 N/mm$^2$) bending global elastic modulus values. The A-18mm panels had the lowest mean (2898 N/mm$^2$) and 5th percentile (2504 N/mm$^2$) bending global elastic modulus values in the lateral direction.

Note again the downward trend in the mean and 5th percentile bending global elastic modulus values with increasing nominal thickness in both material directions for panels produced by Manufacturer A. This was commented on above in Sections 3.5.3.7.3 and 3.5.3.7.1 above for bending ultimate strength and local elastic modulus respectively. Similar trends had also been highlighted in Sections 3.5.1.6.3, 3.5.2.6.1, 3.5.2.6.3, 3.5.2.6.5 and 3.5.2.6.7 above for tensile elastic modulus, compressive yield strength, ultimate strength, local elastic modulus and global elastic modulus respectively. This strengthens the claim that
size effects were having an impact on the mechanical performance of the materials produced by Manufacturer A.

### 3.5.3.7.5 Plate-Shear Modulus

Figure 3-48 below compares the mean and 5th percentile plate-shear modulus results in both material directions for the materials tested.

![Plate-Shear Modulus](image)

In the longitudinal direction, the results show that the A-18mm panels had the highest mean (4441 N/mm²) plate-shear modulus value. The B-15mm panels had the highest 5th percentile (3077 N/mm²) plate-shear modulus value in the longitudinal direction. This discrepancy is likely due to the greater variability of the plate-shear modulus results in the longitudinal direction for the A-18mm panels ($CoV = 29.82\%$) when compared to the B-15mm panels ($CoV = 15.86\%$). The C-15mm panels had the lowest mean (3178 N/mm²) plate-shear modulus value in the longitudinal direction. The A-11mm panels had the lowest 5th percentile (1160 N/mm²) plate-shear modulus value in the longitudinal direction. This discrepancy is likely due to the greater variability of the plate-shear modulus results in the longitudinal direction for the A-11mm panels ($CoV = 50.27\%$) when compared to the C-15mm panels ($CoV = 35.50\%$).
In the lateral direction, the results demonstrate that the B-15mm panels had the highest mean (1483 N/mm²) plate-shear modulus value. The A-18mm panels had the highest 5th percentile (966 N/mm²) plate-shear modulus value in the lateral direction. This discrepancy is likely due to the greater variability of the B-15mm panels ($CoV = 38.90\%$) when compared to the A-18mm panels ($CoV = 34.55\%$). The C-15mm panels had the lowest mean (843 N/mm²) and 5th percentile (552 N/mm²) plate-shear modulus values in the lateral direction.

The most noticeable feature of using the standard 4-point bending test to evaluate the plate-shear modulus is the variability of the results. The $CoV$ values varied from 15.86% up to 50.27%. It was also anticipated in advance that the plate-shear modulus would not exhibit orthotropic behaviour, i.e. the longitudinal and lateral values would be equal. The results presented in Figure 3-47 above suggest that the plate-shear modulus does exhibit orthotropic behaviour. These findings suggest that the standard 4-point bending test is not appropriate for evaluating the plate-shear modulus. A separate test is therefore required to properly evaluate this property. As a result, no further reference will be made to plate-shear modulus for the remainder of this study.

### 3.5.3.8 Degree-of-Orthotropy

Table 3-33 below presents the degree-of-orthotropy for the bending elastic properties for the materials tested. The degree-of-orthotropy was calculated using the same method described in Section 3.5.1.7 above.

<table>
<thead>
<tr>
<th>Panel Type</th>
<th>Mean Local Elastic Modulus</th>
<th>Mean Global Elastic Modulus</th>
<th>5th Percentile Local Elastic Modulus</th>
<th>5th Percentile Global Elastic Modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-11mm</td>
<td>0.460</td>
<td>0.527</td>
<td>0.527</td>
<td>0.557</td>
</tr>
<tr>
<td>A-15mm</td>
<td>0.436</td>
<td>0.482</td>
<td>0.431</td>
<td>0.503</td>
</tr>
<tr>
<td>A-18mm</td>
<td>0.399</td>
<td>0.450</td>
<td>0.377</td>
<td>0.450</td>
</tr>
<tr>
<td>B-15mm</td>
<td>0.421</td>
<td>0.492</td>
<td>0.403</td>
<td>0.464</td>
</tr>
<tr>
<td>C-15mm</td>
<td>0.375</td>
<td>0.446</td>
<td>0.401</td>
<td>0.452</td>
</tr>
</tbody>
</table>

Table 3-33 – Degree-of-Orthotropy Results for Bending Elastic Properties

Table 3-34 below presents the degree-of-orthotropy for the bending failure properties for the materials tested.
Table 3-34 – Degree-of-Orthotropy Results for Bending Failure Properties

3.5.3.8.1 Bending Ultimate Strength

The results presented in Table 3-34 above suggest that all materials tested exhibit orthotropic behaviour and that ultimate strength is enhanced in the longitudinal direction. This is demonstrated by the fact that the degree-of-orthotropy values for all panels tested had values that were greater or less than a value of 1. This is consistent with the general trend observed in Sections 3.5.1.7.2, 3.5.2.6.1 and 3.5.2.6.3 above for tensile ultimate strength, compressive yield strength and ultimate strength respectively.

Of the materials tested, the A-18mm panels were the most orthotropic in terms of mean (0.587) and 5th percentile (0.587) values. The A-11mm panels were the least orthotropic in terms of both mean (0.683) and 5th percentile values (0.709). Note that the degrees-of-orthotropy for bending ultimate strength were of a similar order to those recorded for tensile ultimate strength for the A-SURF panels as reported in Section 3.5.1.7.2 above. Unlike tension and compression loading, bending loading does not produce a uniform stress state over the full thickness of the test specimen. Classic simple elastic bending theory for members consisting of isotropic materials assumes a linear variation of bending stress across the cross-section. The bending stress varies from a value of zero at the neutral axis to a maximum at the fibre furthest from the neutral axis (Hearn, 1997). In laminated materials, the lay-up of the material has a significant influence on the bending stress distribution (Vinson and Sierakowski, 1987). Wong (2003) showed that the vertical density profile had a significant influence on the stress distribution of particleboard subjected to bending. This is shown in Figure 3-49 below.
The results for tensile ultimate strength for the A-SURF panels discussed in Section 3.5.1.7.2 above show that the degree-of-orthotropy for tensile ultimate strength is of a similar order to that reported here for bending ultimate strength. The results for compressive ultimate strength for the A-SURF panels discussed in Section 3.5.2.7.3 above show that the degree-of-orthotropy for compressive ultimate strength is noticeably less than that reported here for bending ultimate strength. The results for elastic modulus discussed in Sections 3.5.1.6.3, 3.5.2.6.5 and 3.5.2.6.6 above for tensile elastic modulus, compressive local elastic modulus and global elastic modulus respectively prove that the A-SURF panels were significantly stiffer than the A-CORE panels. The mechanical behaviour in bending shown in Figure 3-41 and Figure 3-42 above has far more in common
with that shown in Figure 3-15 and Figure 3-16 above for tension than with that shown in Figure 3-27 and Figure 3-28 above for compression. This suggests that bending performance is strongly influenced by the performance of the tensile surface and that a plot of bending stress versus depth for OSB would be similar to that shown in Figure 3-49 above for particleboard.

3.5.3.8.2  **Bending Ultimate Strain**

The results presented in Table 3-34 above suggest that all materials tested exhibit orthotropic behaviour and that ultimate strain is enhanced in the lateral direction. This is in direct contradiction to all other properties thus far which had all been found to be either not affected by direction or else enhanced in the longitudinal direction. The reasons for this were unclear at this stage. It is likely due to the variation of tensile ultimate strain that would exist across the thickness of the commercial OSB/3 panels on account of the vertical density profile. Of the materials tested, the C-15mm panels were the most orthotropic in terms of mean (1.591) and 5th percentile (1.521) bending ultimate strain values. The A-18mm panels were the least orthotropic in terms of mean (1.340) and 5th percentile (1.238) bending ultimate strain values.

3.5.3.8.3  **Bending Local Elastic Modulus**

The results presented in Table 3-32 above suggest that all materials tested exhibit orthotropic behaviour and that local elastic modulus is enhanced in the longitudinal direction. This is consistent with the findings discussed in Sections 3.5.1.7.4, 3.5.2.6.5, 3.5.2.6.6 and 3.5.2.6.7 above for tensile elastic modulus, compressive local elastic modulus, global elastic modulus and tangent modulus respectively. Of the materials tested, the C-15mm panels were the most orthotropic in terms of mean (0.375) bending local elastic modulus values. The A-18mm panels were the most orthotropic in terms of 5th percentile (0.377) bending local elastic modulus values. This is likely due to the greater variability of the bending local elastic modulus results in the longitudinal direction for the C-15mm panels ($\text{CoV} = 17.03\%$) when compared with the A-18mm panels ($\text{CoV} = 10.32\%$) as shown in Table 3-32 above. The A-11mm panels were the least
orthotropic in terms of both mean (0.460) and 5th percentile (0.527) bending local elastic modulus values.

3.5.3.8.4 Bending Global Elastic Modulus

The results presented in Table 3-32 above suggest that all materials tested exhibit orthotropic behaviour and that global elastic modulus is enhanced in the longitudinal direction. This is consistent with the results for bending local elastic modulus discussed in Section 3.5.3.8.3 above. It is also consistent with the findings discussed in Sections 3.5.1.7.4, 3.5.2.6.5, 3.5.2.6.6 and 3.5.2.6.7 above for tensile elastic modulus, compressive local elastic modulus, global elastic modulus and tangent modulus respectively.

Of the materials tested, the C-15mm were the most orthotropic in terms of mean (0.446) bending global elastic modulus values. The A-18mm panels were the most orthotropic in terms of 5th percentile (0.450) bending global elastic modulus values. This is consistent with the results obtained for bending local elastic modulus discussed in Section 3.5.3.8.3 above. This is likely due to the greater variability of the bending global elastic modulus results in the lateral direction for the C-15mm panels (CoV = 12.97%) when compared with the A-18mm panels (CoV = 7.74%) as shown in Table 3-32 above. The A-11mm panels were the least orthotropic in terms of both mean (0.527) and 5th percentile (0.557) values.

3.5.3.9 Comparison with Code

Table 3-35 below presents the characteristic values for bending ultimate strength and stiffness as presented in BS EN 12369-1 (BSI, 2001).

<table>
<thead>
<tr>
<th>Thickness Range</th>
<th>Longitudinal</th>
<th>Lateral</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ultimate Strength (N/mm²)</td>
<td>Local Elastic Modulus (N/mm²)</td>
</tr>
<tr>
<td>10-18mm</td>
<td>16.4&lt;sup&gt;1)&lt;/sup&gt;</td>
<td>4930&lt;sup&gt;2)&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

1) Code values for characteristic bending ultimate strength were 5th percentile values
2) Code values for characteristic bending elastic modulus were mean values

Table 3-35 – Code Values for Bending Ultimate Strength and Elastic Modulus
The results demonstrate that all materials tested not only meet but exceed the code values for ultimate strength and elastic modulus by factors of 1.5 to greater than 3. The results were likely a result of the traditional and still most common use of OSB as floor sheeting as well as the quality control methods used to ensure continued compliance with BS EN 300 (BSI, 2006).

The standard requires producers to conduct 3-point bending tests in accordance with BS EN 310 (BSI, 1993a) and internal bond tests in accordance with BS EN 319 (BSI, 1993b) as quality control measures. Producers were not required to conduct any other mechanical properties tests. It is assumed that all other properties will achieve their code values provided that the material passes both these tests. The results thus far had indicated that this is not necessarily the case. This raises the question as to whether producers should be compelled to perform additional load tests as part of their quality control regime. However, the sample sizes and sampling methods used in this study were limited and it is therefore possible that the trends witnessed thus far are isolated incidents. Testing a wider variety of panels from a wider variety of producers using larger sample sets is required before any definitive conclusions can be drawn about the performance of OSB products and effectiveness of quality control procedures.

One the other hand, the significantly better than expected performance of the panels in bending is a positive endorsement of the quality control methods as well as demonstrating the potential for improving OSB performance. These results make a strong case for either increasing the characteristic values for bending strength and elastic modulus presented in BS EN 12369-1 (BSI, 2001) or allowing producers to supply characteristic values for their own products.

### 3.5.4 Panel-Shear

#### 3.5.4.1 Test Piece Details

Panel-shear test specimens were prepared in accordance with the guidelines given in Annex B of BS EN 789 (BSI, 2004b). The test specimen consists of a rectangular piece of material, 440 mm wide by 900 mm long with opposite corners removed to formed transition curves. Timber rails, 145 mm × 35 mm ×
700 mm were glued to the test specimen in order to transfer the applied load from the loading head to the OSB test specimen. The timber rails were made from grade C16 timber and were glued to the test specimen using a two-part Phenol-Resorcinol Formaldehyde (PRF) wood adhesive. The timber rails were planed and cut to length immediately prior to gluing and clamped for a minimum of 24 hours to ensure maximum bond strength between the rails and the shear panel. Figure 3-50 below provides full details of the panel-shear test specimen.

![Figure 3-50 – Shear Test Piece](image)

The dimensions and thickness reported in the results section is taken as the average of the readings taken at the locations indicated in Figure 3-51 below.

![Figure 3-51 – Panel-Shear Test Piece - Recorded Dimensions](image)
The thickness and gauge length of the test specimens were measured and recorded using an electronic caliper with an accuracy of 0.02 mm. The length, width and distance between the rails of the test specimens were measured with a ruler to an accuracy of 0.5 mm.

3.5.4.2 Sample Size

Fifteen 11 mm, 15 mm and 18 mm thick OSB/3 panels produced by Manufacturer A were manually cut and tested. Fifteen 15 mm thick OSB/3 panels produced by Manufacturers B and C were CNC cut. Twenty surface-layer (fifteen of which were tested) and four core-layer panels were CNC cut. Table 3-36 and Table 3-37 below present details of the final number of panel-shear test replications for each panel type, thickness and material directions.

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Manufacturer A</th>
<th>Manufacturer B</th>
<th>Manufacturer C</th>
</tr>
</thead>
<tbody>
<tr>
<td>11mm</td>
<td>29</td>
<td>25</td>
<td>-</td>
</tr>
<tr>
<td>15mm</td>
<td>20</td>
<td>15</td>
<td>-</td>
</tr>
<tr>
<td>15mm</td>
<td>20</td>
<td>15</td>
<td>-</td>
</tr>
</tbody>
</table>

1) Includes 10 tests conducted as part of previous study (O’Toole, 2006)
2) Includes 5 tests conducted as part of previous study (Gill and Grennan, 2007)

Table 3-36 – Panel-Shear Test Repetitions (Commercial OSB/3 Panels)

<table>
<thead>
<tr>
<th>Material</th>
<th>Manufacturer A</th>
<th>Manufacturer B</th>
<th>Manufacturer C</th>
</tr>
</thead>
<tbody>
<tr>
<td>SURF</td>
<td>15</td>
<td>15</td>
<td>-</td>
</tr>
<tr>
<td>CORE</td>
<td>4</td>
<td>4</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3-37 – Panel-Shear Test Repetitions (Single-Layer OSB)

3.5.4.3 Testing arrangement

Testing was conducted in accordance with the method described in BS EN 789 (BSI 2004) using a Dartec hydraulic beam testing machine with a 500kN load cell. Load was applied through a ball joint bolted to the underside of the loading beam to ensure the load was applied evenly over end of the test specimen. The panel-shear test rig was constructed in accordance with the guidelines presented in Figure 6 of BS EN 789 (BSI, 2004b) during the course of a previous study conducted by O’Toole (2006). Vertical movement is resisted by the vertical...
support at the end of the rails at one edge of the test specimen. A force couple generated by the two horizontal supports located diagonally opposite each other prevents rotation of the test specimen. This arrangement is demonstrated by the free body diagram shown below in Figure 3-52 below.

![Free Body Diagram](image)

**Figure 3-52 – Shear Test Piece Free-Body Diagram**

Figure 3-53 below presents a drawing of the shear test rig used for this study. Out of plane movement is resisted by two sets of lateral supports that were adjustable to allow the rig to be used for all panel thicknesses. The test specimen is placed in the rig and is lightly clamped between the lateral support plates. The horizontal and lateral supports were lined with two sheets of a low friction material (Polytetrafluoroethylene (PTFE)) to ensure the shear test specimen could deform freely.
The displacement of the machine crosshead was recorded with a MPE type HS full bridge linearly varying differential transducer (LVDT) with a ram length of 50 mm and an accuracy of 1%. The displacement of the shear test specimens was measured using two MPE type HS full bridge linearly varying differential transducer (LVDTs) with a ram length of 5 mm and an accuracy of 1%. The LVDTs were mounted to the test specimen at 45° to the load direction at the center of the shear area over a gauge length of 120 mm.

A selection of test specimens was instrumented with strain gauges (TML Tokyo Sokki Kenkyujo Co PL-60-11 gauges) with a gauge length of 60 mm. The strain gauges were centered between the LVDT mounts and recorded displacement at 45° to the direction of load application. Figure 3-54 below shows a schematic layout of the instrumentation used to monitor the panel-shear test.
3.5.4.4 Loading Rate

Loading rates were estimated using Equation below and the code of practice values for panel-shear strengths and moduli presented in BS EN 12369-1 (BSI, 2001) with a target average failure time of 300 ± 120 s.

\[ \delta h_{est} = \frac{d_1 f_{b,est}}{G_{v,est} T} \]  

(3.21)

where: \( \delta h_{est} \) = estimated crosshead movement rate; \( f_{b,est} \) = estimated panel-shear ultimate strength; \( G_{v,est} \) = estimated panel-shear modulus; \( T \) = average test time; \( d \) = height of shear area of the test specimen

The loading rates were adjusted as necessary following based on the results of the first few test runs. The adjusted loading rates for each panel type, thickness and direction were summarised in Table 3-38 below.

<table>
<thead>
<tr>
<th>Manufacturer A</th>
<th>Manufacturer B</th>
<th>Manufacturer C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness</td>
<td>LONG (mm/s)</td>
<td>LAT (mm/s)</td>
</tr>
<tr>
<td>11mm</td>
<td>0.025</td>
<td>0.025</td>
</tr>
<tr>
<td>15mm</td>
<td>0.030</td>
<td>0.030</td>
</tr>
<tr>
<td>18mm</td>
<td>0.040</td>
<td>0.040</td>
</tr>
</tbody>
</table>

Table 3-38 – Panel-Shear Test Loading Rates

Figure 3-54 – Shear Test Instrumentation
The nature of this particular test procedure meant that the LVDTs mounted to the test specimen could not be left in place until the piece failed because of the risk of the LVDTs being damaged in the event of a sudden rupture. To overcome this difficulty, the test specimen was loaded to approximately 40% of its expected capacity, after which it was unloaded and the LVDTs removed (referred to as the “MOE” test). The test specimens were then reloaded to failure (referred to as the “MOR” test), using the LVDT monitoring the crosshead and the strain gauges (where applicable) to record the material behaviour up to the failure point. A summary of the MOE stop loads is given in Table 3-39 below.

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Manufacturer A</th>
<th>Manufacturer B</th>
<th>Manufacturer C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LONG (kN)</td>
<td>LAT (kN)</td>
<td>LONG (kN)</td>
</tr>
<tr>
<td>11mm</td>
<td>40</td>
<td>40</td>
<td>-</td>
</tr>
<tr>
<td>15mm</td>
<td>45</td>
<td>45</td>
<td>-</td>
</tr>
<tr>
<td>18mm</td>
<td>50</td>
<td>50</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3-39 – Panel-Shear MOE Test Stop Loads

3.5.4.5 Results:

3.5.4.5.1 Material Properties

The material strength and elastic properties were calculated according to BS EN 789 (BSI, 2004b). The panel-shear ultimate strength was calculated using Equation 3.22 below.

$$
\tau_{u,xy} = \frac{F_{max}}{d_1t} \quad (3.22)
$$

where: \( \tau_{u,xy} \) = panel-shear ultimate strength; \( F_{max} \) = maximum load; \( d_1 \) = length of test specimen measured along centre of shear area (see Figure 3-51 above); \( t \) = thickness of test specimen

The panel-shear ultimate strength was calculated using Equation 3.23 below.

$$
\gamma_{u,xy} = 1 - \frac{l_1}{\sqrt{2}}(l_1 - u_{max}) \cos \left( \sin^{-1} \left( \frac{l_1}{\sqrt{2}}(l_1 - u_{max}) \right) \right) \quad (3.23)
$$

where: \( \gamma_{u,xy} \) = panel-shear ultimate strain; \( u_{max} \) = displacement corresponding to maximum load; \( l_1 \) = gauge length (see Figure 3-51 above)
The panel-shear modulus was calculated using the portion of the load-displacement curve between $0.1F_{\text{max}}$ and $0.4F_{\text{max}}$ and Equation 3.24 below.

$$G_{xy} = \frac{0.5(F_2 - F_1)l_1}{(u_2 - u_1)d_1t} \quad (3.24)$$

where: $G_{xy}$ = panel-shear modulus; $F_1 = 0.1F_{\text{max}}$; $F_2 = 0.4F_{\text{max}}$; $u_1$ = displacement corresponding to $F_1$; $u_2$ = displacement corresponding to $F_2$; $l_1$ = gauge length (see Figure 3-51 above); $d_1$ = length of test specimen measured along centre of shear area (see Figure 3-51 above); $t$ = thickness of test specimen

A custom-developed computer program used Equations 3.22 to 3.24 to automatically calculate the shear properties as discussed in more detail in Chapter 4. Table 3-40 and Table 3-41 below summarise the panel-shear test results for the commercial OSB/3 and single-layer OSB panels, respectively.

<table>
<thead>
<tr>
<th>Panel Type</th>
<th>Ultimate Stress</th>
<th>Ultimate Strain</th>
<th>Global Stiffness</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (N/mm²)</td>
<td>CoV (%)</td>
<td>Mean ($\times 10^4$)</td>
</tr>
<tr>
<td>Long</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-11mm</td>
<td>9.01$^{(1,2)}$</td>
<td>11.34</td>
<td>7.70</td>
</tr>
<tr>
<td>A-15mm</td>
<td>8.82$^{(1)}$</td>
<td>9.07</td>
<td>8.30</td>
</tr>
<tr>
<td>A-18mm</td>
<td>8.89$^{(1)}$</td>
<td>8.58</td>
<td>8.86</td>
</tr>
<tr>
<td>Lat</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-11mm</td>
<td>8.92$^{(1)}$</td>
<td>11.83</td>
<td>7.82</td>
</tr>
<tr>
<td>A-15mm</td>
<td>7.46</td>
<td>10.02</td>
<td>7.60</td>
</tr>
<tr>
<td>A-18mm</td>
<td>7.14</td>
<td>10.35</td>
<td>6.67</td>
</tr>
</tbody>
</table>

1) Includes 10 tests conducted as part of previous study (O’Toole, 2006)
2) Includes 5 tests conducted as part of previous study (Gill and Grennan, 2007)

Table 3-40 – Panel-Shear Test Results Summary (Standard OSB Panels)

<table>
<thead>
<tr>
<th>Panel Type</th>
<th>Ultimate Stress</th>
<th>Ultimate Strain</th>
<th>Global Stiffness</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (N/mm²)</td>
<td>CoV (%)</td>
<td>Mean ($\times 10^4$)</td>
</tr>
<tr>
<td>Long</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-SURF</td>
<td>10.56</td>
<td>12.33</td>
<td>6.72</td>
</tr>
<tr>
<td>A-CORE$^{(1)}$</td>
<td>6.73</td>
<td>5.03</td>
<td>8.55</td>
</tr>
<tr>
<td>Lat</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-SURF</td>
<td>11.84</td>
<td>8.83</td>
<td>7.79</td>
</tr>
<tr>
<td>A-CORE$^{(1)}$</td>
<td>5.89</td>
<td>5.16</td>
<td>7.91</td>
</tr>
</tbody>
</table>

1) Calculated using a sample size of 4 assuming a normal distribution

Table 3-41 – Panel-Shear Test Results Summary (Single-Layer OSB Panels)
3.5.4.5.2 Mechanical Behaviour

Figure 3-55 below shows a typical load-deflection curve recorded for an A-15mm panel loaded in longitudinal panel-shear. Note that this particular test specimen was instrumented with both LVDTs and strain gauges.

Figure 3-56 below shows a typical load versus crosshead displacement curve recorded for an A-15mm panel loaded in longitudinal panel-shear. Note the slight non-linearity at low strains that is visible in Figure 3-56 below. This can be attributed to a combination of settlement of the test specimen into the testing rig and slack in the ball joint of the loading head. This was the same problem encounter with the load versus crosshead displacement curves recorded in the compression test discussed in Section 3.5.2.5.2 above. The non-linearity has been corrected by projecting the linear portion of the load-deflection curve such that it intersects the strain axis and then offsetting the whole curve back towards the stress axis by a distance equal to the intercept. This has been done automatically by the results processing macro (see Chapter 4) using the same method used for the compression test results as described in Section 3.5.2.5.2 above. Additionally, it was observed during testing the vertical member of the shear test rig as shown in Figure 3-53 above underwent visible horizontal deformation during the test. It
is likely that this would result in a substantially higher than expected crosshead deformation readings over the full load versus crosshead displacement.

Figure 3-56 – Panel-Shear Crosshead Displacement Curve (MOE and MOR Results)

Figure 3-57 below shows a typical stress versus strain curve observed for a 15 mm thick commercial OSB/3 panel produced by Manufacturer A loaded in longitudinal panel-shear.

Figure 3-57 – Panel-Shear Stress vs Strain Curve (MOE and MOR Results)
Failure of the panel-shear test specimens typically commenced with an internal bond failure in the lower transition curve. This failure initiation was very similar manner to the initiation of compression failure reported in Section 3.5.2.5.2 above. Finite element stress plots (see Chapter 5) show the presence of a compression stress acting at right angles to the direction of the shear loading. This compression stress is as a result of the two equal and opposite horizontal reaction forces as shown in the free-body diagram shown in Figure 3-52 above. This compression stress is a maximum at the inside of the lower transition curve. The magnitude of the compression stress peaks at a value that is approximately equal to the compressive ultimate strength of the material determined from experimental testing as discussed in Section 3.5.2.5 above. Therefore, as was the case with the compressive ultimate strength, the internal bond strength is likely limiting the panel-shear ultimate strength. After the internal bond failure, the test specimens fractured slowly with increasing strain resulting gradual loss of strength. The crack propagated from at the location where the internal bond failure occurred through the test specimen, following a path that either passed through the shear area or along the timber rail that transferred the applied load from the crosshead to the shear panel.

Figure 3-58 below shows the internal bond failure along with the fracture path propagating from the location where the internal bond failure occurred.

Figure 3-59 below shows the spread of the crack through the shear area.
3.5.4.6 Discussion

3.5.4.6.1 Panel-Shear Ultimate Strength

Figure 3-60 below compares the mean and 5th percentile panel-shear ultimate strength results in both material directions for the materials tested.

![Panel-Shear Ultimate Strength](image)

In the longitudinal direction, the A-SURF panels had the highest mean (10.56 N/mm²) and 5th percentile (8.69 N/mm²) panel-shear ultimate strength values.
The A-CORE panels had the lowest mean (6.73 N/mm²) and 5th percentile (6.39 N/mm²) panel-shear ultimate strength values in the longitudinal direction. In the lateral direction, the A-SURF panels had the highest mean (11.84 N/mm²) and 5th percentile (9.95 N/mm²) panel-shear ultimate strength values. The A-CORE panels had the lowest mean (5.89 N/mm²) and 5th percentile (5.61 N/mm²) panel-shear ultimate strength values in the lateral direction.

As anticipated, the results show that for both the A-SURF and A-CORE panels, the panel-shear ultimate strength is slightly higher in the when the load is applied at right angles to the wood strand orientation. Solid wood tends to have a slightly better shear strength when the shear load is applied at right angles to the grain (Bodig and Jayne, 1993). Therefore, applying the shear load at right angles to the wood strands results in the load being resisted at right angles to the grain direction accounting for the slightly improved panel-shear strength at right angles to the wood strand orientation.

Of the commercial OSB/3 panels, the A-11mm panels had the highest mean (9.01 N/mm²) and 5th percentile (7.98 N/mm²) panel-shear ultimate strength values in the longitudinal direction. The A-18mm panels had the lowest mean (7.46 N/mm²) and 5th percentile (6.70 N/mm²) panel-shear ultimate strength values in the longitudinal direction. In the lateral direction, the A-11mm panels had the highest mean (8.92 N/mm²) panel-shear ultimate strength value. The A-15mm panels had the highest 5th percentile (7.91 N/mm²) panel-shear ultimate strength value in the lateral direction. This is likely due to the slightly greater variability of the panel-shear ultimate strength results for the A-11mm panels (CoV = 11.83%) when compared to the A-15mm panels (CoV = 10.02%) as shown by Table 3-40 above. Figure 3-60 above shows that the A-18mm panels had the lowest mean (7.14 N/mm²) and 5th percentile (6.26 N/mm²) panel-shear ultimate strength values in the lateral direction.

Note that unlike the other load conditions discussed in Sections 3.5.1.6.1, 3.5.2.6.3 and 3.5.3.7.1 above, the panel-shear ultimate strength does not appear to be influenced by loading direction for the commercial OSB/3 panels. This suggests that commercial OSB/3 panels effectively behave in an isotropic
manner when loaded in panel-shear. This will be discussed in more detail in Section 3.5.4.7.1 below.

### 3.5.4.6.2 Panel-Shear Ultimate Strain

Figure 3-61 below compares the mean and 5th percentile panel-shear ultimate strain results in both material directions for the materials tested.

![Figure 3-61 – Panel-Shear Ultimate Strain](image)

In the longitudinal direction, the A-CORE panels had the highest mean (8.55×10^{-3}) and 5th percentile (7.88×10^{-3}) panel-shear ultimate strain values. The A-SURF panels had the lowest mean (6.72×10^{-3}) and 5th percentile (5.38×10^{-3}) longitudinal panel-shear ultimate strain values. The A-CORE panels had the highest 5th percentile (7.12×10^{-3}) panel-shear ultimate strain values in the lateral direction.

As with the results for panel-shear ultimate strength discussed in Section 3.5.4.6.1 above, the results suggest that panel-shear ultimate strain is slightly enhanced when the load is applied perpendicular to the wood strands. This is consistent with the compressive yield and ultimate strain results discussed in Sections 3.5.2.6.2 and 3.5.2.6.4 above. Section 3.5.4.5.2 notes the similarities
between the initiations of failure of the panel-shear test specimens and the compression test specimens. Section 3.5.2.6.1 above suggests that the failure mechanism is limiting the load carrying capacity of compression tests pieces, particularly in the direction parallel to the wood strand orientation, thus making the material less orthotropic in compression than tension. Sections 3.5.2.7.2 and 3.5.2.7.4 above suggest that this failure mechanism is responsible for orthotropic behaviour for compressive yield and ultimate strain respectively. These results therefore strengthen the claim that panel-shear test specimens fail as a result of the compression stress acting at right angles to the direction of shear loading and that panel-shear strength is strongly influenced by internal bond strength.

Of the commercial OSB/3 panels, the A-15mm panels had the highest mean \(8.30 \times 10^{-3}\) and 5\(^{th}\) percentile \(7.20 \times 10^{-3}\) panel-shear ultimate strain values in the longitudinal direction. The A-18mm panels had the lowest mean \(7.60 \times 10^{-3}\) panel-shear ultimate strain in the longitudinal direction. The A-11mm panels had the lowest 5\(^{th}\) percentile \(5.42 \times 10^{-3}\) panel-shear ultimate strain value in the longitudinal direction. This is likely due to the greater variability of the longitudinal panel-shear ultimate strain for the A-11mm panels \(\text{CoV} = 19.54\%\) when compared to the A-18mm panels \(\text{CoV} = 14.90\) as shown by Table 3-40 above. In the lateral direction, Figure 3-61 above shows that the A-15mm panels had the highest mean \(8.86 \times 10^{-3}\) and 5\(^{th}\) percentile \(6.87 \times 10^{-3}\) panel-shear ultimate strain values. The A-18mm panels had the lowest mean \(6.67 \times 10^{-3}\) and 5\(^{th}\) percentile \(5.48 \times 10^{-3}\) panel-shear ultimate strain values.

Figure 3-61 above does not clearly identify whether or not panel-shear ultimate strain behaves in an orthotropic manner for commercial OSB/3 panels. The results suggest that the panel-shear ultimate strain for A-11mm panels do not exhibit orthotropic behaviour but that the panel-shear ultimate strain for the remaining panels do exhibit orthotropic behaviour. This will be investigated further in Section 3.5.4.7.2 below.

3.5.4.6.3 Panel-Shear Modulus

Figure 3-62 below compares the mean and 5\(^{th}\) percentile panel-shear modulus results in both material directions for the materials tested.
In the longitudinal direction, the results shown in Figure 3-62 above demonstrate that the A-SURF panels had the highest mean (1651 N/mm²) and 5th percentile (1308 N/mm²) panel-shear modulus values. The A-CORE panels had the lowest mean (880 N/mm²) and 5th percentile (838 N/mm²) panel-shear modulus values in the longitudinal direction. In the lateral direction, the results demonstrate that the A-SURF panels had the highest mean (1619 N/mm²) and 5th percentile (1357 N/mm²) panel-shear modulus values. The A-CORE panels had the lowest mean (829 N/mm²) and 5th percentile (768 N/mm²) panel-shear modulus values in the lateral direction. Unlike the results for panel-shear ultimate strength and ultimate strain discussed in Sections 3.5.4.6.1 and 3.5.4.6.2 above respectively, the results shown in Figure 3-62 above suggest that panel-shear modulus does not exhibit orthotropic behaviour for the single-layer OSB panels. This will be examined further in Section 3.5.4.7.3 below.

Of the commercial OSB/3 panels, the results show the A-11mm panels had the highest mean (1347 N/mm²) and 5th percentile (1058 N/mm²) longitudinal panel-shear modulus values. The A-18mm panels had the lowest mean (1176 N/mm²) and 5th percentile (908 N/mm²) panel-shear modulus values in the longitudinal
direction. In the lateral direction, the A-11mm panels had the highest mean (1324 N/mm²) while the A-15mm panels had the highest 5th percentile (1105 N/mm²) lateral panel-shear modulus values. This discrepancy is likely a result of the greater variability of the panel-shear modulus for the A-11mm panels (CoV = 15.05%) when compared to the A-15mm panels (CoV = 10.66%). The A-18mm panels had the lowest mean (1161 N/mm²) and 5th percentile (917 N/mm²) panel-shear modulus values in the lateral direction. As with panel-shear ultimate strength and ultimate strain discussed in Sections 3.5.4.6.1 and 3.5.4.6.2 above respectively, the results shown in Figure 3-62 above suggest that panel-shear modulus does not exhibit orthotropic behaviour for the commercial OSB/3 panels. This will be examined further in Section 3.5.4.7.3 below.

### 3.5.4.7 Degree-of-Orthotropy

Previous research has found that OSB tends not to exhibit orthotropic behaviour when loaded in panel-shear (Shrestha, 1999, Karacabeyli et al., 1996, Thomas, 2001). This is reflected in BS EN 12369-1 (BSI, 2001) which specifies the same characteristic panel-shear ultimate strength and modulus values in both material directions. Table 3-42 below presents the degree-of-orthotropy results for the panel-shear properties for each material tested. The degree-of-orthotropy was calculated using the same method described in Section 3.5.1.7 above.

<table>
<thead>
<tr>
<th>Panel Type</th>
<th>Mean Ultimate Stress</th>
<th>Mean Ultimate Strain</th>
<th>Mean Shear Modulus</th>
<th>5th Percentile Ultimate Stress</th>
<th>5th Percentile Ultimate Strain</th>
<th>5th Percentile Shear Modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-11mm</td>
<td>0.990</td>
<td>1.015</td>
<td>0.983</td>
<td>0.944</td>
<td>1.072</td>
<td>0.889</td>
</tr>
<tr>
<td>A-15mm</td>
<td>1.008</td>
<td>1.068</td>
<td>1.000</td>
<td>1.017</td>
<td>0.953</td>
<td>1.145</td>
</tr>
<tr>
<td>A-18mm</td>
<td>0.957</td>
<td>0.877</td>
<td>0.987</td>
<td>0.935</td>
<td>0.869</td>
<td>1.010</td>
</tr>
<tr>
<td>A-SURF</td>
<td>1.121</td>
<td>1.159</td>
<td>0.981</td>
<td>1.144</td>
<td>1.219</td>
<td>1.038</td>
</tr>
<tr>
<td>A-CORE</td>
<td>0.876</td>
<td>0.926</td>
<td>0.941</td>
<td>0.878</td>
<td>0.904</td>
<td>0.917</td>
</tr>
</tbody>
</table>

Table 3-42 – Degree-of-Orthotropy Results for Panel-Shear Properties

#### 3.5.4.7.1 Panel-Shear Ultimate Strength

Section 3.5.4.6.1 above noted that the results in Figure 3-60 above suggested that the commercial OSB/3 panels did not exhibit orthotropic behaviour in terms of panel-shear ultimate strength. The results in Table 3-42 above also suggest that
the panel-shear ultimate strength of commercial OSB/3 panels does not exhibit orthotropic behaviour. This is shown by degree-of-orthotropy values that were approximately equal to a value of 1 for both mean and 5\textsuperscript{th} percentile values. Section 3.5.4.6.1 above also noted that the single-layer OSB panels did exhibit orthotropic behaviour in terms of panel-shear ultimate strength. This is also reflected by the results presented in Table 3-42 above which show that the degree-of-orthotropy values for the single-layer OSB panels had values that less than or greater than a value of 1. Student’s $t$-tests were conducted to determine conclusively whether or not the panel-shear ultimate strength behaves in an orthotropic manner for the materials tested.

Table 3-43 below shows the results of $t$-tests conducted to determine conclusively if panel-shear ultimate strength exhibits orthotropic behaviour for the materials tested. The Student’s $t$-tests were conducted using the same method described in Section 3.5.1.7.3 above.

<table>
<thead>
<tr>
<th>Material</th>
<th>Sample A Size</th>
<th>Sample B Size</th>
<th>$t$-Value</th>
<th>$p$-Value(^2)</th>
<th>Accept/Reject(^1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-11mm</td>
<td>29</td>
<td>25</td>
<td>0.310</td>
<td>0.759</td>
<td>Accept</td>
</tr>
<tr>
<td>A-15mm</td>
<td>20</td>
<td>15</td>
<td>0.266</td>
<td>0.794</td>
<td>Accept</td>
</tr>
<tr>
<td>A-18mm</td>
<td>20</td>
<td>15</td>
<td>1.293</td>
<td>0.217</td>
<td>Accept</td>
</tr>
<tr>
<td>A-SURF</td>
<td>15</td>
<td>15</td>
<td>3.214</td>
<td>0.006</td>
<td>Reject</td>
</tr>
<tr>
<td>A-CORE</td>
<td>4</td>
<td>4</td>
<td>5.719</td>
<td>0.011</td>
<td>Reject</td>
</tr>
</tbody>
</table>

\(^1\) $H_0$: The longitudinal and lateral panel-shear ultimate strength values had the same mean
\(^2\) A level of significance of $\alpha = 0.05$ has been used

Table 3-43 – Student’s $t$-Test Results for Panel-Shear Ultimate Strength

The results presented in Table 3-43 above confirm that the commercial OSB/3 panels do not exhibit orthotropic behaviour in terms of panel-shear ultimate strength. This is consistent with the panel-shear ultimate strength results discussed in Section 3.5.4.6.1 above. These results were also consistent with the findings of studies by Karacabeyli (1996), Shrestha (1999) and Thomas (2001) and is consistent with current design practice as per BS EN 12369-1 (BSI, 2001). However, the results presented in Table 3-43 above suggest that the single-layer panels do behave in an orthotropic manner. This is consistent with the panel-shear ultimate strength results discussed in Section 3.5.4.6.1 above but is a
considerable deviation from the findings of past research on the panel-shear behaviour of OSB as well as current design practice which uses the same value for panel-shear ultimate strength in both material directions.

3.5.4.7.2 Panel-Shear Ultimate Strain

Section 3.5.4.6.2 above did not identify any clear trend in terms of orthotropic behaviour for panel-shear ultimate strain. Similarly, no clear trend is visible in the results presented in Table 3-42 above. Student’s $t$-tests were conducted to determine conclusively whether or not the panel-shear ultimate strain behaves in an orthotropic manner for the materials tested.

Table 3-44 below shows the results of Student’s $t$-tests conducted to determine conclusively if the longitudinal and lateral panel-shear ultimate strain values were equal for the panels tested. The Student’s $t$-tests were conducted using the same method described in Section 3.5.1.7.3 above.

<table>
<thead>
<tr>
<th>Material</th>
<th>Sample A Size</th>
<th>Sample B Size</th>
<th>$t$-Value</th>
<th>$p$-Value$^2$</th>
<th>Accept/Reject$^1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-11mm</td>
<td>14</td>
<td>15</td>
<td>0.170</td>
<td>0.867</td>
<td>Accept</td>
</tr>
<tr>
<td>A-15mm</td>
<td>15</td>
<td>15</td>
<td>0.978</td>
<td>0.345</td>
<td>Accept</td>
</tr>
<tr>
<td>A-18mm</td>
<td>15</td>
<td>15</td>
<td>2.660</td>
<td>0.019</td>
<td>Reject</td>
</tr>
<tr>
<td>A-SURF</td>
<td>15</td>
<td>15</td>
<td>3.083</td>
<td>0.008</td>
<td>Reject</td>
</tr>
<tr>
<td>A-CORE</td>
<td>4</td>
<td>4</td>
<td>1.557</td>
<td>0.217</td>
<td>Accept</td>
</tr>
</tbody>
</table>

1) $H_0$: The longitudinal and lateral panel-shear ultimate strain values had the same mean
2) A level of significance of $\alpha = 0.05$ has been used

Table 3-44 – Student’s $t$-Test Results for Panel-Shear Ultimate Strain

The results of the $t$-tests for ultimate strain were not as clear cut as for panel-shear ultimate strength. They show that the A-18mm panels and the A-CORE panels behave in an orthotropic manner whereas the remaining panels do not. It is worth highlighting that the panel-shear ultimate strain could not be measured by LVDTs as was the case with all other loading scenarios. The result was that ultimate shear strain could only be directly measured using electrical resistance strain gauges. The time and cost involved in the use of strain gauges meant that they could only be used on a limited number of specimens. For the remaining test specimens, the ultimate shear strain was estimated based on the results from the
LVDTs used in the MOE test. It is likely that this method has introduced a margin of error in some of the values for ultimate strain quoted here. Further testing with strain gauges to measure the ultimate strain should eliminate this.

3.5.4.7.3 **Panel-Shear Modulus**

Section 3.5.4.6.3 above noted that the panel-shear test results presented in Figure 3-62 above suggested that none of the materials tested showed orthotropic behaviour in terms of panel-shear modulus. This is also shown by the results presented in Table 3-42 above which show that the degree-of-orthotropy values for both mean and 5\textsuperscript{th} percentile panel-shear modulus had values approximately equal to a value of 1.

Table 3-45 below shows the results of Student’s $t$-tests conducted to determine conclusively if the longitudinal and lateral panel-shear modulus values were equal for the panels tested. The Student’s $t$-tests were conducted using the same method described in Section 3.5.1.7.3 above.

<table>
<thead>
<tr>
<th>Material</th>
<th>Sample A Size</th>
<th>Sample B Size</th>
<th>$t$-Value</th>
<th>$p$-Value</th>
<th>Accept/Reject</th>
<th>$\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A-11\text{mm}$</td>
<td>14</td>
<td>15</td>
<td>0.439</td>
<td>0.663</td>
<td>Accept</td>
<td>0.05</td>
</tr>
<tr>
<td>$A-15\text{mm}$</td>
<td>15</td>
<td>15</td>
<td>0.005</td>
<td>0.996</td>
<td>Accept</td>
<td>0.05</td>
</tr>
<tr>
<td>$A-18\text{mm}$</td>
<td>15</td>
<td>15</td>
<td>0.208</td>
<td>0.836</td>
<td>Accept</td>
<td>0.05</td>
</tr>
<tr>
<td>$A-$SURF</td>
<td>15</td>
<td>15</td>
<td>0.521</td>
<td>0.606</td>
<td>Accept</td>
<td>0.05</td>
</tr>
<tr>
<td>$A-$CORE</td>
<td>4</td>
<td>4</td>
<td>1.636</td>
<td>0.153</td>
<td>Accept</td>
<td>0.05</td>
</tr>
</tbody>
</table>

1) $H_0$: The longitudinal and lateral panel-shear modulus had the same mean
2) A level of significance of $\alpha = 0.05$ has been used

Table 3-45 – Student’s $t$-Test Results for Panel-Shear Modulus

The results confirm that none of the panels tested exhibit orthotropic behaviour in terms of panel-shear modulus. This is consistent with the findings of studies by Karacabeyli (1996), Shrestha (1999) and Thomas (2001) and is consistent with current design practice as per BS EN 12369-1 (BSI, 2001) which specifies the same value for panel-shear modulus in both material directions.

3.5.4.8 **Comparison with Code**

Table 3-46 below presents the characteristic values for panel-shear ultimate strength and panel-shear modulus as presented in BS EN 12369-1 (BSI, 2001).
Table 3-46 – Code Values for Panel-Shear Ultimate Strength and Panel-Shear Modulus

<table>
<thead>
<tr>
<th>Thickness Range</th>
<th>Longitudinal</th>
<th>Lateral</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ultimate Strength (N/mm²)</td>
<td>Panel-Shear Modulus (N/mm²)</td>
</tr>
<tr>
<td>10-18 mm</td>
<td>6.8¹</td>
<td>1080²</td>
</tr>
</tbody>
</table>

1) Code values for characteristic panel-shear ultimate strength were 5th percentile values
2) Code values for characteristic panel-shear modulus were mean values

In terms of ultimate strength, the results demonstrate that only the A-18mm and the A-CORE panels fail to achieve their specified characteristic values for ultimate strength. The A-CORE panels were made only from low density core material and therefore were not expected to achieve code values. The A-18mm panels had a characteristic ultimate strength of 6.7 N/mm² (-1.47%) in the longitudinal direction and 6.26 N/mm² (-7.94%) in the lateral direction.

In terms of panel-shear modulus, the results demonstrate that only the A-CORE panels failed to achieve panel-shear modulus values at least equal to those specified in the code. All other materials exceeded the code values in both material directions.

3.6 Physical Properties

3.6.1 Moisture Content

3.6.1.1 Specimen Details

Moisture content was determined using the “oven dry” method described in BS EN 322 (BSI, 1993c). Moisture content specimens for the tension, bending and panel-shear test specimens were cut using a 76 mm diameter holesaw such that the minimum initial mass of specimens was at least 20 g. For the compression test specimens, a band saw was used to slice a block approximately 15 mm thick from the end of the test specimen, producing a rectangular moisture content specimen with a minimum initial mass of at least 20 g. Moisture content specimens were numbered and a record was kept of the test specimen from which they were cut.
3.6.1.2 Testing arrangement

The mass of each specimen was recorded immediately after cutting to an accuracy of 0.01 g followed by drying to equilibrium mass in a ventilated oven at 103° C. Test pieces were weighed intermittently to an accuracy of 0.01 g at minimum intervals of 24 hours. Equilibrium mass was said to have been attained when the results of two successive weighing operations did not differ by more than 1%. The moisture content was calculated from Equation 3.25 below.

\[ H = \frac{m_H - m_0}{m_0} \]  

(3.25)

where: \( H = \) moisture content; \( m_H = \) initial mass of test specimen; \( m_0 = \) dry mass of test specimen

The moisture content reported for the tension, bending and panel-shear test specimens was reported as the average of the two specimens. The moisture content reported for the compression test specimens was that of the single moisture content specimen.

3.6.1.3 Sample Size

For the tension, bending and panel-shear test specimens, two moisture content specimens per test specimen were cut and the moisture content was reported as the average of the two specimens. For the compression test specimens, one moisture content specimen per test specimen was taken. Moisture content is not dependent on material direction. Therefore, unlike load test results, moisture content results were not grouped according to panel direction. Table 3-47 below presents details of the total number of moisture content specimens taken for the commercial OSB/3 panels.

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Manufacturer A</th>
<th>Manufacturer B</th>
<th>Manufacturer C</th>
</tr>
</thead>
<tbody>
<tr>
<td>11 mm</td>
<td>340</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>15 mm</td>
<td>206</td>
<td>150</td>
<td>144</td>
</tr>
<tr>
<td>18 mm</td>
<td>207</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3-47 – Moisture Content Test Replications (Commercial OSB/3 Panels)

Table 3-48 below presents details of the total number of moisture content specimens taken for the single-layer OSB panels.
### Table 3-48 – Moisture Content Test Replications (Single-layer OSB)

<table>
<thead>
<tr>
<th>Material</th>
<th>Manufacturer A</th>
<th>Manufacturer B</th>
<th>Manufacturer C</th>
</tr>
</thead>
<tbody>
<tr>
<td>SURF</td>
<td>150</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CORE</td>
<td>40</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

### 3.6.1.4 Results:

Table 3-49 and Table 3-50 below present a summary of the moisture content results for the commercial OSB/3 and single-layer OSB panels, respectively.

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Mean (%)</th>
<th>CoV (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-11mm</td>
<td>8.90</td>
<td>5.72</td>
</tr>
<tr>
<td>A-15mm</td>
<td>8.30</td>
<td>6.38</td>
</tr>
<tr>
<td>A-18mm</td>
<td>8.62</td>
<td>5.74</td>
</tr>
<tr>
<td>B-15mm</td>
<td>7.49</td>
<td>14.12</td>
</tr>
<tr>
<td>C-18mm</td>
<td>7.97</td>
<td>8.86</td>
</tr>
</tbody>
</table>

**Table 3-49 – Moisture Content Results (Commercial OSB/3 Panels)**

<table>
<thead>
<tr>
<th>Material</th>
<th>Mean (%)</th>
<th>CoV (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-SURF</td>
<td>7.48</td>
<td>4.68</td>
</tr>
<tr>
<td>A-CORE</td>
<td>7.83</td>
<td>6.80</td>
</tr>
</tbody>
</table>

**Table 3-50 – Moisture Content Results (Single-Layer Panels)**

It is worth noting that this study did not investigate the effects of moisture content and data was only used as a quality control check to ensure the conditioning was functioning correctly. The results presented in Table 3-49 and Table 3-50 above show that the moisture contents of the materials tested were reasonably consistent as shown by the values of the coefficients of variation having values less than 9% for all except one material tested. The results indicate that the moisture content for the B-15mm panels was the most variable ($CoV = 14.12\%$). It is unclear at this stage as to the reasons behind this.

### 3.6.1.5 Discussion

Figure 3-63 below compares the mean and 5th percentile moisture content results for the materials tested.
Of the material tested, the A-11mm panels had the highest mean and 5th percentile moisture contents while the B-15mm panels had the lowest mean and 5th percentile moisture contents after conditioning to equilibrium at 20 ±2 ºC and 65% ±5% relative humidity. Note the relatively small difference between the mean and 5th percentile moisture content values for all except the B-15mm panels. This reflects the low variability in the moisture content values for the materials and demonstrates that the conditioning process used during the study was effective at eliminating moisture content as a variable.

3.6.2 Density and Vertical Density Profile

3.6.2.1 Specimen Details

Density properties were evaluated using 50×50 mm square specimen prepared in accordance with BS EN 323 (BSI, 1993d). The material was re-conditioned to equilibrium mass according prior to cutting density specimens. This was to ensure any dimensional changes in the material had taken place prior to specimen cutting. The as-cut dimensions and thickness of the test specimens were measured using an electronic calliper and recorded to an accuracy of 0.02 mm. The weights of the test specimens were recorded to the nearest 0.01 g. The
thickness of the specimen was measured at the point of intersection of the diagonals unless a visible surface defect was present. The edges ($b_1$ and $b_2$) were recorded along lines that pass through the centres of opposite edges. Density specimens were stored in the conditioning chamber until testing.

For the tension and bending test specimens, density specimens were cut from the test specimen after failure. For compression and panel-shear, it was not possible to cut density specimens directly from the test specimen due to the construction of these test specimens. Instead, density specimens were cut from waste material directly adjacent to the location in the panel where the compression test specimens were taken from. Density specimens for the panel-shear test specimens were cut from the waste left over after the curved sections were cut. For the compression test specimens, density specimens were cut from unused strips of material left over after gluing. Density specimens were numbered and a record was kept of the test specimen from which they were cut. The material used to prepare density profile specimens was removed from the tension, bending and panel-shear test specimens using a 150 mm diameter holesaw. The 150 mm diameter holesaw was chosen because the resulting cores were large enough to be trimmed to form 50 × 50 mm specimens while avoiding the central hole left by the arbour. This is demonstrated in Figure 3-64 below.

![Figure 3-64 – Density Specimen Removed from Core](image-url)
In the case of compression test specimens, the density profile was taken from the rectangular strips of material left over from the test specimen fabrication (see Section 3.5.2.1 above for full details). The strips were trimmed to form 50 ×50 mm specimens.

### 3.6.2.2 Average Density

The average density was determined using Equation 3.26 below. Results were reported in kg/m³.

\[
\rho = \frac{m}{b_1 b_2 t}
\]

where: \( \rho \) = density; \( m \) = mass of test specimen; \( b_1, b_2 \) = dimensions of the test specimen; \( t \) = thickness of the test specimen

### 3.6.2.3 Vertical Density Profile

The vertical density profile was determined using an IMAL - DPX200 Density Profile Meter with X-Ray Source (see Figure 3-65 below) and SCADA Software Version 1.0.16.

Density readings were taken every 0.05 mm across the thickness of the specimens. The specimens were weighed, measured and loaded into the machine sixteen at a time separated by aluminium spacers that were used by the machine.
to distinguish the boundaries of adjacent specimens. The density profile scanner scanned specimens horizontally from left to right. The SCADA software used the prefixes “left” and “right” in the results presented below when discussing surface density effects.

It was noted that the surfaces of the commercial OSB/3 panels produced by Manufacturer A were significantly different due to the manufacturing technology used. The “top” surface had a smooth finish while the “bottom” surface was rough textured. Care was taken to scan all Manufacturer A specimens from smooth face to rough face so that the effects of the textured surfaces could be assessed from the results. The remaining panels had no obvious difference between the surfaces.

The SCADA software provided a graphical output showing a plot of density versus depth and a summary table containing the key information (see Figure 3-66 below). The raw data was saved in a Microsoft Office Access database for easy retrieval. Microsoft Excel 2000 combined with a Microsoft VBA macro was used to perform detailed analysis of the results. This is discussed in more detail in Chapter 4.

![Figure 3-66 – Density Profile Graphical Results Summary (SCADA Software)](image-url)
3.6.2.4 Density Profile Approximation

Figure 3-66 above shows the complexity of the vertical density profile present in typical commercial OSB/3 panels. This makes them difficult to compare. The table shown to the right of Figure 3-66 above summarises the density profile in terms of left, core and right density. The purpose of this summary table is to simplify the comparison of vertical density profiles from different specimens. It is used by OSB producers for quality control to ensure that panels are being produced with the correct vertical density profile and by extension, to ensure the panel properties comply with the requirements of BS EN 300. The algorithm used by SCADA to calculate the density profile summary was encrypted within the source code for the software. Additionally, modelling the density profile in a stochastic finite element model required information about the thicknesses of the layers. This was not provided by the SCADA software. Therefore, it was decided to develop a custom algorithm to summarise the density profile in terms of the layer densities and the layer thicknesses. Figure 3-67 below shows the simplified vertical density profile model adopted for this study.

Each layer is defined by a layer density and a thickness. This approach was used in Section 3.6.2.6 below to compare and contrast the vertical density profiles from different specimens, manufacturers and nominal thicknesses. This stepped model was later used to represent the vertical density profile in a stochastic finite element model. This is discussed in more detail in Chapter 5.
The algorithm for determining the stepped density profile shown in Figure 3-67 above first calculated the layer densities and then calculated the layer thicknesses. The global density of the specimen is equal to the mass of the specimen divided by the thickness which is equal to the area under the vertical density profile. The algorithm used the trapezoidal rule to calculate the area of the density profile curve. The trapezoidal rule to calculate the global density is given in Equation 3.27 below.

\[
\rho = \frac{1}{2} \sum_{i=1}^{n} (\rho_{i-1} + \rho_i)(d_i - d_{i-1}) \quad (3.27)
\]

where: \( \rho = \) global density; \( \rho_i = \) density at point \( i \); \( \rho_{i-1} = \) density at point \( i - 1 \); \( d_i = \) depth at point \( i \); \( d_{i-1} = \) depth at point \( i - 1 \); \( n = \) number of data points on density profile curve; \( t = \) specimen thickness

The algorithm then split density profile data into two sections along the centre-line of the specimen. The algorithm copied the density profile data on the left hand side of the centre-line of the specimen to an array and the density profile data on the right hand side of the centre-line of the specimen to a second array. The algorithm calculated the left surface density as the average of the density values to the left of the specimen centre-line that had values greater than the global density. The right surface density was calculated in a similar manner. Similarly, the algorithm calculated the core density as the average of the density values less than the global density. The left surface, core and right surface density values calculated using this algorithm were almost identical to those calculated by the SCADA software. Once the layer densities had been determined, the algorithm proceeded to calculate the layer depths. The principles used to determine the layer thickness were:

- The area under the experimental density profile curve as determined equal to the area under the discretised density profile curve,
- The sum of the thicknesses of the layers must equal the total thickness of the test specimen.

This gave rise to Equations 3.28 and 3.29 below which define the simplified, stepped vertical density profile in terms of ten unknowns.
\[ \rho t = \rho_{dam,l} t_{dam,l} + \rho_{s,l} t_{s,l} + \rho_c t_c + \rho_{s,r} t_{s,r} + \rho_{dam,r} t_{dam,r} \]  
\[ t = t_{dam,l} + t_{s,l} + t_c + t_{s,r} + t_{dam,r} \]

where: \( \rho \) = global density; \( t \) = specimen thickness; \( \rho_{dam,l} \) = density of left surface damage layer; \( t_{dam,l} \) = thickness of left surface damage layer; \( \rho_{s,l} \) = density of left high-density surface-layer; \( t_{s,l} \) = thickness of left high-density surface-layer; \( \rho_c \) = density of low-density core-layer; \( t_c \) = thickness of low-density core-layer; \( \rho_{s,r} \) = density of right high-density surface-layer; \( t_{s,r} \) = thickness of right high-density surface-layer; \( \rho_{dam,r} \) = density of right surface damage layer; \( t_{dam,r} \) = thickness of right surface damage layer.

To solve Equations 3.28 and 3.29 above, the algorithm assumed the following:

- The left surface density and right surface density were equal,
- The thickness of the left high-density surface layer is equal to the thickness of the right high-density surface layer,
- The density of the damaged fibres due to overheating of the panel surfaces during the pressing process is equal to the core density.

For each specimen, the algorithm calculated the total thickness of material with density greater than or equal to the global density. The algorithm divided the total thickness of high-density material by two and set that equal to the surface layer thickness. The algorithm then subtracted the total thickness of the high-density material from the total thickness of the specimen, giving the total thickness of low-density material. The algorithm determined the left and right surface damage thickness using linear interpolation to determine the depth below the surfaces where the density dropped below the core density. Finally, the algorithm subtracted the sum of the surface damage and the high-density layer thicknesses from the total specimen thickness, giving the core thickness.

### 3.6.2.5 Sample Size

Two density specimens were cut from all pieces tested. Further density specimens were also taken from tension test specimens left over from a previous study conducted by O’Toole (2006). As was the case with moisture content, density profile is not dependent on material direction. Therefore, density profile
results were grouped according to panel thickness and manufacturer only. Table 3-51 and Table 3-52 below give details of the total numbers of vertical density profile specimens tested for the commercial OSB/3 panels and for the single-layer OSB panels respectively.

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Manufacturer A</th>
<th>Manufacturer B</th>
<th>Manufacturer C</th>
</tr>
</thead>
<tbody>
<tr>
<td>11 mm</td>
<td>346</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>15 mm</td>
<td>229</td>
<td>113</td>
<td>119</td>
</tr>
<tr>
<td>18 mm</td>
<td>232</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3-51 – Density Profile Test Replications (Commercial OSB/3 Panels)

<table>
<thead>
<tr>
<th>Material</th>
<th>Manufacturer A</th>
<th>Manufacturer B</th>
<th>Manufacturer C</th>
</tr>
</thead>
<tbody>
<tr>
<td>SURF</td>
<td>55</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CORE</td>
<td>16</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3-52 – Density Profile Test Replications (Single-layer OSB)

3.6.2.6 Results:

3.6.2.6.1 Typical Vertical Density Profiles

The raw data for the vertical density profiles was stored in Microsoft Access Database format. The vertical density profiles were plotted using a custom-developed Microsoft Excel program developed for this study. This program is discussed in greater detail in Chapter 4. Figure 3-68 below shows typical vertical density profiles obtained for commercial OSB/3 panels. A comprehensive set of density profiles is contained in Appendix B. The results demonstrate that all commercial OSB/3 panels tested follow the typical “U” shaped vertical density profile. This is as expected since this is the target density profile shape used by OSB manufacturers. The vertical density profiles by enlarge were approximately symmetrical for the specimens tested. This is consistent with past literature on the subject (Wang and Winistorfer, 2000, Wang et al., 2004, Winistorfer et al., 2000, Winistorfer et al., 1996, Wong et al., 1999).

The “U” shaped density profile is characterised by a rapid increase in density with a small increase in depth close to the panel surfaces. The maximum density is typically located in regions located approximately 1 to 2 mm below the panel
surfaces. The density decreases gradually from the maximum before levelling off to a relatively constant value in the middle third of the panel.

Figure 3-68 – Typical Vertical Density Panels (Commercial OSB/3 Panels)
Figure 3-69 and Figure 3-70 below show typical vertical density profiles for A-SURF and A-CORE panels, respectively. A comprehensive set of density profiles is contained in Appendix B.

The density profiles for the single-layer panels as shown in Figure 3-69 and Figure 3-70 above clearly demonstrate that the density profiles for these panels

| Figure 3-69 – Typical Vertical Density Profile (A-SURF Panels) |
| Figure 3-70 – Typical Vertical Density Profile (A-CORE Panels) |
do not follow the typical “U” shaped vertical density profile model that is typically found in commercial OSB/3 panels. The density profiles for these panels show that the density is relatively constant across the thickness of the panel with a distinctive spike at the glue line location. This suggests that the parameters typically used to describe the vertical density profile of commercial OSB/3 panels were not suitable for describing the density profiles of the single-layer panels. Nonetheless, the density profiles for single-layer panels will be discussed using the same parameters used to describe the density profiles of commercial OSB/3 to highlight the key differences between the panel types.

Figure 3-71 below explains the influence the raw materials and manufacturing process on the vertical density profiles for the A-SURF panels.

The thin layer of low density wood-strands were not present on the surfaces of commercial OSB/3 with a sanded finish because they were removed during the sanding process (Whelan, 2008). The maximum density of commercial OSB/3 panels with sanded surfaces therefore would be located closer to the surfaces than for commercial OSB/3 panels without sanded surfaces as shown in Figure 3-71 above. The glue used is significantly denser than the OSB panels as shown
in Figure 3-71 above. The density profile of two 18 mm thick sanded OSB/3 panels produced by Manufacturer A glued with SikaForce-7710 L35 base and SikaForce-7020 hardener would be back-to-back “U” shaped profiles with a high-density spike in the centre as shown in Figure 3-71 above.

The milling process described in Section 3.4.3.4 above produces a final vertical density profile characterised by a sharp, high-density spike in the centre representing the glue line. The density rapidly declines either side of the centre line to values that were approximately equal to the maximum densities for the commercial OSB/3 panels from which the A-SURF panels were produced. This is followed by a further gradual reduction of either side of the centre line towards the milled surface. The densities of the milled surfaces were approximately equal to the global density of the commercial OSB/3 panels from which the A-SURF panels were produced. Therefore, the vertical density profile recorded for a typical A-SURF panel shown in Figure 3-69 above is consistent with the vertical density profile formation process as explained by Figure 3-71 above.

Figure 3-72 below explains the impact the raw materials and manufacturing process had on the vertical density profile for the A-CORE panels.

**Figure 3-72 – Vertical Density Profile Formation (A-CORE Panels)**
The first milling pass as described in Section 3.4.3.4 above removed the high-density surface-layer of the commercial 18 mm thick OSB/3 panels produced by Manufacturer A. This resulted in a panel with an asymmetrical vertical density profile characterised by a high density located at the un-milled surface and low density at the milled surface as shown in Figure 3-72 above. Two panels were then glued together ensuring that the glue line was located between the low density surfaces. This produced a compound panel characterised by a more typical symmetrical “U” shaped vertical density profile with an additional spike in density at the glue line location as shown in Figure 3-72 above. The second and third milling passes removed the high-density surface-layers from either side of the compound panel. The remaining layers consisted of core-layer material taken from the middle third of a commercial OSB/3 panel.

Figure 3-68 above shows that the density across the middle third of commercial OSB/3 panels is fairly constant. Therefore the A-CORE panels had a vertical density profile that is uniform with the exception of a thin spike at mid-depth corresponding to the glue line location. The vertical density profile recorded for a typical A-CORE panel shown in Figure 3-70 above is therefore consistent with what one would expect based on the vertical density profile formation process as explained by Figure 3-72 above.

### 3.6.2.6.2 Density Profile Properties

Table 3-53 below presents a summary of the density profile test results for the commercial OSB/3 panels tested. Table 3-54 below presents a summary of the density profile test results for the single-layer OSB panels tested. A detailed discussion of test results is presented below in Section 3.6.2.7.

The density profile properties had been calculated automatically by a custom-developed computer program written in Microsoft VBA. The program was embedded into a Microsoft Excel 2003 template that also contained a database of raw density profile data. The program imported the raw density profile data from the Microsoft Access database created by the SCADA software. The computer program processed the data to determine the vertical density profile for each specimen tested. The computer program then automatically fitted approximate...
density profiles as defined in the Figure 3-67 above and Equations 3.28 and 3.29 above to the density profile for each density specimen. The approximate density profiles are shown in cyan in Figure 3-68, Figure 3-69 and Figure 3-70 above. The details of this computer program are discussed in detail in Section 4.5 below.

<table>
<thead>
<tr>
<th>Material</th>
<th>Left Density</th>
<th>Right Density</th>
<th>Core Density</th>
<th>Global Density</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (kg/m³)</td>
<td>CoV (%)</td>
<td>Mean (kg/m³)</td>
<td>CoV (%)</td>
</tr>
<tr>
<td>A-11mm</td>
<td>741</td>
<td>8.05</td>
<td>737</td>
<td>8.22</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>702</td>
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<td>587</td>
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</tr>
<tr>
<td>A-18mm</td>
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<td>679</td>
<td>7.83</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>569</td>
<td>6.60</td>
</tr>
<tr>
<td>B-15mm</td>
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<td>735</td>
<td>6.40</td>
</tr>
<tr>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>618</td>
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<tr>
<td>C-15mm</td>
<td>644</td>
<td>9.82</td>
<td>650</td>
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</tr>
<tr>
<td></td>
<td></td>
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<table>
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<tr>
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<th>Surface</th>
<th>Core</th>
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</thead>
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<td>Damage Thickness</td>
<td>Damage Thickness</td>
<td>Thickness</td>
<td>Thickness</td>
</tr>
<tr>
<td></td>
<td>Mean (mm)</td>
<td>CoV (%)</td>
<td>Mean (mm)</td>
<td>CoV (%)</td>
</tr>
<tr>
<td>A-11mm</td>
<td>0.21</td>
<td>66.33</td>
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<td>34.59</td>
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<tr>
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</tr>
<tr>
<td>A-15mm</td>
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<td>0.31</td>
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</tr>
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<td>A-18mm</td>
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<td>68.61</td>
<td>0.30</td>
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</tr>
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</tr>
<tr>
<td></td>
<td></td>
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<td>3.49</td>
<td></td>
</tr>
<tr>
<td>B-15mm</td>
<td>0.11</td>
<td>81.83</td>
<td>0.22</td>
<td>49.25</td>
</tr>
<tr>
<td></td>
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<tr>
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</tr>
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Table 3-53 – Density Profile Test Results Summary (Standard OSB Panels)

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness</th>
<th>Left Density</th>
<th>Right Density</th>
<th>Core Density</th>
<th>Global Density</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean (kg/m³)</td>
<td>CoV (%)</td>
<td>Mean (kg/m³)</td>
<td>CoV (%)</td>
</tr>
<tr>
<td>A-SURF</td>
<td></td>
<td>579</td>
<td>6.27</td>
<td>553</td>
<td>5.39</td>
</tr>
<tr>
<td>A-CORE¹</td>
<td></td>
<td>469</td>
<td>4.40</td>
<td>440</td>
<td>3.72</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>A-CORE¹</td>
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<td></td>
<td></td>
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<td>4.04</td>
</tr>
</tbody>
</table>

Table 3-54 – Density Profile Test Results Summary (Single-layer OSB Panels)
3.6.2.7 Discussion

3.6.2.7.1 Global Density

Figure 3-73 below compares the mean and 5th percentile global densities for the materials tested.

![Global Density](image)

The results in Figure 3-73 above show that the A-SURF panels had the highest mean (686 kg/m³) and 5th percentile (626 kg/m³) global density values. The A-CORE panels had the lowest mean (502 kg/m³) and 5th percentile (474 kg/m³) global density values. This was expected and can be attributed to the manufacturing technique used in the production of these two panel types. The manufacturing process described in Section 3.4.3 above demonstrates how the A-SURF panels consist of the surfaces of two commercial OSB/3 panels glued together while the A-CORE panels consist of the middle portions of two commercial OSB/3 panels glued together. The vertical density profiles shown in Figure 3-68 above show how the surface-layers were denser than the core-layers. Therefore, it was anticipated before testing that the A-SURF panels would have a higher global density than commercial OSB/3 panels while the A-CORE panels would have a lower global density than commercial OSB/3 panels.
Of the commercial OSB/3 panels tested, the A-11mm panels had the highest mean global density (623 kg/m³) value. The B-15mm panels had the highest 5th percentile (566 kg/m³) global density value. This discrepancy is likely a result of greater scatter in the data for the A-11mm panels ($CoV = 7.01\%$) when compared with the data for the B-15mm panels ($CoV = 5.28\%$) as shown in Table 3-53 above. The C-15mm panels had the lowest mean (564 kg/m³) and 5th percentile (478 kg/m³) global density values.

Note that similar to many of the strength and elastic moduli results discussed throughout Section 3.5 above, the global density for the OSB/3 panels produced by Manufacturer A decreases with increasing nominal thickness. This is further evidence of the presence of size effects in panels of different thicknesses. Furthermore, previous research has demonstrated that density has a significant influence on the strength and elastic properties of solid wood and wood-based composites under most loading conditions (Bodig and Jayne, 1993, Anthony and Moslemi, 1969, Bajwa and Chow, 2003, Stürzenbecher et al., 2010, Chen et al., 2010, Jin et al., 2009). This has been attributed to the increasing difficulty in pressing thicker strand mats (Thoemen and Humphrey, 2003, Thoemen, 2006, Thoemen and Ruf, 2008). Therefore, it is likely that this decreasing density with increasing nominal thickness of panels produced by Manufacturer A is partly responsible for the reducing strength and elastic properties as discussed throughout Section 3.5 above. This will be examined in more detail in Chapter 4.

3.6.2.7.2 Surface Density

The mean values for left and right surface density presented in Table 3-53 and Table 3-54 above seem to suggest that there is no significant difference between the surface densities for any panels. Section 3.6.2.3 above noted that one of the surfaces of the panels produced by Manufacturer A had a textured finished while the other surface had a smooth finish due to the pressing system employed by this Manufacturer. Therefore, it was of particular interest to see if this textured finish had any significant impact on the density profile of these panels. Table 3-55 below presents the results of statistical $t$-tests conducted to determine definitively if the left and right surface densities come from a population with the
same mean. The Student’s \( t \)-tests were conducted using the same method described in Section 3.5.1.7.3 above.

<table>
<thead>
<tr>
<th>Material</th>
<th>Sample A Size</th>
<th>Sample B Size</th>
<th>( t )-Value</th>
<th>( p )-Value (^2)</th>
<th>Accept/Reject (^1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-11mm</td>
<td>334</td>
<td>334</td>
<td>1.029</td>
<td>0.304</td>
<td>Accept</td>
</tr>
<tr>
<td>A-15mm</td>
<td>219</td>
<td>219</td>
<td>1.381</td>
<td>0.168</td>
<td>Accept</td>
</tr>
<tr>
<td>A-18mm</td>
<td>221</td>
<td>221</td>
<td>2.058</td>
<td>0.040</td>
<td>Reject</td>
</tr>
<tr>
<td>B-15mm</td>
<td>109</td>
<td>109</td>
<td>0.804</td>
<td>0.422</td>
<td>Accept</td>
</tr>
<tr>
<td>C-15mm</td>
<td>114</td>
<td>114</td>
<td>0.787</td>
<td>0.432</td>
<td>Accept</td>
</tr>
<tr>
<td>A-SURF</td>
<td>55</td>
<td>55</td>
<td>4.204</td>
<td>0.000</td>
<td>Reject</td>
</tr>
<tr>
<td>A-CORE</td>
<td>16</td>
<td>16</td>
<td>4.347</td>
<td>0.000</td>
<td>Reject</td>
</tr>
</tbody>
</table>

\(^1\) \( H_0: \) The left surface density and right surface density had the same mean

\(^2\) A level of significance of \( \alpha = 0.05 \) has been used

Table 3-55 – Results of \( t \)-Tests between Surface Densities

The results in Table 3-55 above show that there is strong evidence to support the claim that there is no significant difference between the left and right surface densities for the A-11mm and A-15mm panels. The results suggest that the A-18mm panels had the significantly different surface densities. It is not clear why at this stage why this is the case. The results for the remaining commercial OSB/3 panels show strong evidence to support the claim that the left and right surface densities were equal for the B-15mm and C-15mm panels. It must however be pointed out that it was not possible to identify the pressing orientation for panels produced by Manufacturers B and C as was the case with Manufacturer A. This made it impossible to ensure consistency in the scanning direction. The result is that any differences between left and right surface density properties that may be present would likely had been disguised by the random nature of scanning direction. Despite the negative result for the A-18mm panels and inability to differentiate between the surfaces of the B-15mm panels and C-15mm panels, these results show that the surface densities were symmetrical about the mid-depth of the panel for commercial OSB/3 panels. This is consistent with the assumptions for calculating the density profile properties described in Section 3.6.2.4 above.

For the single-layer panels, the results in Table 3-55 above indicate strong evidence that the left and right surface densities were not equal. This is as
expected due to the production method used to manufacture theses panels. The results show that the left and right surface densities for single specimens from commercial OSB/3 panels tend to be approximately equal. However, there is also strong evidence to suggest that surface densities vary significantly between specimens. This means that the vertical density profile varies both spatially within panels and between panels. The spatial variation of vertical density profile within panels is referred to as the horizontal density distribution. It is an acknowledged feature of wood-based composite materials and has been attributed to variations in the mat structure, resin distribution and press conditions (Suchsland, 1989, Dai and Steiner, 1994, Steiner and Xu, 1995, Oudjehane and Lam, 1998, Kruse et al., 2000, Painter et al., 2006a)). The material on the left face of single-layer panels is from a different parent panel than the material on the right face. It is unlikely that the parent panels used to make each single-layer panel were pressed under exactly the same conditions. It is therefore logical to expect that the left and right surface densities of the single-layer panels would in general not be equal.

The results presented in Table 3-55 above show that the left and right surface densities were generally equal for the majority of the materials tested. It is therefore deemed acceptable to describe each test specimen in terms of a single surface density value. The surface density value for each specimen is taken as the average of the left and right surface densities. This has also been done for the single-layer panels despite the results of the t-test showing otherwise in order to simplify the comparison of the surface densities of the single-layer and commercial OSB/3 panels.

Figure 3-74 below compares the mean and 5th percentile surface density values for the materials tested. The results show that the A-11mm panels had the highest mean (739 kg/m$^3$) surface density value. The B-15mm panels had the highest 5th percentile (664 kg/m$^3$) surface density value. This discrepancy is a result of greater scatter in the data for the A-11mm panels ($CoV = 7.94\%$) when compared with the data for the B-15mm panels ($CoV = 6.37\%$). Of the Commercial OSB/3 panels, the C-15mm panels had the lowest mean (647 kg/m$^3$) and 5th percentile
(533 kg/m³) surface density values. As was the case with global density, the average surface density steadily decreased with increasing panel thickness for panels produced by Manufacturer A.

![Figure 3-74 – Average Surface Density](image)

These results were anticipated based on observations made during the drilling phases of density profile specimen preparation as described in Section 3.6.2.1 above and moisture content specimen preparation as described in Section 3.6.1.1 above. The resistance to drilling has been shown to be a crude but reasonably effective method for estimating the vertical density profiles of wood-based panels (Winistorfer, 1995). The surfaces of the B-15mm panels provided significantly more drilling resistance and resulted in far greater wear-and-tear on the equipment than any of the other panels. There was a noticeable difference in the drilling resistance between the surfaces and the cores of these panels. Also, the cut edges of the B-15mm panels were significantly smoother than any of the other panels. These factors suggested that the surfaces of the B-15mm panels were harder and denser than any of the other commercial OSB/3 panels tested.

The C-15mm panels in general proved significantly easier to drill than the other panels tested. There was no noticeable difference in drilling resistance between
the core and surfaces of these panels. The cut surfaces on the C-15mm panels were rough in the vast majority of cases and often splintered when the drill broke through. This suggested that these panels had significantly lower surface densities than the other panels tested and that the density profile was more uniform than those present in the other commercial OSB/3 panels tested. The results presented in Figure 3-74 above were consistent with these observations.

Overall the A-CORE panels had the lowest mean (455 kg/m\(^3\)) and 5\(^{th}\) percentile (430 kg/m\(^3\)) surface density values. As shown in Figure 3-69 above, these panels had a density profile that can be better described as a uniform density profile i.e. density is constant with depth. These panels consist of only of core material from 18 mm thick commercial OSB/3 panels. Therefore, comparing the surface densities of these panels with those of commercial OSB/3 panels is equivalent to comparing the surface and core densities of the 18 mm thick commercial OSB/3 panels from which they were made. The results of tests on 18 mm thick commercial OSB/3 panels produced by Manufacturer A show that the core density is always lower than surface density. It is therefore consistent that surface density of the A-CORE panels has been found to be the lowest overall when compared with the surface densities of the remaining panels. Figure 3-74 above also shows that the A-SURF panels had the second lowest mean (566 kg/m\(^3\)) and 5\(^{th}\) percentile (514 kg/m\(^3\)) density profile values. The results in Figure 3-69 above show that the density of these panels peaks at mid-depth (i.e. at the glue line) and decreases gradually towards the surface. Therefore, the results shown in Figure 3-74 above were consistent with the density profiles shown in Figure 3-68 above and with the process shown in Figure 3-71 above.

Prior to density profile testing, it was anticipated that the global density of the single-layer panels would be approximately equal to the layer density of the material from which they were made. This means that the A-SURF panels were expected to have a mean global density equal to the mean surface-layer density of the A-18mm panels. The results presented in Table 3-54 above indicate that the mean global density of the A-SURF panels is 686 kg/m\(^3\) while Table 3-53 above indicates the mean surface density of the A-18mm panels is 684 kg/m\(^3\).
Table 3-56 below presents the results of Student’s \( t \)-tests conducted to determine conclusively if the global density of the A-SURF panels is equal to the surface density of the A-18mm panels. The Student’s \( t \)-test was conducted using the same method described in Section 3.5.1.7.3 above.

<table>
<thead>
<tr>
<th>Material</th>
<th>Sample A Size</th>
<th>Sample B Size</th>
<th>( t )-Value</th>
<th>( p )-Value(^2)</th>
<th>Accept/Reject</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-SURF</td>
<td>55</td>
<td>221</td>
<td>0.17</td>
<td>0.833</td>
<td>Accept(^1)</td>
</tr>
</tbody>
</table>

1) \( H_0 \): The global density of the A-SURF panels and surface density of the A-18mm panels had the same mean
2) A level of significance of \( \alpha = 0.05 \) has been used

Table 3-56 – Student’s \( t \)-test Results for Densities of A-SURF and A-18mm Panels

The results in Table 3-56 above confirm that the global density of the A-SURF panels is equal to the surface density of the A-18mm panels with 83.3% certainty. This is line with expectations given the production process used to produce the A-SURF panels as described in Section 3.4.3 above.

3.6.2.7.3 Core Density

Figure 3-75 below compares the mean and 5\(^{th}\) percentile core densities for the materials tested.

![Core Density](chart.png)

Figure 3-75 – Core Density
Figure 3-75 above shows that the A-11mm panels had the highest mean (547 kg/m³) core density value. The B-15mm panels had the highest 5th percentile (496 kg/m³) core density value. This discrepancy is a result of greater variability of the core density results for the A-11mm panels ($CoV = 6.94\%$) when compared to the B-15mm panels ($CoV = 4.90\%$) as shown by Table 3-53 above. The A-18mm panels had the lowest mean (498 kg/m³) core density value. The C-15mm panels had the lowest 5th percentile (446 kg/m³) core density value. This discrepancy was a result of greater scatter in the C-15mm panels ($CoV = 7.46\%$) when compared to the A-18mm panels ($CoV = 6.43\%$) as shown by Table 3-53 above.

Figure 3-75 above indicates that the A-SURF panels had the overall highest mean (828 kg/m³) and 5th percentile (743 kg/m³) core density values. This again is consistent with prior expectations. The process shown in Figure 3-69 above demonstrates how unlike with commercial OSB/3 panels, the material with the highest density ends up in the centre of the A-SURF panels. Figure 3-75 above indicates that the A-CORE panels had the second-highest mean (652 kg/m³) and 5th percentile (585 kg/m³) core density values. It is likely that the spike in the density profile at the glue-line location combined with the fact that the algorithm used to calculate the density profile properties was developed based on the assumption of a “U” shaped density profile were responsible for this.

As stated in Section 3.6.2.7.2 above, it was anticipated that the global density of the single-layer panels would be approximately equal to the layer density of the material from which they were made. This means that the A-CORE panels were expected to had a mean global density equal to the mean core density of the A-18mm panels. Table 3-54 above shows that the A-CORE panels had a mean global density equal to 502 kg/m³. Table 3-53 above shows that A-18mm panels had a mean core density equal to 498 kg/m³. Both of these values appear to be practically identical. Table 3-57 below presents the results of Student’s $t$-tests conducted to determine conclusively if the global density of the A-CORE panels is equal to the core density of the A-18mm panels. The Student’s $t$-test was conducted using the same method described in Section 3.5.1.7.3 above.
Table 3-57 – Results of t-Tests between Single-layer Densities and Parent Panels

<table>
<thead>
<tr>
<th>Material</th>
<th>Sample A Size</th>
<th>Sample B Size</th>
<th>t-Value</th>
<th>p-Value</th>
<th>Accept/Reject</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-CORE</td>
<td>16</td>
<td>221</td>
<td>0.67</td>
<td>0.515</td>
<td>Accept 1)</td>
</tr>
</tbody>
</table>

1) $H_0$: The global density of the A-CORE panels and core density of the A-18mm panels had the same mean
2) A level of significance of $\alpha = 0.05$ has been used

The results in Table 3-57 above confirm that the global density of the A-CORE panels is equal to the core density of the A-18mm panels with 51.5% certainty. This is in line with expectations given the production process used to produce the A-CORE panels as described in Section 3.4.3 above.

3.6.2.7.4 Surface Thickness

Figure 3-76 below compares the mean and 5th percentile surface thickness values for the materials tested.

![Surface Thickness](image)

Figure 3-76 – Surface Thickness

It is reasonable to expect that the surface thickness would increase with increasing nominal thickness by virtue of the fact that the thicknesses of each layer will increase in order to produce panels of overall greater thickness. Figure 3-76 above shows that the surface thickness for commercial OSB/3 panels

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produced by Manufacturer A increases with increasing nominal thickness in line with expectations. It is therefore not valid to directly compare the surface thicknesses of panels with different nominal thicknesses. Similar comparisons were not possible for panels produced by Manufacturers B and C as the results were only available for a single panel thickness per producer. It is anticipated that additional testing of a wider range of panel thickness produced by these manufacturers would yield similar trends.

In order to make valid comparisons between the surface thicknesses from panels of different nominal thickness, the surface thickness was represented as a percentage of the total thickness. Figure 3-77 below shows the results for mean and 5th percentile surface thickness values expressed as a percentage of the total thickness for the materials tested.

Figure 3-77 – Relative Surface Thickness

Figure 3-77 above demonstrates that for Manufacturer A, the mean surface thickness is between 19 and 20% of the total panel thickness for all panels tested. The 5th percentile surface thickness is between 15 and 20% of the total thickness for all panels tested. This suggests that the surface thickness increases proportionally to the total thickness of the panel. Similar comparisons were not
possible for panels produced by Manufacturers B and C as the results were only available for a single panel thickness per producer. Further testing a wider range of panel thickness produced by these producers is likely to yield similar trends.

Figure 3-77 above indicates that the mean and 5th percentile surface thickness values for the A-SURF panels were 27.17% and 24.46% of the mean and 5th percentile total thickness, respectively. It also indicates that the mean and 5th percentile surface thickness values for the A-CORE panels were 37.37% and 32.05% of the mean and 5th percentile total thickness, respectively. This suggests that the surface layer of the single-layer panels occupies a significantly greater proportion of the total thickness of the panel. This suggests that as was the case with the layer densities discussed in Sections 3.6.2.7.2 and 3.6.2.7.3 above, the relative layer thicknesses for the single-layer panels were significantly different from those found in commercial OSB/3 panels.

3.6.2.7.5 Core Thickness

Figure 3-78 below compares the mean and 5th percentile core thickness values for the materials tested.

![Core Thickness](image-url)
Similar to the surface thickness results discussed in Section 3.6.2.7.4 above, it is reasonable to expect that the core thickness would increase with increasing nominal thickness. Figure 3-78 above shows that as with the surface thickness discussed in Section 3.6.2.7.4 above, the core thickness for commercial OSB/3 panels produced by Manufacturer A increases with increasing nominal thickness in line with expectations. Similar comparisons were not possible for panels produced by Manufacturers B and C as the results were only available for a single panel thickness per producer. It is anticipated that additional testing of a wider range of panel thickness produced by these manufacturers would yield similar trends. Using the approach described in Section 3.6.2.7.4 above, Figure 3-77 below shows the mean and the 5th percentile core thickness values expressed as a percentage of the total thickness for the materials tested.

![Core Thickness / Total Thickness](image)

**Figure 3-79 – Relative Core Thickness**

Unlike the results for surface thickness discussed in Section 3.6.2.7.4 above, the relative mean core thickness for the commercial OSB/3 panels produced by Manufacturer A seems to increase slightly with increasing panel nominal thickness. Figure 3-79 above shows the mean core thickness for the A-11mm panels occupies 57.75% of the total thickness whereas the mean core thickness
for the A-18mm panels is 59.43% of the total thickness for the A-18mm panels. This slight increase in the mean relative core thickness values with increasing nominal thickness can probably be explained by the slight decrease in the relative surface damage thickness for the thicker panels produced by Manufacturer A. Similar comparisons were not possible for Manufacturers B and C since the results for only one nominal thickness per manufacturer were available. Further testing using a wider variety of panel thicknesses produced by these manufacturers would likely yield similar trends.

The results also show that the relative 5th percentile core thickness for the panels produced by Manufacturer A is constant with increasing panel nominal thickness. Figure 3-79 above shows that the 5th percentile core thickness for the panels produced by Manufacturer A occupy between 50 to 53% of the total panel thickness. The results presented in Table 3-53 above show that the coefficients of variation of the core thickness results for the A-11mm, A-15mm and A-18mm panels were 12.05%, 8.83% and 13.02% respectively. This shows that the core thickness results for the A-15mm panels were slightly less variable than the remaining panels produced by Manufacturer A. This explains why the A-15mm panels had a slightly higher 5th percentile relative core thickness than the other two panels thicknesses produced by Manufacturer A. If further testing resulted in an increase in the CoV of the core thickness results for the A-15mm panels, this would result in a slight reduction in the 5th percentile relative core thickness. Therefore, it is still valid to claim that the 5th percentile relative core thickness is constant for all panel thicknesses produced by Manufacturer A. It is possible that differences between the coefficients of variability in the relative surface damage thickness results for the panels produced by Manufacturer A may be responsible for this. This will be examined in further detail in Section 3.6.2.7.6 below.

As with the relative surface thicknesses, the results suggest that the relative core thicknesses for the A-SURF and A-CORE panels were significantly different to the commercial OSB/3 panels. Figure 3-79 above indicates that the mean and 5th percentile surface thickness values for the A-SURF panels were 46.66% and 39.14% of the mean and 5th percentile total thickness respectively. Figure 3-79
above indicates that the mean and 5\textsuperscript{th} percentile surface thickness values for the A-CORE panels were 25.26\% and 15.82\% of the mean and 5\textsuperscript{th} percentile total thickness respectively. These results indicate that the core-layer of the single-layer panels occupies a significantly lesser proportion of the total thickness of the panel. This is consistent with the relative surface thickness results discussed in Section 3.6.2.7.4 above which showed that the surface thickness in the single-layer panels accounted for a greater proportion of the total thickness than for commercial OSB/3 panels. This further strengthens the claim that the vertical density profiles for the single-layer panels were significantly different from those found in commercial OSB/3 panels.

3.6.2.7.6 Surface Damage Thickness

The results presented in Table 3-53 above suggest that there is a significant difference between the left and right surface damage thickness. Table 3-58 below presents the results of Student’s $t$-tests conducted to investigate if there is a significant difference between the left a right surface damage thickness. The Student’s $t$-tests were conducted using the method described in Section 3.5.1.7.3 above. Note that the surface damage thickness for the single-layer panels has been assumed to be zero. This is because the low density wood strands typically found on the surfaces of commercial OSB/3 panels resulting from prolonged contact with the hot pressing platens would not be present on the surfaces of the single-layer panels.

<table>
<thead>
<tr>
<th>Material</th>
<th>Sample A Size</th>
<th>Sample B Size</th>
<th>$t$-Value</th>
<th>$p$-Value$^{2)}$</th>
<th>Accept/Reject$^{1)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-11mm</td>
<td>334</td>
<td>334</td>
<td>15.584</td>
<td>&lt;0.01</td>
<td>Reject</td>
</tr>
<tr>
<td>A-15mm</td>
<td>219</td>
<td>219</td>
<td>12.440</td>
<td>&lt;0.01</td>
<td>Reject</td>
</tr>
<tr>
<td>A-18mm</td>
<td>221</td>
<td>221</td>
<td>14.282</td>
<td>&lt;0.01</td>
<td>Reject</td>
</tr>
<tr>
<td>B-15mm</td>
<td>109</td>
<td>109</td>
<td>6.425</td>
<td>&lt;0.01</td>
<td>Reject</td>
</tr>
<tr>
<td>C-15mm</td>
<td>114</td>
<td>114</td>
<td>7.793</td>
<td>&lt;0.01</td>
<td>Reject</td>
</tr>
</tbody>
</table>

1) $H_0$: The left surface damage and right surface damage thicknesses had the same means
2) A level of significance of $\alpha = 0.05$ has been used

Table 3-58 – Student’s $t$-Tests Results for Left and Right Surface Damage Thickness

The results presented in Table 3-58 above indicate conclusively that the left and right surface damage thicknesses were significantly different for all commercial
OSB/3 panels tested. Section 3.6.2.3 above noted that the surface finish of the commercial OSB/3 panels produced by Manufacturer A was different on the two faces, as a result of the pressing system used by this manufacturer. Care was taken to ensure that the density profile specimens taken from panels produced by Manufacturer A were scanned in the direction “smooth” surface to “textured” surface. This means the left surface corresponds to the “smooth” surface while the right surface corresponds to the “textured” surface. This could possibly explain the reason why the left surface damage thickness is significantly different to the right surface damage thickness for the commercial OSB/3 panels produced by Manufacturer A.

Section 3.6.2.3 above also noted that there was no visible difference between the surfaces of the panels produced by Manufacturers B and C. Therefore, it was anticipated that the results of the Student’s *t*-tests would indicate that no significant difference existed between the left and right surface damage thicknesses. However, the results presented by Table 3-58 above suggest otherwise. Table 3-53 above shows that the coefficients of variability for the left surface damage depth results fall in the region of 66 to 81% while the coefficients of variability of the right surface damage depth results fall in the region of 34 to 52%. This indicates that the left and right surface damage thickness results were highly variable. In the case of the panels produced by Manufacturer A, this also goes against initial expectations because it suggests that the “textured” surface is significantly more variable than the “smooth” surface. Another prominent feature present in the left and right surface damage thickness is the extremely small thicknesses involved. Table 3-53 above shows the mean left surface damage thickness varies from 0.08 mm to 0.21 mm while the mean right surface damage thickness values from 0.20 mm to 0.35 mm for the commercial OSB/3 panels tested.

Section 3.6.2.3 above noted that the density profile specimens were scanned in 0.05 mm increments. This is a relatively large increment in the context of the distances involved while assessing the surface damage thicknesses. It is therefore possible that 0.05 mm increments were too large to get an accurate assessment of
the surface damage thickness. A smaller increment would enable the density profile meter to evaluate the density profile with greater resolution that may enable a more accurate assessment of the surface damage thickness. The disadvantages of using smaller increments were that each specimen would take significantly longer to scan and that the results database would become significantly larger to the point where it would become unmanageable. Given that the surface damage thickness is relatively small and its effects on tension, compression and panel-shear performance were likely to be negligible, it was decided not to rescan the samples at a higher resolution.

Since the surface damage thickness results had been shown to be highly variable, it was decided to assume that the left and right surface damage thickness were equal in order to increase the sample size available. The surface damage thickness for each specimen was reported as the average of the left and right surface densities. Figure 3-80 below compares the mean and 5th percentile average surface damage thickness values for the materials tested.

![Figure 3-80 – Average Surface Damage Thickness Results](image)

Similar to the surface and core thickness results discussed in Sections 3.6.2.7.4 and 3.6.2.7.5 above respectively, it is reasonable to expect that the surface
damage thickness would increase with increasing nominal thickness. Figure 3-80 above shows that this is true for the mean and 5th percentile average surface damage values for commercial OSB/3 panels produced by Manufacturer A. It is therefore not valid to directly compare the surface damage thicknesses of panels with different nominal thicknesses. Similar comparisons were not possible for panels produced by Manufacturers B and C as the results were only available for a single panel thickness per producer. It is anticipated that additional testing of a wider range of panel thicknesses produced by these manufacturers would yield similar trends. Using the same approach for the surface and core thicknesses described in Sections 3.6.2.7.4 and 3.6.2.7.5 above, respectively, Figure 3-81 below shows the mean and 5th percentile average surface damage thickness values expressed as a percentage of total thickness for the materials tested.

Figure 3-81 – Relative Average Surface Damage Thickness

Figure 3-81 above shows that the mean relative surface damage depth for the commercial OSB/3 panels produced by Manufacturer A decreases with increasing panel nominal thickness. This could possibly be a result of a lower pressing temperature used in the production of the thicker panels or perhaps by improved heat absorption capacity of the thicker mats. The results discussed in
Section 3.6.2.7.4 above showed that the relative surface thickness remained constant with increasing nominal thickness for commercial OSB/3 panels produced by Manufacturer A. The results discussed in Section 3.6.2.7.5 above indicated that the mean relative core thickness for the commercial OSB/3 panels produced by Manufacturer A increased slightly with increasing nominal thickness. Therefore, the downward trend in mean relative surface damage thickness with increasing nominal thickness for commercial OSB/3 panels produced by Manufacturer A is consistent with the surface and core-layer thickness results. Similar commentary is not possible for Manufacturers B and C since results from one nominal thickness per manufacturer were available. Further testing using a wider variety of panel thickness produced by these manufacturers would likely yield similar trends.

3.7 Commercial OSB/3 Panel Overall Performance Comparison

3.7.1 Strength

Table 3-59 below presents a summary of the panels with the highest and lowest mean and 5th percentile strength values in the longitudinal direction for the commercial OSB/3 panels for the loading conditions tested for by the experimental test program.

<table>
<thead>
<tr>
<th>Tension</th>
<th>Compression</th>
<th>Bending</th>
<th>Panel-Shear(^1)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>5th Percentile</td>
<td>Mean</td>
</tr>
<tr>
<td><strong>Lowest</strong></td>
<td>B-15</td>
<td>C-15</td>
<td>C-15</td>
</tr>
</tbody>
</table>

\(^1\) Panel-shear tests conducted on panels produced by Manufacturer A only

Table 3-59 – Commercial OSB/3 Panel Longitudinal Strength Performance

Out of a total of four strength properties, Table 3-59 above shows the A-11mm panels had the highest mean value for three and the highest 5th percentile value for two of the strength properties evaluated in the longitudinal direction. Table 3-59 above shows that the C-15mm panels had the lowest mean value for three and the lowest 5th percentile value for three of the strength properties out of a total of four strength properties evaluated in the longitudinal direction.
Table 3-60 below presents a summary of the panels with the highest and lowest mean and 5\textsuperscript{th} percentile strength values in the lateral direction for the commercial OSB/3 panels for the loading conditions tested for by the experimental test program.

<table>
<thead>
<tr>
<th></th>
<th>Tension</th>
<th>Compression</th>
<th>Bending</th>
<th>Panel-Shear\textsuperscript{1)}</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>5\textsuperscript{th} Percentile</td>
<td>Mean</td>
<td>5\textsuperscript{th} Percentile</td>
</tr>
<tr>
<td><strong>Lowest</strong></td>
<td>C-15</td>
<td>C-15</td>
<td>C-15</td>
<td>C-15</td>
</tr>
</tbody>
</table>

\textsuperscript{1)} Panel-shear tests conducted on panels produced by Manufacturer A only

Table 3-60 – Commercial OSB/3 Panel Lateral Strength Performance

In the lateral direction, Table 3-60 above shows that out of four strength properties evaluated, the A-11mm panels had the highest mean value for three and the highest 5\textsuperscript{th} percentile value for two of the strength properties evaluated. Table 3-60 above shows the C-15mm panels had the lowest mean value for three and the lowest 5\textsuperscript{th} percentile value for three of strength properties out of a total of four strength properties evaluated in the lateral direction.

The summaries presented in Table 3-59 and Table 3-60 above suggest that the A-11mm overall had the best overall strength performance of the commercial OSB/3 panels tested. They had the highest mean value for six and the highest 5\textsuperscript{th} percentile value for four out of total of eight strength properties evaluated. The results also suggest that the C-15mm panels overall had the poorest overall strength performance of the commercial OSB/3 panels tested. They had the lowest mean value for six and the lowest 5\textsuperscript{th} percentile value for six out of total of eight strength properties evaluated.

3.7.2 Elastic Modulus

Table 3-61 below presents a summary of the panels with the highest and lowest mean and 5\textsuperscript{th} percentile elastic modulus values in the longitudinal direction for the commercial OSB/3 panels for the loading conditions tested by the experimental test program. In the longitudinal direction, the results show the A-11mm panels had the highest mean value for five and the highest 5\textsuperscript{th} percentile value for two out of a total of six elastic modulus properties evaluated in the
longitudinal direction. Table 3-61 below also shows the A-15mm panels had the highest 5th percentile value for four out of a total of six elastic modulus properties evaluated in the longitudinal direction.

<table>
<thead>
<tr>
<th>Tension</th>
<th>Compression</th>
<th>Bending</th>
<th>Panel-Shear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>5th Percentile</td>
<td>Mean</td>
<td>5th Percentile</td>
</tr>
</tbody>
</table>

1) Panel-shear tests conducted on panels produced by Manufacturer A only
2) Local elastic modulus
3) Global elastic modulus

Table 3-61 – Commercial OSB/3 Panel Longitudinal Elastic Modulus Performance

The results in Table 3-61 above show that the B-15mm panels had the lowest mean value for four out of a total of six elastic modulus properties evaluated in the longitudinal direction. The results also show the A-18mm panels had the lowest 5th percentile value for three out of a total of six elastic modulus properties evaluated in the longitudinal direction.

Table 3-62 below presents a summary of the panels with the highest and lowest mean and 5th percentile elastic modulus values in the lateral direction for the commercial OSB/3 panels for the loading conditions tested for by the experimental test program.

<table>
<thead>
<tr>
<th>Tension</th>
<th>Compression</th>
<th>Bending</th>
<th>Panel-Shear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>5th Percentile</td>
<td>Mean</td>
<td>5th Percentile</td>
</tr>
<tr>
<td></td>
<td>C-15 3)</td>
<td>C-15 3)</td>
<td>C-15 3)</td>
</tr>
</tbody>
</table>

1) Panel-shear tests conducted on panels produced by Manufacturer A only
2) Local elastic modulus
3) Global elastic modulus

Table 3-62 – Commercial OSB/3 Panel Lateral Elastic Modulus Performance

In the lateral direction, Table 3-62 above shows that the A-11mm panels had the highest mean value for six and the highest 5th percentile value for four out of a
total of six elastic modulus properties evaluated. The results also show that both the C-15mm and the A-18mm panels had the lowest mean value for three and the lowest 5th percentile value for three out of a total of six elastic modulus properties evaluated in the lateral direction.

Unlike the strength performance discussed in Section 3.7.1 above, the summaries presented in Table 3-61 and Table 3-62 above do not provide as definitive conclusion as to which panel performed the best. They suggest that the A-11mm overall had the best overall strength performance of the commercial OSB/3 panels tested. They had the highest mean value for eleven and the highest 5th percentile value for six out of total of twelve elastic modulus properties evaluated. The results also show that the A-11mm panels did not had the lowest mean or 5th percentile values for any of the elastic modulus properties evaluated. However, they also show that the A-15mm panels had the highest mean value for one and the highest 5th percentile value for six out of total of twelve elastic modulus properties evaluated. This suggests that the A-11mm panels had overall better mean elastic modulus but the A-15mm panels had better 5th percentile values. This could be as a result of the lower coefficients of variability recorded for the A-15mm panels when compared to the A-11mm panels.

Similarly, the summaries presented in Table 3-61 and Table 3-62 above do not provide as definitive conclusion as to which panel performed the poorest. The results show that the C-15mm panels the lowest mean value for three and the lowest 5th percentile value for five out of total of twelve elastic modulus properties evaluated. The results also show that the A-18mm panels the lowest mean value for five and the lowest 5th percentile value for six out of total of twelve elastic modulus properties evaluated. Neither panel recorded the highest mean or 5th percentile value for any of the twelve elastic modulus properties evaluated. This suggests that the A-18mm panels performed marginally the poorest overall followed closely by the C-15mm panels.

3.8 Concluding Remarks

The experimental testing program produced a substantial database of information about the physical properties and mechanical behaviour of commercial OSB/3
panels in a variety of thicknesses produced by a variety of manufacturers. Additionally, this study developed a novel approach for collecting information regarding the physical properties and mechanical behaviour of the constituent layers that make up a typical commercial OSB/3 panel.

3.8.1 Mechanical Testing Procedures

3.8.1.1 Specimen Preparation

The mechanical testing program demonstrated that it is possible to prepare specimens with good accuracy using simple manual marking out and cutting techniques as described in Section 3.4.2.1 above. However, the time and labour involved makes this approach impractical for testing on an industrial scale. Full industrial scale testing would require automated specimen cutting using the CNC method described in Section 3.4.2.2 above. Additionally, the CNC milling technique described in Section 3.4.3 above proved that it is possible to isolate the constituent layers that comprise typical commercial OSB/3 panels. Previous studies of this nature relied on testing laboratory-produced single-layer panels or small-scale testing of commercial OSB/3 panels. The novel approach described in Section 3.4.2.2 above filled a significant knowledge gap because it enabled full-scale testing of the lamina that constitutes typical commercial OSB/3 panels.

The bending and tension test specimens required the least amount of effort to prepare as they could be cut to their final shape directly from the parent panel. The compression test specimens were significantly more difficult to prepare as they could not be cut to their final shape directly from the parent panel. As described in Section 3.5.2.1 above, they required a second cutting pass to reduce them to thin strips, a gluing pass to get them to their final form and a third cutting pass to trim the ends to get them to their final size. However, the relatively small size of the compression test specimens meant they could be easily handled and that large numbers of specimens could be prepared during each cutting and gluing operation. The required clamping pressures were low enough such that they could be applied using “C” clamps. The PVA adhesive used to glue these specimens was cheap, safe and effective for preparing compression test
specimens. Out of a total of 198 compression tests conducted, not a single specimen failed along the PVA glue line.

The panel-shear test specimens were the most difficult and the most expensive to prepare. This is mainly because of the gluing phase required to attach the C16 timber rails. The size, shape and clamping forces required meant that these specimens had to be clamped using a large scale clamping rig designed originally for gluing glulam beams (Raftery and Harte, 2011). The geometry of the test specimens meant that only one side could be glued at a time. The size of the gluing rig and the time involved meant that a maximum of 12 specimens could be glued at time. This resulted in a 2 day time frame to prepare 12 panel-shear test specimens. The glued specimens were difficult to handle and took up a lot of space in the conditioning chamber further inhibiting the maximum amount of specimens that could be produced at a time. The C16 rails contributed significantly to the cost of this test as they could not be easily removed from the specimens after testing, meaning that they could not be reused. The PRF adhesive also contributed significantly to the cost and posed a significant health and safety risk during gluing. BS EN 789 (BSI, 2004b) permits the use of re-useable steel rails which would be costly to make but would eliminate many of the problems associated with gluing C16 timber rails to shear test specimens.

### 3.8.1.2 Testing Arrangements and Procedures

The tension test was the easiest to perform. The testing arrangement and procedure were described in detail in Section 3.5.1 above. The test rig consisted of a universal test machine with self-aligning grips to grab the end tabs. The full test could be completed in one run by loading the specimen to failure. It was possible to leave the LVDTs in position up until the specimen failed because there was no risk of them being damaged during specimen failure. This provided a cheap, effective and accurate way of recording the mechanical behaviour in tension up to failure. The mounting blocks shown in Figure 3-14 above proved extremely effective as they could easily be re-used. They could also be removed from one test specimen and reattached to another with the minimum of delay. One oversight that was not realised until the numerical modelling phase of the
study was that the Poisson’s ratios for OSB had not been studied in any significant detail. It would have been relatively straightforward to attach some additional instrumentation in the form of strain gauges under the LVDTs orientated at right angles to the loading direction on a selection of test specimens. The data from the strain gauges could have been used to establish the Poisson’s ratios for the materials tested. A more sophisticated alternative would be to use an optical data acquisition system that would be capable of recording movement in all directions simultaneously. The data from such a system would provide much more information about the mechanical behaviour without the labour involved with mounting traditional instrumentation.

The compression test was also relatively easy to setup and perform. The testing arrangement and procedure were described in detail in Section 3.5.2 above. The test rig consisted of a universal testing machine with platens, one of which was connected to the machine crosshead with a ball joint. Unlike the tension test, the compression test had to be conducted in using two separate runs. The specimens were loaded to approximately 50% of their failure load before being unloaded so that the LVDTs could be removed to avoid damage during rupture. The specimens were then reloaded to failure using the crosshead displacement to record mechanical behaviour to failure. Errors in the cross-head displacement readings can arise through settlement of the test specimen, slack in the ball-joint and second-order stresses arising near the support and loading head due to the restraint of Poisson’s effects. Past studies have used the crosshead displacement results to characterise the mechanical behaviour of wood-based composites subject to compression (Clouston and Lam, 2001, Clouston and Lam, 2002, Arwade et al., 2009). Errors arising from settlement or slack in the loading apparatus can be allowed for as described in Section 3.5.2.5.2 above. Therefore, this approach was deemed acceptable for use in this study.

The testing arrangement and procedure were described in detail in Section 3.5.3 above. The testing arrangement was relatively complicated as shown in Figure 3-38 above. Despite the complex testing arrangement, the test procedure was relatively straightforward to carry out. Like the compression test, the bending test
was conducted in using two separate runs. The specimens were loaded to approximately 50% of their failure load before being unloaded so that the LVDTs mounted to the hanger could be removed to eliminate the risk of damage during rupture. The specimens were then reloaded to failure using just the two LVDTs mounted to the loading frame to record the mechanical behaviour over the full span of the test specimens. The global displacement readings recorded by the LVDTs that were mounted to the loading frame include both bending and plate-shear displacement components. While not theoretically correct, plate-shear and bending normally co-exist and therefore calculating elastic properties based on global displacement results is considered acceptable in practice.

The panel-shear test was the most complicated to setup and to perform. The panel-shear testing arrangement and procedure were described in detail in Section 3.5.4 above. The panel-shear test is extremely complicated and requires a specially-fabricated test rig to hold the test specimen in place as shown in Figure 3-53 above. Like the compression and bending tests, the panel-shear test was conducted in using two separate runs. The specimens were loaded to approximately 50% of their failure load before being unloaded so that the LVDTs could be removed to avoid damage during rupture. The specimens were then reloaded to failure using just the crosshead displacement to record mechanical behaviour up to failure. The upright at the right hand side of the panel-shear test rig underwent visible horizontal deformation during testing. This meant that the cross-head displacement readings were of limited use. The only accurate way to record the mechanical behaviour of panel-shear test specimens up to the point of failure was to add strain gauges directly under the LVDTs as shown in Figure 3-54 above. This is a costly solution because the strain gauges get destroyed once the specimen fails. Therefore, only a limited selection of test specimens was instrumented with strain gauges.

3.8.2 Mechanical Testing Results

3.8.2.1 All Panels

The results from the mechanical testing program discussed in Section 3.5 above had shown that for all panels tested:
- The mechanical behaviour for all panels is effectively linear at low strains but significant non-linearities exist at high strains, particularly when loaded in compression.

- Failure of tension and bending test specimens occurs rapidly with little or no warning of the onset of failure. Failure was initiated by a combination of strand rupture and a bond failure. This suggested that the strength of the strands and the bonds developed between them had a significant influence on the performance of the materials tested when subjected to tension or bending. The similarities of the failure mechanisms, the shape of the load-displacement curves and the fact that tension strength was lower than compression strength for all materials suggest that mechanical behaviour and failure of all materials subjected to bending is governed by the tension surface. This has been shown to be consistent with past research on this subject.

- Failure of compression and panel-shear test specimens occurred more gradually with clear warnings of the onset of failure. Failure of compression test specimens was initiated by debonding of the core of followed by a gradual loss of strength resulting from the buckling of the remaining, intact layers. Failure of panel-shear test specimens was initiated by debonding in the core were the lower transition radius followed by a slow crack propagation either through the shear area or along one or the other of the C16 timber rails. Finite element models presented in Chapter 5 below will later demonstrated that a compression stress that is almost equal to the compression strength exists at right angles to the loading direction in the panel-shear test specimens. The similarities of the failure modes lead to the suggestion that the internal bond strength is the limiting factor governing the performance of the material tested when subjected to compression or panel-shear loading.

- The variability of the test results significantly influences the characteristic values for material strengths and elastic properties. In practice, characteristic values were normally divided by a partial safety factor to produce design values. Therefore, it can be stated that the variability of
the test data significantly influences the design values for OSB strength and elastic properties.

- Although the sample sizes were relatively small, the results derived from them still provided a good overall picture of the performance of the materials tested under the most commonly encountered loading scenarios in practice. The exceptions to this were the samples where the results from one or more specimens were noticeably different from the remaining results in the specimens. Poor results from these isolated specimens may have disproportionally effects the overall results from the affected samples.

### 3.8.2.2 Commercial OSB/3 Panels

The results from the mechanical testing program discussed in Section 3.5 above had shown that for the commercial OSB/3 panels tested:

- The strength and elastic properties for all panels exhibit orthotropic behaviour when loaded in tension, compression and bending with enhanced performance when loaded parallel to the longer dimension of the panel.
- The strength and elastic properties for all panels exhibit isotropic behaviour when loaded in panel-shear with no significant performance enhancement being detected in either material direction.
- The ultimate strain for all panels exhibits isotropic behaviour when loaded in tension. The ultimate strain for all panels exhibits orthotropic behaviour when loaded in compression and bending. It is not clear whether it can be definitively stated that ultimate strain for all panels exhibits isotropic or orthotropic behaviour when loaded in panel-shear.
- All panels failed to achieve characteristic values specified in BS EN 12369 (BSI, 2001) for one or more of tension, compression and panel-shear loading in one or more material directions. Bending was shown to be the only loading condition where all panels achieved characteristic values specified in BS EN 12369 in both material directions. This has been attributed to the fact that three-point bending according to BS EN
310 (BSI, 1993a) is conducted as part of the quality control testing regimes used by OSB producers. If this were to be repeated in large sample tests, then either:

- The characteristic values presented in BS EN 12369 were too ambitious, or else,
- The quality control procedures were only sufficient to guarantee good bending performance but were not sufficient to guarantee good performance under other loading conditions.

- Some evidence of size effects has been detected in the results for certain mechanical properties of the panels produced by Manufacturer A. However, the results were mixed and therefore make it impossible to state with any degree of certainty whether or not size effects were definitely influencing the performance of these panels.
- The discussion presented in Sections 3.7.1 and 3.7.2 above suggest that overall, the A-11mm panels performed the best while the C-15mm panels performed the poorest.

### 3.8.2.3 Single-Layer Panels

The results from the mechanical testing program discussed in Section 3.5 above had shown that for the single-layer OSB panels tested:

- The strength and elastic properties for the single-layer panels exhibit orthotropic behaviour for all loading conditions and were significantly more orthotropic than the commercial OSB/3 panels. This has been attributed to the lack of wood strands oriented at 90° to the loading direction.
- The ultimate strain for the single-layer panels exhibits isotropic behaviour when loaded in tension and orthotropic behaviour when loaded in compression. The results proved inconclusive in terms of proving whether or not the single-layer panels exhibit orthotropic behaviour for panel-shear ultimate strain.
- The A-SURF panels had higher strength and elastic properties in the longitudinal direction for tension, compression and panel-shear loading
than the commercial OSB/3 panels. This has been attributed to their effectively uniform vertical density profile and higher global density.

- The A-SURF panels had comparable strength and elastic properties in the lateral direction for tension, compression and panel-shear loading than the commercial OSB/3 panels in spite of the load being resisted only by wood strands orientated at 90° to the loading direction. This has been attributed to their effectively uniform vertical density profile and their greater global density.

- The A-CORE panels had poorer strength and elastic properties in the longitudinal direction for tension, compression and panel-shear loading than the A-SURF panels. This has been attributed to their relatively low global density when compared to the A-SURF panels and that loads applied parallel to the longer dimension A-CORE panels were resisted only by wood strands oriented at 90° to the loading direction.

- The A-CORE panels had comparable or better strength and elastic properties than the A-SURF panels in the lateral direction despite their lower global density when compared to the A-SURF panels. This has been attributed to the fact that the A-CORE panels consist entirely of wood strands aligned perpendicular to the longer dimension of the panel. This produces enhanced mechanical performance when the load is applied at right angles to the longer dimension. This further highlights the significance of the alignment of the wood strands relative to the direction of loading.

### 3.8.3 Physical Properties Testing Procedures

#### 3.8.3.1 Specimen Preparation

The methods used to prepare moisture content specimens as described in Section 3.6.1.1 above proved to be very efficient and straightforward to carry out. The method used to prepare density profile specimens as described in Section 3.6.2.1 above proved very effective in terms of ensuring consistency in the sampling location and keeping the specimens within the strict tolerance limits. However,
the method also proved to be very time consuming and labour intensive and an alternative system would need to be developed for larger scale testing programs.

### 3.8.3.2 Testing Arrangements and Procedures

Both the moisture content test procedure described in Section 3.6.1.2 above and the density profile test procedure described in Section 3.6.2.3 above proved very straightforward and efficient to conduct. Large quantities of samples could be tested with minimum handling or human intervention.

### 3.8.4 Physical Properties Testing Results

#### 3.8.4.1 All Panels

The results from the physical properties testing program discussed in Section 3.6 above had shown that for all panels tested:

- The moisture contents were relatively consistent and had low coefficients of variability for all materials tested. This confirmed that the conditioning procedure used to standardise the moisture contents of the material tested was more than adequate.
- The 0.05 mm increments used to scan the vertical density profile specimens was effective at providing an accurate representation of the internal density structure of the materials tested.

#### 3.8.4.2 Commercial OSB/3 Panels

The results from the physical properties testing program discussed in Section 3.6 above had shown that for the commercial OSB/3 panels tested:

- All commercial OSB/3 panels tested exhibited the traditional “U” shaped vertical density profile characterised by high density surfaces and a low density core. A thin layer (less than 0.3 mm) of low-density wood strands was found to be present on the surfaces of these panels as is typical of commercial OSB/3 panels with an “as pressed” surface finish. However, the scanning resolution of 0.05 mm increments proved to be too coarse to accurately capture the boundary between the surface damage layer and the high density surface layer.
• The algorithm described in Section 3.6.2.4 above used to calculate an approximate stepped vertical density profile proved extremely useful for simplifying and comparing the vertical density profiles recorded for different specimens and materials.

• Evidence of size effects has been detected in the density profile results for panels produced by Manufacturer A. The global and layer densities decreased with increasing panel nominal thickness. The layer thicknesses increased proportional to the increase in total panel thickness.

• Representing the layer thicknesses as a percentage of the total thickness of the panel proved effective for comparing the vertical density profiles of panels with different nominal thicknesses.

3.8.4.3 Single-Layer Panels

The results from the physical properties testing program discussed in Section 3.6 above had shown that for the single-layer OSB panels tested:

• Both the A-SURF and the A-CORE panels had vertical density profiles that were radically different from those observed in the commercial OSB/3 panels. The density profiles for these panels were generally uniform with a sharp spike located at the glue line were the two panels were glued together as described in Section 3.4.3 above. No surface damage effects were observed for these panels. These findings were consistent with the manufacturing methods used to produce these panels.

• A-SURF panels had greater global densities than commercial OSB/3 panels while the A-CORE panels had lower global densities than the commercial OSB/3 panels. This finding was consistent with the manufacturing methods and the vertical density profiles recorded for the raw materials used to produce the single-layer panels.

• The algorithm described in Section 3.6.2.4 above used to calculate an approximate stepped vertical density profile was found not to be particularly relevant for the single-layer panels because they can be accurately described in terms of their global density only.
4 Statistical Analysis

4.1 Introduction

The literature review presented in Chapter 2 identifies a lack of published data on the probabilistic properties of commercial wood-based composite materials. Chapter 2 also showed that most of the past studies on modelling of wood-based composite materials relied on linear or multi-linear material models to describe the mechanical behaviour of wood-based composites. The experimental data presented in Chapter 3 shows that the mechanical behaviour of single-layer and commercial OSB/3 panels exhibit significant non-linear behaviour, particularly at high strains. The generation of probabilistic data and non-linear material models therefore form two of the key objectives of this research.

This chapter provides details of the methods used to fulfil these two key objectives. The results were used to in a stochastic finite element model to accurately simulate the mechanical behaviour and variability of commercial OSB/3 panels observed from experimental tests. The stochastic finite element model will be discussed in greater detail in Chapter 5. Section 4.3 below describes the statistical methods used in this study. Sections 4.3.1 and 4.3.2 below outline the statistical analysis methods used to determine suitable probability distribution models to represent the variability of each parameter. Section 4.3.3 below describes the methods used to identify the nature and the strength of relationships between multiple variables evaluated in the experimental testing program. Section 4.3.4 below describes the methods used to establish mathematical models to describe mechanical behaviour under different load conditions. Section 4.5 below describes a series of computer programs developed for this study to process raw experimental data, to manage the experimental results database, to automate the statistical analysis and to present the results in a format that could be interpreted by ANSYS Multiphysics.

The goodness-of-fit analysis indicated that most of the variables evaluated under the experimental test program can be described using either a normal, lognormal or uniform probability distribution. Variables that did not fit either a normal or
lognormal probability distribution were assumed to be uniformly distributed for the purpose of this study. The correlation analysis showed that the relationships between parameters varied significantly covering the entire spectrum of possibilities from a strong positive correlation to a strong negative correlation. The results of the regression analysis showed that the mechanical behaviour for all loading conditions and materials could be represented by polynomial expressions with high degrees of accuracy.

4.2 Scope of Statistical Analysis Program

The primary aim of the statistical analyses was to use the database of experimental results to generate inputs required by the stochastic FE model as described in Chapter 5. Two key inputs required by this model consisted of probabilistic data to describe the variability of the parameters and mathematical models to describe the mechanical behaviour of the material subject to a variety of loading conditions. Knowledge of probability theory is assumed and therefore is not described in detail. Reference should be made to Levine (2001), Rumsey (2003) and Rumsey (2007) for further information. The scope of the statistical analysis program also includes the comparison of numerical predictions with experimental results. This is covered in more detail in Chapter 5.

4.3 Statistical Methods

The software developed for this study utilised several statistical analysis techniques including:

- Probability plots,
- Anderson-Darling goodness-of-fit test (Anderson and Darling, 1952),
- Least-squares regression analysis,
- Correlation analysis.

4.3.1 Probability Plots

Probability plots are a graphical method for visually assessing the goodness-of-fit between the empirical distribution function (EDF) of a data set and the cumulative distribution function (CDF) of any probability distribution. They are much more reliable than histograms as they do not require discretization of the
data set. They are useful in preliminary investigations to differentiate between
good and bad fitting probability distributions but should not form the sole basis
for determining the best fitting probability distribution for a data set (D'Agostino
and Stephens, 1986).

### 4.3.1.1 Empirical Distribution Function (EDF)

The empirical distribution function (EDF) for a random sample \( X_1, X_n \) is defined
by Equation 4.1 below.

\[
F_N(x) = \frac{\#(X_i \leq x)}{N}, \quad -\infty < x < +\infty
\]  

where:  \( \#(X_i \leq x) \) = rank of observation \( X_i; \) \( N \) = sample size.

The EDF can be evaluated without prior knowledge of the underlying probability
distribution of the population that the sample was taken from. The EDF can be
plotted on a scatter plot where the horizontal axis is in units of the variable being
examined and the vertical axis is in units of probability (i.e. on a scale from 0 to
1). Such a scatter plot is referred to as a cumulative or \( P-P \) probability plot as
described in Section 4.3.1.3 below. The EDF is a step function but is rarely
shown as such when the sample size is large and the underlying probability
distribution is continuous (D'Agostino and Stephens, 1986).

### 4.3.1.2 Cumulative Distribution Function (CDF)

The cumulative distribution function (CDF) for a given probability distribution is
a mathematical expression that gives the probability that an observed value \( X_i \) of
a random variable \( x \) will be found at a value less than or equal to \( X_i \) (D'Agostino
and Stephens, 1986). Each probability distribution is characterised by a unique
CDF. The probability distributions used in this study are:

- Normal (Gaussian) distribution
- Lognormal distribution
- Uniform distribution

The CDF is a function of a set of parameters that are specific to the probability
distribution it characterises. For example, the normal distribution is defined by a
location parameter (e.g. mean, \( \mu \)) and a scale parameter (e.g. standard deviation, \( \sigma \)). If a data set comes from a population that defined by a CDF \( F(x) \), then, for large samples, the EDF \( F_n(x) \) will converge to \( F(x) \) for all values of \( x \). In other words, if the variability of the dataset can be accurately described by the probability distribution, then the EDF and CDF converge.

4.3.1.3 Cumulative Probability Plot

A cumulative or percent-percent (P-P) probability plot (see Figure 4-1 below) is a plot that shows the EDF and the CDF plotted one on top of the other.

![Figure 4-1 – Sample P-P Probability Plots (D’Agostino and Stephens, 1986)](image)

The data set is plotted against the probability of observing any value \( X_i \) of a random variable \( x \) at a value less than or equal to \( X_i \). The horizontal axis is measured in the same units as the variable while the vertical axis is measured in units of probability on a scale of 0 to 1. It is difficult to visually assess the goodness-of-fit between the stepped EDF function of the sample and the CDF of the hypothesized probability distribution using P-P probability plots.

4.3.1.4 Quantile-Quantile (Q-Q) Probability Plot

A quantile-quantile (Q-Q) probability plot (see Figure 4-2 below) eliminates the difficulty of assessing the goodness-of-fit between two curves by transforming the scale of the vertical axis such that if the sample follows the hypothesized
probability distribution, the EDF will form a perfectly straight line (D’Agostino and Stephens, 1986).

![Figure 4-2 – Sample Q-Q Probability Plot (D'Agostino and Stephens, 1986)](image)

Take a sample from a population characterised by a probability distribution defined by a location parameter \( \mu \) and a scale parameter \( \sigma \). It is worth noting that \( \mu \) and \( \sigma \) are not necessarily mean and standard deviation but instead are the first and second statistical moments for the probability distribution. The CDF of the underlying probability distribution can be written as:

\[
F(x) = G \left( \frac{x - \mu}{\sigma} \right) = G(z) \quad (4.2)
\]

\[
z = \frac{x - \mu}{\sigma} \quad (4.3)
\]

The variable \( Z \) is referred to as the standardised variable. The function \( G(z) \) is the CDF of the standardised variable. Note that \( z \) is a single observation of the random variable \( Z \). Where sample data is used, \( F(x) \) is replaced by \( F_N(x) \). Plotting values of \( Z \) against observed values of \( X \) on a scatter plot will result in a straight line provided the sample comes from a population that follows the hypothesized probability distribution. For sample data Equation (4.3) above can be rewritten as follows in Equation (4.4) below:

\[
F_N(x) = G \left( \frac{x - \mu}{\sigma} \right) = G(z) \quad (4.4)
\]
\[ z_i = G^{-1}(F_N(x_i)) \] (4.4)

where: \( z_i \) = value of the standardised variable \( Z \) corresponding to the observed value \( x_i \) of the random variable \( X \); \( G^{-1}(F_N(x_i)) \) is the inverse of the CDF of the standardised random variable \( Z \)

### 4.3.2 Anderson-Darling (1952) Test

The Anderson-Darling test is a quadratic one-tailed statistical hypothesis test for examining the goodness of fit between the EDF of a sample and the CDF of any probability distribution. The goodness-of-fit is be represented by a single number referred to as the Anderson-Darling statistic \( A^2 \). The Anderson-Darling test is considered the most robust goodness-of-fit test for both small and large samples (D’Agostino and Stephens, 1986, Stephens, 1974) and is widely used in commercial statistical software packages (Minitab, 2010).

The null hypothesis in the Anderson-Darling test states that the data comes from a population that follows a specific probability distribution. For example, test the hypothesis that the tensile ultimate strength in the longitudinal direction of 11 mm thick OSB/3 panels produced by Manufacturer A follows a normal distribution. The data set is ranked in ascending order. The EDF is evaluated using Equation (4.1) above and Anderson-Darling statistic is calculated using Equation (4.5) below and modified to take into account the effect of sample size using Equation (4.6) below.

\[ A^2 = \sum_{i=1}^{N} \frac{2i - 1}{N} \left[ \ln F(Y_i) + \ln(1 - F(Y_{N+1-i})) \right] \] (4.7)

The \( P \)-value is calculated from \( A^2 \) using the formulae derived by D’Agostino and Stephens (1986). A high \( P \)-value indicates a strong probability that the sample
comes from a population that follows the hypothesized probability distribution. A level of significance ($\alpha$) is chosen such that any value of $P$, that is less than the value of $\alpha$, results in the immediate rejection of the null hypothesis. This means the hypothesized probability distribution model does not accurately describe the variability of the sample. Similarly, any value of $P$, that is greater than the value of $\alpha$, leads to the acceptance of the null hypothesis. This means the hypothesized probability distribution is suitable at describing the variability of the sample. For the purposes of this study, a value of $\alpha = 0.05$ has been used throughout. The $P$-Value also indicates the degree-of-certainty that accepting the null hypothesis is correct. For example, a value of $P$ equal to 0.9 indicated with 90% certainty that the null hypothesis is correct.

4.3.3 Correlation Analysis

4.3.3.1 Pearson’s Correlation Coefficient

Correlation analysis determines the strength of the linear association between two random variables (Levine et al., 2001). The Pearson’s correlation coefficient is a test statistic for examining the strength of the relationship between two random variables based on an initial assumption of a linear relationship. The Pearson’s correlation coefficient $r$ between two random variables $X$ and $Y$ can be calculated using Equation (4.8) below.

$$r = \frac{\sum XY - \frac{\sum X \sum Y}{N}}{\sqrt{\left(\sum X^2 - \frac{\left(\sum X\right)^2}{N}\right)\left(\sum Y^2 - \frac{\left(\sum Y\right)^2}{N}\right)}}$$  \hspace{1cm} (4.8)

The Pearson’s correlation coefficient measures the strength of the association between the variables on a scale of -1 to +1. A Pearson’s correlation coefficient equal to -1 indicates that a perfectly linear, negative correlation exists. A Pearson’s correlation coefficient with a value of +1 indicates a perfectly linear positive correlation exists. It is important to note that the Pearson’s correlation coefficient only tests for a linear relationship between pairs of variables. Therefore, a Pearson’s correlation of 0 only indicates that a linear correlation does not exist between the variables but does not necessarily indicate that the
variables are not correlated in some other manner (Minitab, 2010). This is demonstrated in the series of scatter plots shown below in Figure 4-3.

(a) $r = -0.93$
Strong Negative Linear Correlation

(b) $r = +0.92$
Strong Positive Linear Correlation

(c) $r = +0.23$
Weak Positive Linear Correlation

(d) $r = 0$
No Linear Correlation

Figure 4-3 – Pearson’s Correlation Coefficient (Minitab, 2010)

4.3.3.2 Correlation Matrix

The Pearson’s correlation coefficients were calculated because ANSYS requires the user to specify the correlation coefficients between each pair of correlated, random variables. The correlation coefficients are stored in a correlation matrix. ANSYS performs a mathematical method known as Cholesky decomposition on the correlation matrix during Monte Carlo simulation. The purpose of this is to ensure that correlations between variables that are known to exist in the real system being simulated are preserved in the simulated system. This ensures that the system is accurately reproduced by the Monte Carlo simulation. The Monte Carlo method and Cholesky decomposition will be discussed in greater detail in Chapter 5.

The correlation matrix is populated by Pearson’s correlation coefficients calculated between each pair of variables being simulated using the Monte Carlo
method. Figure 4-4 below shows a typical correlation matrix for a set of random variables \(x_1, x_2, x_3, \ldots, x_n\)

\[
\begin{bmatrix}
    x_1 & x_2 & x_3 & \cdots & x_j & \cdots & x_n \\
    x_1 & 1 & r_{12} & \cdots & r_{1j} & \cdots & r_{1n} \\
    x_2 & r_{21} & 1 & r_{23} & \cdots & r_{2j} & \cdots & r_{2n} \\
    x_3 & r_{31} & r_{32} & 1 & \cdots & r_{3j} & \cdots & r_{3n} \\
    \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \cdots & \vdots \\
    x_i & r_{i1} & r_{i2} & r_{i3} & \cdots & 1 & \cdots & r_{in} \\
    \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \cdots & \vdots \\
    x_n & r_{n1} & \cdots & \cdots & \cdots & r_{nj} & \cdots & 1
\end{bmatrix}
\]

Figure 4-4 – Correlation Matrix Structure

where: \(r_{ij} = \) Pearson’s correlation coefficient between the pair of variables \(x_i\) and \(x_j\) calculated using Equation (4.8); \(n\) = total number of variables.

The correlation matrix is always symmetric (i.e. \(r_{ij} = r_{ji}\)) and positive definite (i.e. \(x^T R x > 0\) for all vectors \(x \neq 0\) in \(R\)) (Kreyszig, 2000). ANSYS checks if the correlation matrix is positive definite prior to executing the Monte Carlo method and returns an error if the conditions are not satisfied. This will be discussed in greater detail in Chapter 5.

4.3.4 Least Squares Regression Analysis

As mentioned in Chapter 3, the relationship between stress and strain tended to be non-linear at strains approaching ultimate strain and varying significantly between loading conditions. In order to implement these relationships in a finite element model, it was necessary to determine mathematical representations of the non-linear relationships between stress and strain for each loading condition.

The definition of regression analysis is the development of statistical models that can be used to predict values of a response variable based on the values of one or more predictor variables (Levine et al., 2001). The output from a regression analysis is a mathematical expression for the response variable as a function of the predictor variable(s). Regression equations typically take the form of familiar mathematical functions. Common examples include polynomial, logarithmic, exponential or trigonometric expressions. The results from experimental testing
discussed in Chapter 3 show suggest that polynomial relationships exist between stress and strain for the loading conditions examined. Equation (4.9) below shows a general $n^{th}$ order polynomial regression equation.

$$\hat{Y}_i = b_0 + b_1 X_i + b_2 X_i^2 + \cdots + b_n X_i^n$$  \hspace{1cm} (4.9)

where: $b_0, b_1, b_2, \ldots, b_n =$ polynomial regression coefficients; $\hat{Y}_i =$ predicted value of variable $Y$ for observation $i$; $X_i =$ value of variable $X$ at observation $i$

The regression analyses focused on establishing polynomial stress-strain relationships for tension, compression and panel-shear loading.

4.4 Preliminary Investigation

4.4.1 Identifying Probability Distribution Models

4.4.1.1 Method

A preliminary analysis, conducted using Minitab statistical analysis, identified the probability distributions that would be likely to fit the data. A Minitab database populated with the experimental results from longitudinal tension tests conducted on 11 mm thick panels produced by Manufacturer A was used for the preliminary study. Q-Q probability plots were generated to visually inspect the goodness-of-fit between the empirical distribution function (EDF) for each variable and the cumulative distribution function (CDF) for Normal, Lognormal and Weibull probability distribution models. The probability plots generated by Minitab (see Figure 4-5 below) included a summary table containing the Anderson-Darling statistic and corresponding $P$-value.

4.4.1.2 Results

Figure 4-5 below shows a selection of typical probability plots generated by Minitab during the preliminary investigation. The results showed that, of the probability distributions examined, only the normal and lognormal probability distributions were suitable for describing the experimental data.
4.4.1.3 Limitations of Minitab

Although useful for preliminary investigation, Minitab was not particularly suitable for wider use throughout this study. This was partly due to the fact that the database structure does not lend itself well to being continuously updated. The experimental program was carried out over a period of two years. This meant that the experimental results database required constant updating as additional results became available. Furthermore, LabVIEW produced raw experimental data in the form of text (.txt) files while density profile output was in the form of a Microsoft Access database (.mdb). All experimental data required significant further processing prior to statistical analysis. This process would have proved very difficult to automate using Minitab. Additionally, Minitab does not have the capability of outputting data in text (.txt) file format. ANSYS can only read data in text (.txt) file format and it was therefore essential that the results from the statistical analysis could be output in this format.

4.4.1.4 Microsoft Visual Basic for Applications (VBA)

It was decided to develop a series of customised computer programs to overcome the limitations of Minitab identified in the preliminary study. Microsoft Visual
Basic for Applications (VBA) was adopted for this purpose. Microsoft VBA is an object-oriented programming language that runs inside the Microsoft Office Excel environment (Simpson, 2004, Walkenbach, 2004). It was chosen for a variety of reasons including:

- Compatibility with file format used to store raw experimental data,
- Allowed the power of Microsoft Excel’s spreadsheet capabilities, database structures and graphical tools to be automated,
- Relatively straightforward learning curve,
- Capability of outputting results in a format compatible with ANSYS.

### 4.4.2 Stress-Strain Relationships

#### 4.4.2.1 Methods

The experimental results discussion presented in Chapter 3 showed that the relationship between stress and strain varied depending on the type of loading. In order to replicate the material behaviour in a numerical model, it was necessary to develop mathematical models to describe the relationship between stress and strain for each load condition. A preliminary study was conducted using Microsoft Excel to fit linear, quadratic and cubic polynomial expressions to the experimental stress-strain data. The general form of the fitted regression expressions is given in Equations (4.10) to (4.12) below.

\[
\sigma = a\varepsilon \quad (4.10)
\]

\[
\sigma = a\varepsilon + b\varepsilon^2 \quad (4.11)
\]

\[
\sigma = a\varepsilon + b\varepsilon^2 + c\varepsilon^3 \quad (4.12)
\]

where: \( a, b, c \) = polynomial regression coefficients; \( \sigma \) = predicted value of stress at strain value \( \varepsilon \)

#### 4.4.2.2 Results

Figure 4-6 below shows a set of experimental stress-strain results (one set for each loading condition) superimposed with fitted linear, quadratic and cubic regression equations.
Figure 4-6 – Preliminary Stress-Strain Regression Analysis Results

Figure 4-6 above also displays residual plots for each type of regression polynomial for each loading condition. The residual plots are generated by
subtracting the recorded value for stress from the predicted value for stress at each strain value. When the residual plot falls above the horizontal axes, it indicates that the stress value predicted by the model is greater than the recorded value for the range of strain values where the residual plot falls above the horizontal axes. Similarly, the when the residual plot falls below the horizontal axes, it indicates that the stress value predicted by the model is less than the recorded value for the range of strain values where the residual plot falls below the horizontal axes. A perfectly horizontal line that falls on the horizontal axes and passes through the origin indicates that the predicted values and the observed values are exactly equal. Therefore, the closer the residual plot is to a perfectly straight line along the horizontal axes, the better the model fits the recorded data.

Figure 4-6 above shows that the linear model underestimated the stress at low strains and overestimated the stress at failure for all loading conditions. The results indicate that for tension and panel-shear, the relationship between stress and strain was best represented by a quadratic polynomial expression. This is demonstrated by the fact that the residual plots fall almost exactly along the horizontal axis. Higher order polynomial expressions showed no significant improvement in the quality of the model. Therefore, a quadratic regression model was adopted for tension and panel-shear loading.

In the case of 4-point bending, the residual plot in Figure 4-6 above suggested that the cubic model did offer a significant improvement over both the linear and the quadratic models. This is because the residual plot for the cubic polynomial (green) sits noticeably closer to the horizontal axis than the residual plot for the cubic polynomial (red). However, plots of the fitted linear, quadratic and cubic equations superimposed on top of the experimental results showed that all three fitted the experimental results reasonably well. Experimental observations presented in Chapter 3 suggested that behaviour of the tension surface influenced bending failure more than the compression surface. The experimental results show the stress-strain curve in bending is a similar shape to that observed for tension and that the failure modes are also similar. The experimental results also show that the tension strength is lower than the compression strength, suggesting
that the ultimate strength on the tension surface will likely be exceeded prior to the ultimate strength of the compression surface being exceeded. Therefore it was decided to adopt a quadratic model to maintain compatibility with the model used to simulate the tension behaviour. It is possible that the slightly increased curvature shown by the bending stress-strain relationship may be attributed to local compression yielding at high strains on the compression surface. Further research is required to verify this.

In the case of compression, experimental results showed significant non-linear behaviour at high strains. The residual plots shown in Figure 4-6 above clearly demonstrates that relationship between stress and strain was best represented by a cubic polynomial expression. This is because the residual plot obtained for the cubic model falls almost exactly along the horizontal axis whereas the quadratic model deviates noticeably from the horizontal axis.

### 4.4.2.3 Normalised Stress-Strain Relationships

Figure 4-7 below shows a plot of all stress-strain curves observed for A-11mm panels loaded in longitudinal tension. Similar plots for other load conditions and materials are provided in Appendix C.

![Stress-Strain Relationships](image-url)

**Figure 4-7 – Experimental Stress-Strain Curves (Longitudinal Tension, A-11mm Panels)**
Figure 4-7 above demonstrates that even though the relationship between stress and strain is quadratic in all cases, significant variability exists in the response to tension loading in the longitudinal direction. The experimental results show similar degrees of variability for other materials, loading conditions and material directions. These results prompted an investigation to see if this variability could be explained by differences in the fundamental mechanical response or if it was something simpler such as the natural variation in material strength properties.

The experimental stress-strain data for all longitudinal tension tests conducted on A-11mm panels was normalised by dividing the stress and the strain readings for each test specimen by the ultimate strain and ultimate strength. Figure 4-8 below shows plots for the normalised stress-strain data for all longitudinal tension tests conducted on A-11mm panels.

![Normalised Stress-Strain Relationships](image)

**Figure 4-8 – Normalised Stress-Strain Curves (Longitudinal Tension, A-11mm Panels)**

This process was repeated for all other loading conditions and material directions examined by the experimental testing program. A full set of normalised stress vs strain plots is presented in Appendix C. The results demonstrate that normalising the stress-strain data significantly reduces the appearance of this variability. This indicates that the fundamental relationship between stress and strain is similar and that the variability can be explained by natural variation in the strength
properties of the material. Chapter 5 explains the benefits of this result in the context of developing user material model subroutines and replicating the natural variability in the mechanical response of the material in a finite element model.

4.5 **Software Design and Functionality**

4.5.1 **Overview**

A series of computer programs, developed specifically for this study, performed the tasks necessary to convert raw experimental data into a useable format. The programs were written using Microsoft Visual Basic for Applications (VBA) running in the Microsoft Excel 2003 environment. The program consisted of subroutines (referred to as macros) embedded in Excel workbooks. The workbooks included standardised templates stored on worksheets for storing the raw experimental data, the processed experimental data and summary tables for displaying outputs. The software carried out the following tasks:

- Imported raw experimental data from formatted text files data generated from tension, compression, bending, panel-shear, moisture content and density profile tests,
- Processed raw experimental data,
- Generated summary reports for each batch of experimental results,
- Compiled and continuously updated a unified database containing all experimental results,
- Performed goodness-of-fit analyses between experimental results and probability distribution models,
- Performed regression analysis to determine mathematical models to represent the mechanical behaviour of OSB,
- Generated normalised stress-strain relationships for each material,
- Performed correlation analyses to identify relationships between variables,
- Outputted the information required by ANSYS to formatted text files.
Figure 4-9 below gives an outline of how the software works starting with raw experimental data and finishing with a set of inputs that can be used by the ANSYS model.
4.5.2 Experimental Data Processing (Stage 1)

4.5.2.1 Raw Load Test Data

The software included a series of Excel macros for processing raw experimental data. LabVIEW stored raw data in formatted text (.txt) files in units of Volts × 10^6. Four Excel macros were developed, one to process the output from each load test. Each macro was embedded in an Excel workbook and was accompanied by a standard template for displaying results. The tasks performed by the Excel macros included:

- Imported results from formatted text (.txt) files into a spreadsheet,
- Zeroed the readings for load and displacement by subtracting the instrumentation readings recorded at time = 0 from the remaining results,
- Applied the correct gauge factors to convert load and displacement readings from Volts to kN and mm, respectively,
- Looked up the measured cross-sectional dimensions and gauge lengths for each test specimen and calculated stresses and strains from the load and displacement readings,
- Calculated material properties including ultimate strength, ultimate strain and elastic modulus for each test specimen,
- Plotted a series of charts including load versus displacement, load versus crosshead displacement and stress versus strain,
- Removed non-linearities recorded in crosshead displacement readings at beginning of test data due to initial settlement of test specimen and slack in the testing equipment.

The results from each replication were stored in separate files named after the test specimen. The file names used the same convention used to name test specimens as described in Chapter 3 with the addition of the file extension “.xls” (Microsoft Excel format). This prevented confusion as to which test specimen the results file corresponded to. A standardised folder tree was used to store the results files for each batch of tests. The standardised folder tree ensured that the macro for updating the results database did not accidentally omit any results.
4.5.2.2 Load Test Data Processing Macro Interface

Figure 4-10 below shows a screen shot of the interface for the bending test results processing macro. The layout of the interface is similar for all other load test results processing macros.

Figure 4-10 – Screen Shot of Bending Results Processing Macro

The interface has three buttons (labelled “A”) for executing the various macros embedded in the workbook. The cells containing red text (labelled “B” and “C” above) are cells requiring user input.

When processing the results for a new test specimen, the user started by pressing the “Create New Workbook” button to execute a macro for creating a new workbook. The user named the workbook after the test specimen and saved it in the folder for the current batch of test results. This action automatically clears any data already stored in the workbook. The user could also clear any existing data from the workbook manually by pressing “Reset Workbook”. The user entered the names and the relevant gauge factors for the instrumentation equipment at location C according to the NUIG equipment inventory. Failing to do so returns an error, halting the program execution and prompting the user to
fill out this information. On entry of the gauge factors, the program uses them to convert the raw data recorded by LabVIEW from Volts × 10^6 to kN and mm.

The user executed the results processing macro by pressing the “Process Results” button. The macro prompts the user to enter a test specimen number, a nominal thickness and material directions. The macro stores these values at location “B” as shown in Figure 4-10 below. The macro then prompted the user to select the Excel file used to store the test specimen dimensions, followed by the text files containing raw MOE test data and (where relevant) the raw MOR test data file. The macro imports the relevant data into the workbook and processes the results. The macro used the equations presented in Chapter 3 to calculate results such as elastic modulus, failure load, ultimate stress and ultimate strain. A full set of the outputs generated by this series of programs is presented in Appendix B.

4.5.2.3 Load Test Results Summary Report

The software included a series of four (one for each loading condition) macros for generating summary reports for each batch of experimental results. Figure 4-11 below shows a screen shot of the compression test results summary macro.

Figure 4-11 – Screen Shot of Compression Results Summary Macro
The interface consists four buttons (labelled “A”) and two templates with room for storing the results from up to fifteen test specimens. The first table (labelled “B”) stores MOE test results while the second table (labelled “C”) stores MOR test results. The user started a summary report by pressing the “Create New Workbook” button. This executes a macro that prompts the user to enter a new file name and specify the directory where the results to be summarised are stored. The user then pressed the “Summarise Results” button to execute the macro for generating the results summary. The macro prompts the user to enter a nominal thickness, material directions and the file containing moisture content results. The macro searched the results directory for results matching the load test, panel manufacturer, nominal thickness and a material direction specified by the user and imports the results to Tables B and C indicated above. The macro calculated summary statistics for the results batch and displays them in a table (not shown) at the bottom of the workbook. The macro also calculated the covariance and correlation matrices for the results batch and displayed them on separate worksheets. The interface also included a button that allows the moisture content results to be independently updated without having the rerun the entire procedure. This feature was included because moisture content specimens could take up to two weeks to fully dry-out.

4.5.2.4 Raw Density Profile Data

The software included an Excel database containing a list of specimen numbers, the test specimen each specimen was taken from and the panel from which the test specimen was taken. The database is manually populated during sample preparation. The database also includes a series of embedded subroutines for importing and processing raw density profile data. The SCADA software used to monitor the density profile meter (see Figure 3-65 in Chapter 3 above) stored raw density profile data in Microsoft Access database (.mdb) format. The density readings were recorded in Volts while the depths measured were recorded in mm. The Access database also contained information about the density profile specimens including the specimen names, weights, dimensions and gauge factors. The VBA subroutines embedded in the Excel database performed the following tasks:
- Imported the raw density profile data and the specimen information from the Access database into the Excel database,
- Retrieved the specimen names, weights, dimensions, gauge factors and link them to the test specimen and panel from which they were taken,
- Apply the correct gauge factor to the density readings to convert them from Volts to kg/m³,
- Plotted a density profile chart for each specimen,
- Calculated simplified stepped density profile properties and superimpose it on top of the measured density profile for each specimen,
- Plotted a set of charts showing density profile results grouped according to test specimen and panel.

The database includes a template for displaying output from the embedded subroutine. The subroutine exported the density profile plot for each specimen to a separate workbook and linked it to the database using a hyperlink. This was to minimise the file size of the density profile database and overcome the maximum chart limit that can be created in a single Excel file.

4.5.2.5 Density Profile Data Processing Macro Interface

Figure 4-12 below shows a screen shot of the density profile results summary macro. The interface contained 4 buttons (A), a list of density profile specimens, the parent test specimen and panel (B) and a table for displaying the output (C). The user populated the list of specimen numbers, test specimens and parent panels prior to specimen preparation. Reference is made to the database during sampling and each specimen is marked immediately after cutting.

The user started by pressing the “Import Density Data” button. This executed a macro that clears all existing data from the workbook and connected the Excel workbook to the Access database containing raw density profile data. The macro imported the entire contents of the database to the workbook. The macro looped through the list of specimen numbers and linked them to the measured dimensions, raw data and gauge factor for each specimen and displayed the density profile properties on the output table. The macro also calculated the
approximate stepped density profile using the method described in Section 3.6.2.4 in Chapter 3 above.

![Figure 4-12 – Screen Shot of Density Profile Data Processing Macro](image)

Once complete, the macro prompted the user to plot the density profile charts for each specimen followed by the option to generate charts showing density profiles grouped for each test specimen and panel. The chart plotting macros saved all charts to separate Excel workbooks and use hyperlinks to link them to the database. The user could access the density profile plots by clicking on the density specimen number/test specimen name/panel name. The interface also included buttons to allow the user to manually execute the chart plotting macros without first having to import the raw data from the Access database.

### 4.5.3 Experimental Results Database (Stage 2)

#### 4.5.3.1 Overview

Stage 2 of the analysis can be broken into two separate sub-steps. The first sub-step collects all data into a single database. The second step groups results into
categories of similar results and hands them over to Stage 3 where they are analysed and used to generate finite element inputs.

### 4.5.3.2 Database Compilation and Updating

The experimental results database consisted of an Excel workbook subdivided into separate worksheets for containing the data from tension, compression, 4-point bending, panel-shear, moisture content and vertical density-profile tests. The database also included a worksheet for storing the quality control data supplied by Manufacturer A. Each worksheet contained a template for storing experimental data and a macro for importing and updating the worksheet with latest test results. The experimental results database contained a series of embedded macros that performed the following tasks:

- Scanned all experimental results folders and update the worksheet with the latest experimental results,
- Linked load test results to moisture content and density profile results,
- Categorised experimental results according to load test, manufacturer, nominal thickness and load direction.

Further details on the database layout are explained in Section 4.5.3.4 below.

### 4.5.3.3 Categorising Data

A second set of macros scanned the database and broke the results into different categories according to material directions, load test, nominal thickness and panel manufacturer (e.g. longitudinal tension tests conducted on 11 mm thick panels produced by Manufacturer A). In the case of moisture content and density profile data, the results were categorised according to nominal thickness and panel manufacturer (e.g. density profile results performed on 11 mm panels produced by Manufacturer A). As is the case with the macros for building and updating the database, each worksheet had its own macro for categorising results contained in the worksheet. Each macro outputs the list of categories to a specific location on the relevant worksheet. Further details on the database layout are explained in Section 4.5.3.4 below.
4.5.3.4 User Interface

Figure 4-13 below shows a screen shot taken of the tension results worksheet from the experimental results database workbook. The databases for compression, panel-shear, bending, moisture content and density profile results followed a similar format.

![Screen Shot of Experimental Results Database](image)

The worksheet contains five buttons (labelled “A”) at the top left hand corner, a list of field names (labelled “B”) and the database (labelled “C”). The button labelled “Import Tension Results” executed the macro for updating the tension results database. The macro scanned only folders containing tension results and adds any newly found results to the bottom of the database below the last entry. Two more buttons labelled “Import Moisture Content” and “Import Density Profile” could be used to execute macros that scan the list of test specimens and retrieve moisture content and density profile results corresponding to each tension test specimen. Below that is a button labelled “Analyse”. This button executes the macro that categorises the results contained in the tension worksheet and calls the subroutines for analysing the data and generating the finite element input files.
The interface design allowed the user to update and re-analyse only worksheets affected by changes to the experimental data. For example, if an additional batch of tension tests is performed, then the tension results worksheet can be updated and re-analysed without having to re-run the analysis for the compression, bending or panel-shear databases. The macro also hyperlinks the experimental results files to the test specimen names thus allowing the user to retrieve the test results file for each test specimen by pressing on the specimen name.

4.5.4 Data Analysis (Stage 3)

4.5.4.1 Overview
Stage 3 involves the statistical analysis of the data. A number of macros embedded in the results database workbook performed the necessary tasks to determine suitable probability distributions, non-linear mathematical models to represent mechanical behaviour and correlations between parameters.

4.5.4.2 Goodness-of-Fit Analysis
The first of the data analysis macros used probability plots as described in Section 4.3.1 above and the Anderson-Darling test (Anderson and Darling, 1952) as described in Section 4.3.2 above to select suitable probability distributions to describe the natural variability of each variable. Results from the preliminary study (see Section 4.4.1 above) suggested that only the normal and lognormal probability distributions be considered.

The subroutine sequentially processed each variable and selected the probability distribution with the higher $P$-value as the best-fitting probability distribution. Any $P$-values that fell below the level of significance ($\alpha = 0.05$) prompted the subroutine to reject the null hypothesis (i.e. the probability distribution is not appropriate for simulating the variable). In cases where the subroutine rejected both normal and lognormal probability distributions, the variable was assumed to be uniformly distributed. The probability plots complemented the Anderson-Darling test by providing a visual assessment of the goodness-of-fit but did not form the basis for choosing the more appropriate probability distribution. The subroutine stored the goodness-of-fit results for each category in separate
workbooks. The reasons for this were to minimise the size of the experimental results database and to overcome the limits on the maximum number of charts that can be generated in a single Excel file. The experimental results database contained tables for summarising the goodness-of-fit results. The subroutine populated the summary table with the key results and used hyperlinks to link the workbooks containing the analysis to the experimental results database for easy retrieval.

4.5.4.3 Correlation Matrix

The second set of the data analysis subroutines generated correlation matrices for each category. The macro calculates each entry in the correlation matrix using the Pearson’s correlation coefficient formula as described in Section 4.3.3.1 above. The macro includes a routine for checking the positive, definiteness of the correlation matrix to ensure that the matrix satisfied the criteria prior to passing it over to ANSYS. The macro saved the correlation matrices in separate workbooks and linked them to the database using hyperlinks.

4.5.4.4 Stress-Strain Relationship

The third of the data analysis subroutines performed least-squares regression analyses as described in Section 4.3.4 above to fit a mathematical expression to describe the relationship between stress and strain. The subroutine used Excel’s “LINEST” function (Microsoft, 2003) to fit quadratic and cubic polynomial expressions to experimental stress-strain data for each test specimen.

The subroutine generated separate workbooks for each load condition and imported the experimental stress-strain data for each test specimen. The subroutine inserted hyperlinks in the experimental results database to link the results file to the database for easy retrieval. The subroutine plotted all experimental stress-strain curves on a single chart similar to the one shown above in Figure 4-7 above. The subroutine normalised the experimental data by dividing the stress and the strain results by the ultimate strength and ultimate strain for each test specimen. The subroutine plotted and superimposed the normalised stress-strain curves for all results in the category on a single chart similar to the one shown in Figure 4-8 above.
Once complete, the subroutine generated average stress-strain curves for each results category from both the original and normalised stress-strain data. Average curves were generated by calculating the mean stress along lines of constant strain (Clouston and Lam, 2001, Clouston, 2001, Clouston and Lam, 2002, McTigue and Harte, 2011). The subroutine generated charts showing the average stress-strain curves and the associated 95% confidence intervals for both original data and normalised data.

4.5.4.5 Statistical Analysis Output Window

Figure 4-14 below shows a screen shot of the statistical analysis output window for the tension test results. The output window is stored on the same worksheet as the tension results database. The output windows for all other test data follow a similar format.

The window displays the results from the statistical analyses and the hyperlinks to any external workbooks used during the analyses. The macro distinguishes between categories by inserting a heavy black line horizontally across the table,
indicating the end of one category and the beginning of the next as indicated by label A in Figure 4-14 above. The results table contains a list of relevant properties, the results of the probability distribution analysis for each property and the descriptive statistics calculated as indicated by label B. The descriptive statistics presented in this table are calculated using the formulae appropriate to the probability distribution. The table also displays hyperlinks (label C) to all external workbooks created during the analysis under the heading “Available Results”.

### 4.5.4.6 FE Model Inputs

The fourth and final data analysis subroutine collected the results from the preceding analyses described in Sections 4.5.4.2, 4.5.4.3 and 4.5.4.4 above and generated the finite element inputs required by ANSYS including:

- Probability distribution and associated parameters for each variable,
- Correlation matrix,
- Normalised stress-strain relationship,
- Regression coefficients for normalised stress-strain relationships.

The subroutine standardised all number formats and outputted the results to formatted text (.txt) files. The subroutine used text files to store output because ANSYS cannot read data directly from Excel (.xls) files. The macro outputted all results files to a standard location where ANSYS would search for the relevant information during model execution. The full details of the inputs required by the ANSYS model will be discussed in Chapter 5.

### 4.6 Outputs

#### 4.6.1 Goodness-of-Fit Analysis

#### 4.6.1.1 Results

Table 4-1 below shows a sample table containing the results of the goodness-of-fit analysis for tensile ultimate strength in both material directions. A full set of results is presented in Appendix C.
### Tensile Ultimate Strength

<table>
<thead>
<tr>
<th>Panel</th>
<th>Normal $A^2_{adj}$</th>
<th>Normal P-Value</th>
<th>Lognormal $A^2_{adj}$</th>
<th>Lognormal P-Value</th>
<th>Conclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-11mm</td>
<td>0.262</td>
<td>0.703</td>
<td>0.218</td>
<td>0.841</td>
<td>Lognormal</td>
</tr>
<tr>
<td>A-15mm</td>
<td>0.334</td>
<td>0.508</td>
<td>0.514</td>
<td>0.193</td>
<td>Normal</td>
</tr>
<tr>
<td>A-18mm</td>
<td>0.752</td>
<td>0.047</td>
<td>0.612</td>
<td>0.104</td>
<td>Lognormal</td>
</tr>
<tr>
<td>B-15mm</td>
<td>0.410</td>
<td>0.343</td>
<td>0.346</td>
<td>0.482</td>
<td>Lognormal</td>
</tr>
<tr>
<td>C-15mm</td>
<td>0.534</td>
<td>0.172</td>
<td>0.748</td>
<td>0.048</td>
<td>Normal</td>
</tr>
<tr>
<td>A-SURF</td>
<td>0.500</td>
<td>0.208</td>
<td>0.577</td>
<td>0.134</td>
<td>Normal</td>
</tr>
<tr>
<td>Lateral</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-11mm</td>
<td>0.189</td>
<td>0.902</td>
<td>0.422</td>
<td>0.322</td>
<td>Normal</td>
</tr>
<tr>
<td>A-15mm</td>
<td>0.327</td>
<td>0.519</td>
<td>0.311</td>
<td>0.553</td>
<td>Lognormal</td>
</tr>
<tr>
<td>A-18mm</td>
<td>0.211</td>
<td>0.859</td>
<td>0.369</td>
<td>0.427</td>
<td>Normal</td>
</tr>
<tr>
<td>B-15mm</td>
<td>1.043</td>
<td>0.009</td>
<td>1.096</td>
<td>0.006</td>
<td>Uniform</td>
</tr>
<tr>
<td>C-15mm</td>
<td>0.486</td>
<td>0.226</td>
<td>0.418</td>
<td>0.329</td>
<td>Lognormal</td>
</tr>
<tr>
<td>A-SURF</td>
<td>0.464</td>
<td>0.255</td>
<td>0.435</td>
<td>0.300</td>
<td>Lognormal</td>
</tr>
</tbody>
</table>

Table 4-1 – Goodness-of-Fit Results for Tensile Ultimate Strength

Figure 4-15 below presents typical Q-Q probability plots for tensile ultimate strength for the A-11mm panels using both Normal and Lognormal distributions.

![Q-Q Probability Plot (Normal)](image)

![Q-Q Probability Plot (Lognormal)](image)

Figure 4-15 – Typical Q-Q Probability Plots

Figure 4-16 below presents typical P-P probability plots for tensile ultimate strength for the A-11mm panels using both Normal and Lognormal distributions. A full set of probability plots is presented in Appendix C.
4.6.1.2 Discussion

Table 4-1 above demonstrates that for tensile ultimate strength in the longitudinal direction, either normal or lognormal probability distribution models are suitable for describing the variability observed in the experimental data for the majority of cases. The full set of results presented in Appendix C show that this is also true for the majority of the other mechanical properties that were experimentally evaluated by this study. In some cases, where neither normal nor lognormal probability distributions fit the data, the discussion of the experimental results presented in Chapter 3 had already highlighted irregularities in the some individual results. This is likely to be a contributing factor in failing to determine the best fitting probability distribution model. For the other cases, it is likely that the sample size is too small to capture the underlying probability distribution or that the variables involved follow probability distributions other than those covered in this study. Expanding the experimental testing program to include larger sample sizes would likely solve this problem.

In the case of the physical properties, the results demonstrate that, for the majority of cases, either normal or lognormal probability distribution models are suitable for describing the variability observed in experimental data. Notable
exceptions include moisture content, total thickness and surface damage thickness. Of these quantities, this study did not investigate the influence of moisture content on mechanical behaviour. Moisture content was only evaluated as a quality control procedure rather than to consider it as a variable. In the case of surface damage thickness, exceptionally high variability in this quantity was observed and suggested that it is partially due to inadequate resolution of the density profile scanner to properly measure the small depths involved. In the case of total thickness, it is likely that this quantity comes from a probability distribution other than those considered in this study considering the substantial sample size should be sufficient to capture the underlying probability distribution.

The probability plots demonstrate that it is quite difficult to determine the better fitting probability distribution by visual inspection. This highlights the benefits of the Anderson-Darling test when choosing the probability distribution that best describes the variability of the sample. The results also indicated that it is impossible to say, for example, that the tensile ultimate strength in the longitudinal direction always follows a lognormal distribution. The results tend to suggest that all properties are non-stationary (i.e. that the probability distribution the sample follows varies with time). Previous studies have made similar observations in solid wood and methods have been developed to include such effects (Lam and Barrett, 1992, Lam et al., 1994, Wang et al., 1995). Non-stationary probabilistic analysis is beyond the scope of the present study.

4.6.2 General Stress-Strain Relationships

4.6.2.1 Results

Figure 4-17 below shows sample averaged stress-strain relationships along with 95% confidence intervals for the A-11mm panels loaded in longitudinal tension using the original experimental data. Figure 4-18 below shows sample averaged stress-strain relationships along with 95% confidence intervals for the A-11mm panels loaded in longitudinal tension using the normalised experimental data. A full set of averaged stress-strain curves is presented in Appendix C.
4.6.2.2 Discussion

The results demonstrate that normalising the experimental stress-strain data as described in Section 4.4.2.3 above proves, for example, that the mechanical behaviour of all A-11mm panels is fundamentally the same when tension load is applied in the longitudinal direction. Comparing the 95% confidence interval for
the average stress-strain curve generated from the normalised data with that generated from the original data shows the normalised curve is much less variable and did not display discontinuities at high strains. Conversely, the goodness-of-fit analysis shows that ultimate strength and ultimate strain vary according to either normal or lognormal probability distributions. This suggests that the variability in mechanical behaviour demonstrated in Figure 4-7 above results from variations in the values of ultimate strength and ultimate strain.

Additionally, Figure 4-19 below shows the averaged normalised stress-strain curves for all materials loaded in direct tension/compression in both material directions.

![Figure 4-19 – Average Normalised Stress-Strain Curves (Direct Loading, All Materials)](image)

The results demonstrate that the fundamental mechanical behaviour is almost identical for all materials in both material directions. This further strengthens the claim that the variations in mechanical behaviour are primarily a result of variations in the values of ultimate strength and strain. This proved extremely useful when modelling the material behaviour as will be discussed in Chapter 5. In the case of direct loading, the smooth transition from tension to compression behaviour is in keeping with the design code practice of specifying equal elastic moduli for tension and compression at low strains.
Furthermore, Figure 4-20 below shows an overlay of the averaged normalised stress-strain curve for the A-SURF panels subject to direct loading on top of the averaged normalised stress-strain curve for the A-11mm panels subject to bending.

![Normalised Stress vs Normalised Strain](image)

**Figure 4-20 – Direct Stress-Strain for A-SURF-LONG on Bending Curve for A-11-LONG**

The results demonstrate that in positive strains (i.e. tensile loading), the curves sit almost perfectly on top of each other. For negative strain (i.e. compressive loading), Figure 4-20 above shows the averaged normalised stress-strain curve for bending deviates from the average normalised stress-strain curve for direct loading. This strengthens the claim made in Chapter 3 that bending behaviour is governed primarily by the behaviour of the tension surface.

### 4.6.3 Correlation Analysis

#### 4.6.3.1 Results

Table 4-2 below presents part of correlation matrix containing the Pearson’s correlation coefficient between each pair of variables relating to the A-11mm panels when loaded in longitudinal tension. The entries of the correlation matrix are calculated using the Pearson’s correlation coefficient formula as given by Equation (4.8) above.

<table>
<thead>
<tr>
<th>Normalised Stress, $\sigma/\sigma_u$</th>
<th>Normalised Strain, $\varepsilon/\varepsilon_u$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1.00</td>
<td>-1.00</td>
</tr>
<tr>
<td>-0.75</td>
<td>-0.75</td>
</tr>
<tr>
<td>-0.50</td>
<td>-0.50</td>
</tr>
<tr>
<td>-0.25</td>
<td>-0.25</td>
</tr>
<tr>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>0.75</td>
<td>0.75</td>
</tr>
<tr>
<td>1.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>
Chapter 4: Statistical Analysis

Anthony McTigue

Table 4-2 – Partial Correlation Matrix for A-11mm Panels

<table>
<thead>
<tr>
<th></th>
<th>$\sigma_{ut}$</th>
<th>$\varepsilon_{ut}$</th>
<th>$\rho_{s,L}$</th>
<th>$\rho_{s,R}$</th>
<th>$t_s$</th>
<th>$t_c$</th>
<th>$t_{dam,L}$</th>
<th>$t_{dam,R}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{ut}$</td>
<td>1.000</td>
<td>0.613</td>
<td>0.154</td>
<td>0.317</td>
<td>0.398</td>
<td>-0.543</td>
<td>-0.332</td>
<td>0.261</td>
</tr>
<tr>
<td>$\varepsilon_{ut}$</td>
<td>0.613</td>
<td>1.000</td>
<td>0.029</td>
<td>0.084</td>
<td>0.224</td>
<td>-0.504</td>
<td>-0.280</td>
<td>0.315</td>
</tr>
<tr>
<td>$\rho_{s,L}$</td>
<td>0.154</td>
<td>0.029</td>
<td>1.000</td>
<td>0.855</td>
<td>0.735</td>
<td>-0.162</td>
<td>0.138</td>
<td>-0.243</td>
</tr>
<tr>
<td>$\rho_{s,R}$</td>
<td>0.317</td>
<td>0.084</td>
<td>0.855</td>
<td>1.000</td>
<td>0.888</td>
<td>-0.214</td>
<td>-0.038</td>
<td>0.001</td>
</tr>
<tr>
<td>$\rho_{c}$</td>
<td>0.398</td>
<td>0.224</td>
<td>0.735</td>
<td>0.888</td>
<td>1.000</td>
<td>-0.449</td>
<td>-0.244</td>
<td>0.186</td>
</tr>
<tr>
<td>$t_s$</td>
<td>-0.543</td>
<td>-0.504</td>
<td>-0.162</td>
<td>-0.214</td>
<td>-0.449</td>
<td>1.000</td>
<td>0.339</td>
<td>-0.457</td>
</tr>
<tr>
<td>$t_c$</td>
<td>-0.332</td>
<td>-0.280</td>
<td>0.138</td>
<td>-0.038</td>
<td>-0.244</td>
<td>0.339</td>
<td>1.000</td>
<td>0.016</td>
</tr>
<tr>
<td>$t_{dam,L}$</td>
<td>0.261</td>
<td>0.315</td>
<td>-0.243</td>
<td>0.001</td>
<td>0.186</td>
<td>-0.457</td>
<td>0.016</td>
<td>1.000</td>
</tr>
<tr>
<td>$t_{dam,R}$</td>
<td>0.017</td>
<td>0.012</td>
<td>-0.051</td>
<td>-0.050</td>
<td>-0.031</td>
<td>-0.127</td>
<td>0.405</td>
<td>0.532</td>
</tr>
</tbody>
</table>

Note that both mechanical and physical properties are included in the correlation matrix. As mentioned in Section 4.3.3.2 above, the role of the correlation matrix is to enable the Monte Carlo method to reproduce the effects that physical properties have on the mechanical properties. The inclusion of both in the correlation matrix will allow ANSYS to represent the relationships between the physical and mechanical properties during model execution. This will be discussed in more detail in Chapter 5.

4.6.3.2 Discussion

The correlation matrix shown in Table 4-2 is both symmetric about the main diagonal and positive definite. This satisfies the conditions required to perform Cholesky decomposition performed by ANSYS during the Monte Carlo simulation process. The values of the entries suggest varying degrees of correlation exist between pairs of variables. For example, a value of 0.613 calculated between the tensile ultimate strength and tensile ultimate strain suggests a moderate positive correlation exists between these variables. A value of -0.543 calculated between the tensile ultimate strength and the core thickness indicates a moderate negative correlation exists between these variables.

Since the Pearson’s correlation coefficient is calculated based on the assumption of a linear relationship between the two variables, the correlation matrix is a convenient method for summarising the results from a series of linear regression analyses. Figure 4-21 below shows a regression plot of tensile ultimate strength versus tensile ultimate strain.
Figure 4-21 – Tensile Ultimate Strength vs Tensile Ultimate Strain (A-11-LONG)

The figure shows a regression plot of tensile ultimate strength versus core thickness. The equation for the line of best fit is:

\[
y = 2321.3x + 3.8044\]

with a coefficient of determination, \(R^2 = 0.3753\).

Figure 4-22 – Tensile Ultimate Strength vs Core Thickness (A-11-LONG)

The figure shows a regression plot of tensile ultimate strength versus core thickness. The equation for the line of best fit is:

\[
y = -1.3327x + 19.484\]

with a coefficient of determination, \(R^2 = 0.1104\).

Figure 4-21 above shows that a moderately strong linear positive correlation exists between tensile ultimate strength and tensile ultimate strain. Figure 4-22 above shows that a moderately strong linear negative correlation exists between
tensile ultimate strength and core thickness. The coefficients of determination ($r^2$) shown on Figure 4-21 and Figure 4-22 above are the squares of the Pearson’s correlation coefficients. Both of these results were also detected by the Pearson’s correlation matrix.

4.7 Concluding Remarks

4.7.1 Statistical Methods

The statistical methods described in Section 4.3 above were performed to generate inputs required by the stochastic FE model using the database generated by the experimental testing program described in Chapter 3. The methods used successfully fulfilled this role. The Anderson-Darling test described in Section 4.3.2 above effectively assessed the goodness of fit between the EDF of a parameter and the CDF of the probability distribution model. Probability plots as described in Section 4.3.1 above provided a graphical representation of the goodness-of-fit between the EDF and the CDF for the purpose of discussion but were not sufficient to draw definitive conclusions. Least squares regression analysis as described in Section 4.3.4 above successfully established non-linear mathematical models to describe the relationship between stress and strain for each loading condition. The Pearson’s correlation coefficient as described in Section 4.3.3 above effectively determined correlation matrices to describe the inter-dependence of each parameter in both single-layer OSB and commercial OSB/3 panels.

4.7.2 Software Design and Development

The software suite described in Section 4.5 above that was specifically developed for this study played a vital part in processing, managing and interpreting the results from the experimental testing program and to produce the necessary inputs required by the stochastic FE model. The in-built database management structures, graphical analysis tools and worksheet functions in Microsoft Excel 2003 proved to be an extremely effective tool in assisting with this role. Automating the process using MS VBA significantly reduced the time involved in performing repetitive tasks and ensured that the finite element model inputs
were based only on the most up-to-date information. The relatively learning
curves for both MS Excel and MS VBA contributed significantly the relatively
short time spent developing the software. The capability of outputting results into
formatted text files played a significant role because many of the stochastic
model runs had to be performed across multiple computers over periods lasting
several days. It was therefore essential that information could be automatically
exchanged between the Excel and ANSYS using formatted text files without
human intervention. Model runs would have taken significantly longer if they
had to be paused while the user provided input or if the user had to manually
update the input files to reflect the results from additional experimental data.

4.7.3 Results
The results from the goodness-of-fit analyses discussed in Section 4.6.1 above
show that in the majority of cases, the variability in the sample results can be
represented by either normal or lognormal distributions with good accuracy. The
goodness-of-fit analysis results also showed that the sample sizes used in the
experimental testing program described in Chapter 3 were sufficient to capture
the underlying probability distribution for most cases. The results also hinted that
many of the parameters are non-stationary (i.e. the probability distribution
changes with time). The results from the least squares regression analysis
discussed in Section 4.6.2 above show that polynomial regression models are
effective at representing the non-linear mechanical behaviour under a variety of
loading conditions. The results show that quadratic polynomials are suitable for
representing the mechanical behaviour in tension, bending and panel-shear
loading whereas cubic polynomials are suitable for representing the mechanical
behaviour in compression. The normalised stress-strain curves discussed in
4.4.2.3 above showed that the mechanical behaviour of all materials tested is
fundamentally the same for all materials tested. The benefits of this are explained
in more detail in Chapter 5. The results from the correlation analysis discussed in
Section 4.6.3 above show that relationships exist between many pairs of
variables evaluated by the experimental testing program. This proved important
in terms of accurately simulating the system using Monte Carlo simulation as
discussed in Chapter 5. The correlation matrices discussed in Section 4.6.3.2
were found to satisfy the condition of positive definite as required by ANSYS in order to perform Cholesky decomposition as discussed in greater detail in Chapter 5.
Chapter 5 – Numerical Modelling

5 Numerical Modelling

5.1 Introduction

This chapter describes a stochastic finite element model that was developed based on the results from the experimental testing presented in Chapter 3 and the results from the statistical analysis program described in Chapter 4. The aims of developing this model were to accurately represent the mechanical behaviour, the key physical properties influencing the mechanical behaviour and random variability observed in experimental data for commercial OSB/3 products. The approach used followed a similar format to that used by the fibre reinforced polymers industry whereby the behaviour of multi-ply, cross-laminated materials can be predicted based on the results of uniaxial tests conducted on single-plies. The model was developed using ANSYS Multiphysics 12.1 finite element analysis software. The capabilities of this software include probabilistic design in the form of Monte Carlo simulation, layered elements for modelling multi-ply, cross-laminated materials and the facility for the user to include customised user material model subroutines.

The model used the Monte Carlo method to simulate the vertical density profile for commercial 18 mm thick OSB/3 panels produced by Manufacturer A by randomly generating the layer-densities and thicknesses based on the stepped model described in Section 3.6.2.4 in Chapter 3 above. The input parameters were generated by the computer program described in Section 4.5 in Chapter 4 above using the results of density profile testing for these panels. The model used a seven-layer lamination model as described in Section 5.7.2 below to discretise the panels into layers according to layer density and strand orientation.

The orthotropic, non-linear mechanical behaviour observed in the experimental results was modelled using a user material model subroutine described in Section 5.6 below. The user material model used the normalised stress-strain curves described in Section 4.6.2 in Chapter 4 above for the single-layer OSB panels to model the mechanical behaviour of the plies comprising commercial 18 mm thick OSB/3 panels produced by Manufacturer A. The model simulated the
variability observed in the mechanical behaviour by using Monte Carlo simulation to randomly generate values for ultimate stress and ultimate strain. The subroutine was validated by using it to reproduce the experimental observations for the single-layer OSB panels. Its usefulness in the OSB industry was demonstrated by using it to predict the mechanical behaviour for commercial 18 mm thick OSB/3 panels produced by Manufacturer A.

The results showed that the combination of lamination approach, probabilistic design, a new user material model subroutine and the finite element method was highly effective. The model accurately predicted the mechanical behaviour and variability of commercial 18 mm thick OSB/3 panels produced by Manufacturer A. This approach could be applied to any other OSB/3 product regardless of density profile, panel lay-up or manufacturer provided that information is available about the behaviour and variability of the constituent layers.

5.2 Scope of Numerical Modelling

Modelling a mechanical system can be defined as the mathematical idealisation of the physical processes governing its evolution (Sudret and Kiureghian, 2000). The modeller must distinguish between input parameters (e.g. geometry, applied loading, material properties) and response parameters (e.g. stress, strain, displacement) prior to attempting to model a mechanical system. Mathematical expressions commonly referred to as constitutive equations are used to characterise the relationships between the input parameters and the response parameters. The numerical modelling program aimed to:

- Model the internal structure of commercial OSB/3 panels taking into account the relative thicknesses of high and low density layers and the panel lay-up based on the results of the experimental testing program discussed in Chapter 3 above,
- Model the orthotropic, non-linear mechanical behaviour observed in the experimental testing program discussed in Chapter 3 above,
- Model the variability of the internal structure, material properties and mechanical behaviour of OSB/3 panels,
- Model the relationships between parameters observed in the statistical analysis program as discussed in Chapter 4 above,
- Predict the resultant properties and mechanical behaviour of commercial 18 mm thick OSB/3 panels produced by Manufacturer A based on the properties of their constituent layers.

5.3 **Laminated Plate Theory**

5.3.1 **Background**

Laminated plate theory evolved from the general form of Hooke’s law. It allows the resultant properties of a multi-ply, cross-laminated fibre reinforced composite to be calculated from the properties of single-plies of the same material assessed by simple uniaxial load tests. It is widely used in the fibre-reinforced composites industry in the design of structures such as aircraft fuselage and wing structures.

Many commercial finite element codes including ANSYS Multiphysics and ABAQUS include subroutines for applying laminated plate theory.

Single-plies of fibre reinforced polymers tend to exhibit much higher degrees-of-orthotropy than cross-laminated, multi-ply fibre-reinforced composites made from the same ply material. The introduction of fibres in multiple directions results in enhancement of properties in more than one direction. Increasing the number of layers and fibre orientations means that the volume fraction of fibres aligned in any one direction reduces. Reducing the volume fraction of fibres causes in any one direction reduces the resultant properties in that direction. The net result of the introduction of fibres in multiple directions is that the material becomes less anisotropic and more isotropic.

OSB exhibits many similar characteristics to laminated fibre-reinforced composites both in terms of its laminated construction and its mechanical behaviour. The wood strands in OSB are analogous to the reinforcing fibres in fibre-reinforced composites while the thermosetting resin binder is analogous to the polymer resin. The three-ply construction of OSB panels as shown in Chapter 1 is similar to the concept of cross-laminating layers of fibre reinforced polymers. The experimental results discussed in Chapter 3 also proved
conclusively that single-layer OSB panels displayed significantly higher degrees-of-orthotropy than the standard three-layer commercial OSB/3 panels. The uniaxial experimental testing of single plies of OSB has provided the necessary material property and behaviour data for single OSB plies to facilitate the application of laminated plate theory to OSB panels with varying lay-ups.

5.3.2 Hooke’s Law

Hooke’s law is the fundamental constitutive equation used to describe the linear elastic behaviour of a general anisotropic material subjected to a state of multiaxial stress. The general tensorial form of Hooke’s law is presented below in Equation (5.1) below.

$$\sigma_{ij} = C_{ijkl} \varepsilon_{kl} \quad (5.1)$$

where: $i, j, k, l = 1, 2, 3, 4$

The fourth-order stiffness tensor $(C_{ijkl})$ relates nine the components of the stress tensor $(\sigma_{ij})$ to the nine components of the strain tensor $(\varepsilon_{kl})$. The stiffness tensor in its general form is populated with 81 stiffness coefficients. Fortunately, equilibrium requirements mean that both stress and strain equilibrium results are symmetric, thereby reducing the number of independent stresses and strains from nine to six each while the stiffness tensor is reduced from 81 to 36 coefficients (Vinson and Sierakowski, 1987, Clouston, 2001). Substituting into Equation (5.1) for the zero-value stiffness coefficients and transforming the coordinate system from index to global Cartesian yields Equation (5.2) below.

$$\begin{bmatrix}
\sigma_x \\
\sigma_y \\
\sigma_z \\
\tau_{xy} \\
\tau_{yz} \\
\tau_{xz}
\end{bmatrix} =
\begin{bmatrix}
C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\
C_{21} & C_{22} & C_{23} & 0 & 0 & 0 \\
C_{31} & C_{32} & C_{33} & 0 & 0 & 0 \\
0 & 0 & 0 & 2C_{44} & 0 & 0 \\
0 & 0 & 0 & 0 & 2C_{55} & 0 \\
0 & 0 & 0 & 0 & 0 & 2C_{66}
\end{bmatrix}
\begin{bmatrix}
\varepsilon_x \\
\varepsilon_y \\
\varepsilon_z \\
\gamma_{xy}/2 \\
\gamma_{yz}/2 \\
\gamma_{xz}/2
\end{bmatrix} \quad (5.2)$$

where: $\sigma_x$, $\sigma_y$, $\sigma_z$ are normal stresses in principal material directions; $\tau_{xy}, \tau_{yz}, \tau_{xz}$ are shear stresses in principal material directions; $\varepsilon_x$, $\varepsilon_y$, $\varepsilon_z$ are normal strains in principal material directions; $\gamma_{xy}, \gamma_{yz}, \gamma_{xz}$ are shear strains in principal material directions; $C_{11}, C_{12}, C_{13}, C_{21}, C_{22}, C_{23}, C_{31}, C_{32}, C_{33}, C_{44}, C_{55}, C_{66}$ are the stiffness terms
The stiffness terms are calculated based on the mechanical properties of the unidirectional plies that make up the laminate according to Equation (5.3) below.

\[
\begin{align*}
C_{11} &= E_{xx}(x - \nu_{yz} v_{yy})/\Delta, \\
C_{22} &= E_{yy}(x - \nu_{zx} v_{xz})/\Delta, \\
C_{33} &= E_{zz}(x - \nu_{xy} v_{yx})/\Delta, \\
C_{12} &= (\nu_{yx} + \nu_{zx})E_{xx}/\Delta = (\nu_{xy} + \nu_{yz} v_{xz})E_{yy}/\Delta, \\
C_{13} &= (\nu_{zx} + \nu_{yz})E_{xx}/\Delta = (\nu_{xy} + \nu_{yx} v_{yx})E_{zz}/\Delta, \\
C_{23} &= (\nu_{zy} + \nu_{xy} v_{yx})E_{yy}/\Delta = (\nu_{yz} + \nu_{yx} v_{xy})E_{zz}/\Delta, \\
\Delta &= x - \nu_{xy} v_{yx} - \nu_{yz} v_{xy} - \nu_{zx} v_{xz} - 2\nu_{yx} v_{zy} v_{xz}
\end{align*}
\]

where: \( \nu_{xy}, \nu_{yx}, \nu_{yz}, \nu_{zy}, \nu_{zx}, \nu_{xz} \) are the Poisson’s ratios in the principal material directions; \( E_{xx}, E_{yy}, E_{zz} \) are the elastic moduli in the principal material directions; \( G_{yx}, G_{yz}, G_{xz} \) are shear moduli in the principal material directions.

ANSYS Multiphysics implements laminated plate theory using layered elements. This is discussed in further detail in Section 5.6.8.5 below.

### 5.4 Stochastic Finite Element Method

#### 5.4.1 Background

A stochastic system is defined as a system that for a given initial condition is not guaranteed to produce the same output due to the presence of a random process in the system (Sudret and Kiuereghan, 2000). The counterpart of a stochastic system is a deterministic system whereby the output for a given initial condition will always be the same. Engineering structures are inherently stochastic due to random variations in applied loads, material properties and geometric tolerances. Design codes traditionally rely on deterministic approaches with appropriate factors of safety applied to the input parameters to simplify the design of structural elements while still ensuring a safe design. Recent trends in design codes have seen a move away from traditional factor of safety methods and have instead begun to adopt reliability based methods.

Structural elements consisting of wood-based materials including OSB pose a unique set of challenges due to the large number of material properties required
to define their mechanical behaviour and the variability associated with each of these properties. The application of deterministic models in the design of structural elements consisting of wood-based materials requires high factors of safety compared to those associated with other materials. Stochastic modelling offers significant benefits to designers because it enables them to examine the significance of the randomness of the defining parameters on the overall structural response. The results of stochastic modelling methods enable designers to calculate the probability of failure under various design scenarios. This offers significantly improved design efficiency while still ensuring a safe design.

5.4.2 Monte Carlo Simulation

Monte Carlo simulation is a generic term that is used to describe a family of methods that create simulated sample sets of values for a random parameter using random number generation based a uniform probability distribution in the range \([0, 1]\) (Kohnke, 2009b, Robert and Casella, 2004, Billo, 2007). Each randomly generated number represents a probability of occurrence of a particular value of the simulated parameter. If the simulated parameter is known to follow a certain probability distribution, then for any randomly generated number, the value of the simulated parameter that has a probability of occurrence equal to that number can be calculated by inverting the probability density function. It is therefore necessary to obtain information about the probability distribution that the simulated parameter follows prior to using Monte Carlo simulation methods.

One of the benefits of Monte Carlo simulation is that it enables a relatively small sample of experimental data to be used to artificially generate large simulated sample sets. Small-sample experimental programs are designed to generate enough data to determine a suitable probability distribution model to describe the input parameter of a system. Monte Carlo simulation is performed to generate large simulated sample sets for the input parameter. Each simulation loop in a Monte Carlo simulation is analogous to performing a single experimental replication to evaluate the parameter. The constitutive equations are used to calculate the value of the response parameter for each simulated value of the
input parameter in the simulated sample set. The output from this type of analysis is a predicted sample set for the response parameter.

The predicted sample set for the response parameter can be used to perform various statistical analyses in a similar manner to performing statistical analyses on a sample set of experimental data. It can be used to determine probability distribution models to describe the variability of the response parameter and perform sensitivity studies to determine the impact of the randomness of the input parameter on the response of the system. This approach is summarised below in Figure 5-1.

![Monte Carlo Simulation Schematic](image)

**Figure 5-1 – Monte Carlo Simulation Schematic**

### 5.4.3 Multi-variate Systems

Section 5.4.2 above discusses Monte Carlo simulation mainly in the context of single variate systems i.e. the system can be characterised by a single input parameter. However, most engineering systems require two or more input parameters to define them, thus making them bi-variate or multi-variate systems.

In multi-variate systems, careful consideration must be given to correlations between input variables when simulating the system using the Monte Carlo
method. Commercial computer routines generally require the user to specify the covariance or Pearson’s correlation coefficient between correlated input variables prior to executing the simulation routine. Failing to do so will result in the Monte Carlo simulation routine simulating each variable independently. The result will be a simulated sample set where the correlations between input parameters have been lost. The simulated sample set will therefore not be representative of the system being simulated. This is demonstrated below in Figure 5-2.

Figure 5-2 – Monte Carlo Simulation of Correlated vs Non-Correlated Variables

Figure 5-2(a) above shows a regression plot of experimental data obtained for ultimate strength and ultimate strain for 11 mm commercial OSB/3 panels produced by Manufacturer A loaded in longitudinal tension. The results show...
that the Pearson’s correlation coefficient calculated between ultimate strength and ultimate strain was 0.612. Figure 5-2(b) above shows a regression plot of results from a Monte Carlo simulation of a simple system defined by ultimate strength and ultimate strain. The scatter plots shown in Figure 5-2(b) and Figure 5-2(a) above are nearly identical as is reflected by the almost-identical regression equations for both sets of data. This is because the correlation coefficient calculated from the experimental data was input into the Monte Carlo simulation routine prior to execution, therefore enabling it to preserve the relationship between ultimate strength and ultimate strain. Figure 5-2(c) above shows a regression plot of a Monte Carlo simulation of the same system but without specifying any correlation between ultimate strength and ultimate strain. It is clear that little or no correlation exists between ultimate strength and ultimate strain for the regression plot shown in Figure 5-2(c) above as is reflected by the $R^2$ value of 0. The failure to input a correlation coefficient between ultimate strength and ultimate strain has resulted in the Monte Carlo simulation routine treating each variable independently, producing simulated sample sets that are not representative of the real system. It is therefore essential that prior to implementing a Monte Carlo method, the following must be provided:

- Probability distribution models and associated statistical moments required to define them for each random variable to be simulated,
- Correlation coefficients to describe relationships between variables.

5.5 Probabilistic Analysis Using ANSYS Multiphysics 12.1

5.5.1 ANSYS Multiphysics 12.1

The finite element software used throughout this study was ANSYS Multiphysics© Version 12.1 (64-bit edition). ANSYS 12.1 supports parallel processing across multiple processors, enabling it to take full advantage of modern multi-core central processing units (CPUs). The system used for this study was a Dell Precision T5400 workstation with two Intel Xeon quad-core processors, 4GB RAM running Windows 7 Professional (64-bit Edition). This system provided a suitable environment where the high-performance computing capabilities of ANSYS could be exploited.
5.5.2 **ANSYS Parametric Design Language (APDL)**

ANSYS can be highly automated using a scripting language referred to as **ANSYS Parametric Design Language (APDL)**. All models developed in this study used this feature of ANSYS. APDL is a highly flexible scripting language that enables the functionality of ANSYS to be automated (Strain, 2005). This flexibility is achieved by parameterising models. Parameters are used to define all aspects of the model including geometry, material properties, external loads, boundary conditions, element type and mesh size. This allows users to easily modify their models by simply changing the values of the parameters. Parameters can be either be modified directly by users or automatically using FORTRAN like features such as *DO loops and *IF branching statements. APDL scripts are generally written in a text editor and saved in text file format. These are referred to as a batch or command files. APDL batch files contain all the commands required to generate, solve and output the results from the model. The batch file is read into the program where ANSYS will sequentially execute each command.

5.5.2.1 **ANSYS User Programmable Features (UPF’s)**

In addition to the high level of automation and customisation offered by APDL, the source code for ANSYS Multiphysics complies with the “open source” standard. This means that unlike many commercial computer programs, end users can access the source code and modify it to suit their needs. Users can tailor the ANSYS program to suit their needs by adding subroutines to perform customised tasks including material models, element types, failure criteria and a host of other functions. This functionality is referred to as **User Programmable Features (UPF’s)** (Imaoka, 2009, Kohnke, 2007). User subroutines can be accessed through the ANSYS program using APDL commands in a similar fashion to all other ANSYS commands. This enables them to be executed automatically through batch files in the exact same way as any other APDL command.

Users who wish to write their own user subroutines must have an understanding of FORTRAN programming as well as a suitable FORTRAN compiler. Once the code is written, user subroutines must be linked into the ANSYS program using a
suitable FORTRAN compiler. This study used Intel Composer XE 2011 (trial
version) running inside the Microsoft Visual Studio 2008 Professional Edition
integrated development environment to link and compile a customised ANSYS
executable (.exe). This customised executable included additional user
subroutines for implementing the material model developed for this study.
Further details of the material model are discussed below in Section 5.6 below.

5.5.3 ANSYS Probabilistic Design System (PDS)

5.5.3.1 Background

ANSYS Probabilistic Design System (PDS) is a module that is included in
ANSYS Multiphysics program for performing probability based design including
Monte Carlo simulation. It also includes the necessary post-processing tools for
analysing the results (Kohnke, 2009b, Reh et al., 2006). ANSYS PDS can be
interfaced using APDL and can therefore be easily automated and integrated with
the other features of ANSYS.

5.5.3.2 Inputs and Outputs

ANSYS PDS requires the user to define each random input parameter by means
of a probability distribution model it is known to follow and the associated first
and second statistical moments (e.g. parameter $x$ follows a Normal distribution
with a mean of $\mu$ and a standard deviation $\sigma$). ANSYS PDS also requires the user
to enter Pearson’s correlation coefficients between each pair of correlated input
variables. The correlation coefficients are stored in a correlation matrix that must
be positive definite in order for it to be valid. For a matrix to be positive definite,
it must satisfy the following conditions:

- Symmetric (i.e. $r_{ij} = r_{ji}$)
- $x^T R x > 0$ for all vectors $x \neq 0$ in $R$
- All eigenvalues are positive (Kreyszig, 2000)

ANSYS PDS also requires users to declare response variables prior to executing
the model. The response variables are used during post processing to examine the
impact of the random variability of the input parameters on the response of the
system. The response variables can be functions of the random input variables of (e.g. average density, \( \rho_{\text{ave}} = \frac{(2t_s\rho_s + 2t_D \rho_D + t_c \rho_C)}{t} \)) or can be evaluated from the finite element model output (e.g. failure load = vector sum of nodal forces at support).

5.5.4 ANSYS PDS Methods

5.5.4.1 Joint Probability Density Function (PDF)

The joint probability density function (PDF) of a bi or multi-variate system is a multi-dimensional probability density function that describes how all correlated parameters in the system co-vary. The joint PDF of a multivariate system cannot be readily determined using closed-form methods. ANSYS PDS therefore estimates the joint PDF using an approximate solution to the Nataf model as described by Liu and Der Kiureghian (1986). Liu and Der Kiureghian’s method transforms the correlation coefficients specified by the user into the space of standard normal distributed random variables by solving an integral equation. ANSYS PDS uses numerical integration to solve this integral equation rather than the approximation functions suggested by Liu and Der Kiureghian thus making the approach independent of the distribution type (Reh et al., 2006).

5.5.4.2 Sampling Method

ANSYS uses the L’Ecuyer (Press et al., 1996) algorithm for generating random numbers and uses the inverse probability method (Ang and Tang, 1984) to generate random numbers with arbitrary distributions (Reh et al., 2006). ANSYS PDS offers both direct and Latin Hypercube sampling methods. The Latin Hypercube (Ayyub and Lai, 1989, Florian, 1992) method has been used through this study because it drastically reduces the number of sampling points required to simulate the system when compared to the direct method (Reh et al., 2006).

Latin Hypercube sampling works by dividing the range of all random input variables into \( N \) intervals with equal probability, where \( N \) is the number of sampling points specified by the user. The Latin Hypercube method is described as having a memory because it remembers the intervals that have already have sample points and intentionally avoids taking multiple samples from the same
intervals (Kohnke, 2009b) to prevent clustering of sampling points. The Latin Hypercube is more efficient than the “direct” or “crude” Monte Carlo simulation method where no record is kept of previous sampling points. The difficulty with the direct method is that samples tend to cluster together. Figure 5-3 below demonstrates the difference in efficiency between the two sampling methods for a system defined by two random input parameters.

The sampling pattern shown in Figure 5-3(a) above shows how direct sampling methods tend to generate clusters of sampling points in close proximity to each other in the sample space while leaving other areas untouched. This requires very large sample sizes to be generated in order to ensure that system is adequately reproduced by the simulation. The sampling pattern in Figure 5-3(b) above demonstrates how the Latin Hypercube method ensures a much better dispersion of sampling points across the sample space, thereby greatly reducing the number of sampling points needed to accurately simulate the system.

**5.5.4.3 Post Processing**

ANSYS PDS includes its own set of post processing tools that are separate from the other post processing features of ANSYS. The PDS post processing tools are designed explicitly to analyse the results of a probabilistic design. These tools include several of the statistical methods previously described in Chapter 4 including probability plots, regression analyses and the Pearson’s correlation coefficient. Additionally, the post processing tools offered by PDS include sensitivity analysis and response surface fitting.
5.6 Material Model

5.6.1 Background

The results from the experimental testing of OSB and subsequent statistical analysis concluded that the mechanical behaviour of OSB tends to be reasonably linear at low strains but significant non-linearities exist at high strains. While linear models are acceptable for design purposes under in-service conditions, they are not adequate when attempting to predict the failure behaviour of wood-based composites. Past researchers have developed bi-linear and tri-linear representations of mechanical behaviour while examining the failure of wood-based composites. Although these modelling approaches offer a significant improvement over simple linear-elastic theory, they still do not capture the true behaviour of wood-based composites. Furthermore, the literature review in Chapter 2 concluded that most of the work conducted on this subject has been on developing material models to represent the mechanical behaviour of OSB subjected to direct tension and compression. Relatively little work has been done on developing material models for the mechanical behaviour of wood-based composites subjected to shear loading.

5.6.2 ANSYS Built-in Material Models

Part of the current research consisted of the development of a three-dimensional, multi-linear material model to represent the mechanical behaviour of OSB subjected to tension, compression and panel-shear in the in-plane directions. ANSYS has built-in anisotropic, orthotropic and multi-linear material models. However, none of these models were capable of representing the true three-dimensional, non-linear behaviour observed during experimental testing. The anisotropic and orthotropic material models are capable of representing different mechanical behaviour with varying loading directions. However, both models assume linear elastic behaviour to failure. The multi-linear models are capable of representing different mechanical behaviour at varying strain levels but they rely on the assumption of isotropic mechanical behaviour. For these reasons, it was necessary to develop a special user material subroutine that captures the true three-dimensional non-linear orthotropic mechanical behaviour of OSB.
5.6.3 Background to User Material Model
The aim of the material model was to numerically reproduce the mechanical behaviour of single-plies of OSB observed during the experimental testing of single-layer OSB panels in three-dimensional space. The model needed to be capable of being easily used in conjunction with Monte Carlo simulation in order for it to be used to predict the response of OSB materials to the random variability of the layer properties. The model represented the mechanical behaviour using empirical stress-strain relationships established from statistical analysis of the experimental data described in Chapter 4.

The development of the user material model started with a simple 1-D version for reproducing the mechanical behaviour of OSB observed during experimental testing loaded in tension or compression. The model capabilities expanded to a 2-D version capable of reproducing the mechanical behaviour of OSB observed during experimental testing when loaded in tension, compression and panel-shear. The 2-D version of the model also had the capability of representing the Poisson’s effects. The final version of the model was capable of representing the mechanical behaviour of OSB loaded in tension, compression and shear in three dimensions including all Poisson’s effects.

5.6.4 Constitutive Equations
The accurate representation of the non-linear behaviour in three dimensions required a material model with the combined functionality of the built-in anisotropic and multi-linear models. This could only be achieved using a user material model subroutine.

The user material model was based on the normalised stress-strain relationships developed during the statistical analysis of the experimental data and the general form of Hooke’s law presented in Section 5.3.2 above. The normalised stress-strain relationships were re-arranged to give an expression for the elastic modulus as a function of strain. The equations used by the user material model subroutine are given in Equations (5.4) to (5.6) below.
\[ E_t = \frac{\sigma_{ut}}{\varepsilon_{ut}} \left[ \hat{a}_t \left( \frac{\varepsilon}{\varepsilon_{ut}} \right) + \hat{b}_t \right] \]  (5.4)

where: \[ E_t = \text{Elastic modulus in tension}; \quad \sigma_{ut} = \text{Tensile ultimate strength}; \quad \varepsilon_{ut} = \text{Ultimate tension strain}; \quad \varepsilon = \text{Current tension strain}; \quad \hat{a}_t \text{ and } \hat{b}_t \text{ are the coefficients for the normalized stress-strain regression equation of the form } \sigma = \hat{a}_t \varepsilon^2 + \hat{b}_t \dot{\varepsilon} \]

\[ E_c = \frac{\sigma_{uc}}{\varepsilon_{uc}} \left[ \hat{a}_c \left( \frac{\varepsilon}{\varepsilon_{uc}} \right) + \hat{b}_c \left( \frac{\varepsilon}{\varepsilon_{uc}} \right) + \hat{c}_c \right] \]  (5.5)

where: \[ E_c = \text{Elastic modulus in compression}; \quad \sigma_{uc} = \text{Ultimate compression stress}; \quad \varepsilon_{uc} = \text{Ultimate compression strain}; \quad \varepsilon = \text{Current compression strain}; \quad \hat{a}_c, \hat{b}_c \text{ and } \hat{c}_c \text{ are the coefficients for the normalized stress-strain regression equation of the form } \sigma = \hat{a}_c \varepsilon^3 + \hat{b}_c \varepsilon^2 + \hat{c}_c \varepsilon \]

\[ G_s = \frac{\tau_u}{\gamma_u} \left[ \hat{a}_s \left( \gamma \right) + \hat{b}_s \right] \]  (5.6)

where: \[ G_s = \text{Elastic shear modulus}; \quad \tau_u = \text{Ultimate shear stress}; \quad \gamma_u = \text{Ultimate shear strain}; \quad \gamma = \text{Current shear strain}; \quad \hat{a}_s \text{ and } \hat{b}_s \text{ are the coefficients for the normalized stress-strain regression equation of the form } \tau = \hat{a}_s \gamma^2 + \hat{b}_s \gamma \]

The user material subroutine uses the above equations to calculate the elastic moduli at each node as a function of the current strain vector. ANSYS substituted the elastic moduli into the Equation (5.2) above to calculate the stiffness matrix corresponding to the current strain vector at each node and then solved for the stress vector. This enabled the true orthotropic, non-linear behaviour to be accurately represented in a finite element model. This represents a key development in numerical modelling of wood-based composite materials. Previous studies relied on linear models to model the mechanical behaviour of wood-based composite materials in tension and tri-linear models to model the mechanical behaviour of wood-based composites in compression (Clouston and Lam, 2001, Clouston, 2001, Clouston and Lam, 2002, Wang and Lam, 1998b, Wang and Lam, 1998a). Therefore, an orthotropic, non-linear material model that can accurately represent the mechanical behaviour of OSB under all loading conditions up to the point of failure represents a significant development in the numerical modelling wood-based composite materials.
The input for the user material model subroutine is via the ANSYS user material data table (Kohnke, 2009a). This method enables the material properties obtained from either experimental results or Monte Carlo simulation to be input through an APDL script. The ANSYS program automatically transfers information from the user material data table over to the user material subroutine. The inputs consist of material strength properties and the regression coefficients for the normalised stress-strain relationships for each loading condition.

5.6.5 Load Application

As described in Chapter 3, the testing equipment applied loads to the test specimens in “displacement control” mode. This ensured that the specimens are loaded at a constant rate of strain. This method of loading test specimens is generally used because it produces better results than load control (i.e. loaded at a constant rate of stress), particularly for materials that exhibit non-linear behaviour. All models recreated these conditions by applying a total displacement to one end of the test specimen that would induce a strain equal to the ultimate strain of the material. The model applied the displacement using 100 sub-steps. This method allowed the model to capture the mechanical behaviour at a range of strain levels so that the precise nature of the relationship between stress and strain could be assessed and compared with experimental results.

5.6.6 1-D Model

5.6.6.1 Model Capabilities and Limitations

The first version of the user material model subroutine predicted the mechanical behaviour, elastic modulus and failure properties of OSB subjected to axial tension and compression. Simple, 1-D link elements represented the portion between gauge points of the tension and compression test specimens. The 1-D version of the model reproduced the mechanical behaviour and failure characteristics observed experimentally for specific test specimens. When used in conjunction with Monte Carlo simulation, it reproduced the response of the mechanical behaviour, failure load and the elastic modulus to the random variations in the ultimate strength and ultimate strain.
The 1-D model was not capable of modelling the mechanical behaviour of OSB subject to panel-shear loading, orthotropic behaviour or the Poisson’s effect even though the model input includes the Poisson’s ratio. The Poisson’s ratio is only used by the ANSYS program to calculate the transverse shear stiffness, which is used in turn by the non-linear solver help determine appropriate strain increments at each sub step (Kohnke, 2009b). This limits the 1-D version of the user material model subroutine to model OSB subjected to uniaxial loading conditions only. Applications where OSB is simultaneously subject to loading in two directions required the 2-D (see Section 5.6.7 below) or 3-D (see Section 5.6.8 below) version of the user material model. Furthermore, the 1-D elements in ANSYS do not have the capability of modelling laminated materials. This means that the 1-D version of the user material model cannot predict the resultant behaviour of multi-layered OSB materials based on the behaviour of their constituent layers. The 1-D version of the user material model can only represent the resultant properties of multi-layered OSB materials.

5.6.6.2 Element Technology

The LINK180 (Kohnke, 2009a) element was used in conjunction with the 1-D version of the user material model. Details of the element geometry are shown in Figure 5-4 below.

![LINK180 Element Geometry](image)

Figure 5-4 – LINK180 Element Geometry (Kohnke, 2009a)

LINK180 is a 1-D uniaxial tension-compression element defined by two nodes. Each node has three degrees-of-freedom (i.e. translations in the nodal x, y, and z directions). It has the capability to be used in conjunction with advanced, non-linear material models for performing plastic, creep, rotation, large deflection, and large strain analyses. The end nodes of the element are assumed to be pinned with zero rotational stiffness. This makes it suitable for modelling structures such as trusses, sagging cables, links and springs. However, the LINK180 element is
not suitable for modeling structures where the members are subjected to bending or shear loading.

**5.6.6.3 Geometry**

Figure 5-5 below shows the geometry and mesh used to validate the 1-D version of the user material model.

![Figure 5-5 – Geometry and Mesh (1-D Model)](image)

The model geometry was defined by two nodes connected together by a single element to represent the section of the tension test specimen between the mounting points for the LVDTs (see Figure 3-14 above). The link element was assigned a constant area equal to that of the necked section of a typical 11 mm thick tension test specimen (i.e. \( A = 11 \times 100 = 1100 \text{ mm}^2 \)).

**5.6.6.4 Model Input**

**5.6.6.4.1 Material Strength Inputs**

Table 5-1 below summarises the material strength inputs required by the 1-D version of the user material model subroutine.
### Input Source

<table>
<thead>
<tr>
<th><strong>Input</strong></th>
<th><strong>Source</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tension</strong></td>
<td></td>
</tr>
<tr>
<td>• Ultimate Strength ( \sigma_{u,t} )</td>
<td>MC/Exp/DC</td>
</tr>
<tr>
<td>• Ultimate Strain ( \varepsilon_{u,t} )</td>
<td>MC/Exp/DC</td>
</tr>
<tr>
<td><strong>Compression</strong></td>
<td></td>
</tr>
<tr>
<td>• Ultimate Strength ( \sigma_{u,c} )</td>
<td>MC/Exp/DC</td>
</tr>
<tr>
<td>• Ultimate Strain ( \varepsilon_{u,c} )</td>
<td>MC/Exp/DC</td>
</tr>
</tbody>
</table>

1) Explanation of symbols: Exp => Experimental data; MC => Generated by Monte Carlo Simulation; L => Literature; DC => Design value

2) User has the option of using values generated by a Monte Carlo simulation or manually inputting experimental or design values

---

### Table 5-1 – 1-D User Material Model Strength Inputs

#### 5.6.6.4.2 Mechanical Behaviour Inputs

Table 5-2 below summarises the mechanical behaviour inputs required by the 1-D version of the user material model subroutine.

<table>
<thead>
<tr>
<th><strong>Input</strong></th>
<th><strong>Source</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Poisson’s Ratio</strong></td>
<td></td>
</tr>
<tr>
<td>• ( v_{xy} )</td>
<td>L</td>
</tr>
<tr>
<td><strong>Tension</strong></td>
<td></td>
</tr>
<tr>
<td>• Coefficient, ( a_t )</td>
<td>Exp</td>
</tr>
<tr>
<td>• Coefficient, ( b_t )</td>
<td>Exp</td>
</tr>
<tr>
<td><strong>Compression</strong></td>
<td></td>
</tr>
<tr>
<td>• Coefficient, ( a_c )</td>
<td>Exp</td>
</tr>
<tr>
<td>• Coefficient, ( b_c )</td>
<td>Exp</td>
</tr>
<tr>
<td>• Coefficient, ( c_c )</td>
<td>Exp</td>
</tr>
</tbody>
</table>

1) Explanation of symbols: Exp => Experimental data; MC => Generated by Monte Carlo Simulation; L => Literature; DC => Design value

2) User has the option of using values generated by a Monte Carlo simulation or manually inputting experimental or design values

---

### Table 5-2 – 1-D User Material Model Mechanical Behaviour Inputs

#### 5.6.6.5 Model Validation

An APDL script was developed to validate the 1-D version of the user material model subroutine. The APDL script performed the following tasks:

- Imported the correlation matrix, the regression coefficients as defined in Table 5-2 above and the results from the probability distribution fitting exercises described in Chapter 4 for ultimate strength and ultimate strain,
- Built model geometry and generated the mesh,
- Defined the number of Monte Carlo simulation loops,
- Declared ultimate strength and ultimate strain as random input variables,
- Defined the correlation between ultimate strength and ultimate strain,
- Declared failure load and elastic modulus as random output variables,
- Defined the correlation between ultimate strength and ultimate strain,
- Performed Monte Carlo simulation to generate random values of ultimate strength and ultimate strain in tension or compression (depending on which loading condition the model is being validate for),
- Inputted the regression coefficients as defined in Table 5-2 above and the randomly-generated values for ultimate strength and ultimate strain into the 1-D version of the user material model subroutine,
- Applied a displacement to one edge of the test specimens to represent the movement of the cross-head during experimental testing, (the applied displacement was such that it induced a strain at the mid-height of the specimen equal to the simulated value for ultimate strain),
- Applied a zero displacement at the opposite end of the test specimen to represent the support during experimental testing,
- Solved the model using the ANSYS non-linear solver,
- Post-processed the data,
- Calculated the outputs for each Monte Carlo simulation loop,
- Outputted the results to text files for further post-processing and comparison with experimental data using an Excel 2010 VBA macro.

Note that unlike later versions, the APDL script did not include density or thickness as random input parameters nor did it consider correlations between tension and compression properties. The model was validated for single-layer OSB panels, 11 mm and 18 mm OSB/3 panels produced by Manufacturer A loaded in tension and compression in both directions. Figure 5-8 below shows a typical example of the graphical output generated by the APDL script used to validate the 1-D version of the user material model. Figure 5-7 below shows a typical averaged stress-strain curve generated by the 1-D user material model and Monte Carlo simulation.
Figure 5-6 – Graphical Output from 1-D User Material Model

Figure 5-7 – Simulated vs Experimental Averaged Stress-Strain (1-D User Material Model)
The curve shown in Figure 5-7 above was obtained is for single-layer, surface material OSB panels loaded in longitudinal tension. Also shown is the experimental averaged stress vs strain curve. A more comprehensive set of results is presented in Appendix D.

Figure 5-7 above demonstrates that the 1-D version of the user material model predicted the averaged stress-strain curve for single-layer, surface material OSB loaded in longitudinal tension with excellent agreement at low strain. However, at high strains, the results show that the simulated, averaged stress-strain curve deviates considerably from the experimental, averaged stress-strain curve at high strain. Similar results were found for the other loading conditions and materials that the 1-D version of the user material model was validated for.

Figure 5-8 below shows the simulated EDF plot overlaid onto the experimentally observed EDF plots for elastic modulus for single-layer, surface OSB panels loaded in longitudinal tension.

Figure 5-9 below shows the simulated EDF plot overlaid onto the experimentally observed EDF plots for elastic modulus for single-layer, surface OSB panels loaded in longitudinal tension.
The results shown in Figure 5-8 and Figure 5-9 above demonstrate that the 1-D model tends to overestimate the mean values of failure load (+11.2% for single-layer OSB in longitudinal tension) and elastic modulus (+7.17% for single-layer OSB in longitudinal tension). However, in both cases, the model predicted the correct probability distribution model to describe the response parameters.

The error between model predictions and experimental observations can likely be attributed to the significant simplification of the system as outlined above. Link elements do not accurately represent the geometry of the test specimen used during experimental evaluation of the material. Effects such as clamping pressure in the tension test specimen and friction between the loading head and the end of the test specimen that would be present during panel-shear and compression testing cannot be represented in the 1-D version of the user material model. In addition, ignoring the Poisson’s effect will eliminate the interaction between the longitudinal and lateral material properties. This will have the effect of slightly improving the apparent performance in the longitudinal direction and slightly deteriorating the performance in the lateral direction. This has been reflected in the results shown in Figure 5-7 and Figure 5-9 above which show that the 1-D
version of the user material model overestimates the performance of the single-layer, surface OSB panels in longitudinal tension.

5.6.6.6 Remarks

Despite its limited applicability, developing the 1-D version of the model did provide useful insight into:

- Identifying the information transferred between the main ANSYS program and user material model subroutines,
- Developing FORTRAN source code for user material model subroutines,
- Compiling and linking user material model subroutines into the main ANSYS program,
- Passing inputs from the main ANSYS program to user material model subroutines using APDL scripts,
- Incorporating user material model subroutines into Monte Carlo simulation routines.

In addition to developing programming skills that could be applied to more advanced versions of the user material model, the predictions made by the 1-D version matched reasonably well with experimentally assessed values. The error between model predictions and experimental values are relatively low considering the highly simplified geometry, ignoring orthotropic material behaviour, ignoring Poisson’s effects and consequently, the different mechanical behaviour between tension and compression loading. The results indicated that user material model subroutines offered significant potential in terms of accurately representing the mechanical behaviour of OSB.

5.6.7 2-D Model

5.6.7.1 Model Capabilities and Limitations

The 2-D version of the model significantly expanded on the capabilities of the 1-D version described in Section 5.6.6 above. It could be used in conjunction with plane and shell elements. This enabled the geometry of the tension and compression test specimens to be modelled in two dimensions. The 2-D model
could also represent the panel-shear behaviour of OSB, could account for in-plane Poisson’s effects, orthotropic material behaviour and model problems involving in-plane, biaxial loading conditions. Furthermore, many of the 2-D elements included with the ANSYS program have the built-in capability of modelling layered materials using laminated plate theory as described in Section 5.3 above. The 2-D layered elements allow the user to specify the stacking sequence of the laminate and assign a different material set of material properties to each layer (Kohnke, 2005). This enables the 2-D version of the user material model to predict the resultant behaviour of multi-layered OSB materials based on the behaviour of the constituent layers and stacking sequence.

The 2-D version of the user material model includes the necessary code for representing the mechanical behaviour of OSB loaded in panel-shear. However, the geometry of the panel-shear test specimen (see Figure 3-50 above) is a complex three-dimensional shape that cannot be simplified to two dimensions. Therefore, despite containing the necessary code, the 2-D user material model subroutine could not be validated for panel-shear loading. The 2-D model also cannot represent the mechanical behaviour of OSB loaded in planar-shear or out-of-plane effects including plate-shear and out-of-plane Poisson’s effects.

5.6.7.2 Element Technology

The PLANE183 (Kohnke, 2009a) element was used with the 2-D version of the user material model. The element geometry is defined in Figure 5-10 below.

![Figure 5-10 – PLANE183 Element Geometry (Kohnke, 2009a)](image)
PLANE183 is a 2-D element defined by six (triangular version) or eight (rectangular version) nodes. Each node has two degrees of freedom (translations in the $x$ and $y$ directions). The element may be used to model plane (plane stress, plane strain and generalized plane strain) or axisymmetric problems. This element supports plasticity, hyperelasticity, creep, stress stiffening, large deflection, and large strain capabilities. It also has mixed formulation capability for simulating deformations of nearly incompressible elastoplastic materials, and fully incompressible hyperelastic materials (Kohnke, 2009a). The 2-D material model was used in conjunction with this element because the mid-side nodes enable the element to model quadratic displacement behaviour, making it suitable for modelling non-linear materials. They also enable the edges of the element to adopt a curvilinear shape, making it suitable for modelling shapes with curved edges such as those present in the tension test specimen.

5.6.7.3 Geometry

Figure 5-11 below shows a 2-D finite element representation of the tension test specimen using PLANE183 elements.
Figure 5-12 below shows a 2-D finite element representation of the compression test specimen using PLANE183 elements.

Chapter 3 presents the full details of the geometry for the tension and compression test specimens. Keypoints were used to define the vertices of the test specimens. The keypoints were connected together using lines to define the outline of the tension and compression specimens, which in turn were used to create an area. The thickness was represented by assigning a thickness to the PLANE183 mesh using a real constant (Kohnke, 2009a). The user had the option of inputting a specific thickness or using the Monte Carlo method to randomly generate a thickness.

5.6.7.4 Model Input

Table 5-3 below summarises the material strength inputs required by the 2-D version of the user material model subroutine. Table 5-4 below summarises the mechanical behaviour inputs required by the 2-D version of the user material model subroutine.
Chapter 5 – Numerical Modelling

Input Source

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<tr>
<td>• Longitudinal Ultimate Strain ( \varepsilon_{u,t,x} )</td>
<td>MC/Exp/DC</td>
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<td>• Lateral Ultimate Strength ( \sigma_{u,l,y} )</td>
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<td>• Lateral Ultimate Strain ( \varepsilon_{u,l,y} )</td>
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<td>• Ultimate Strain ( \gamma_{u,s,xy} )</td>
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</table>

1) Explanation of symbols: Exp => Experimental data; MC => Generated by Monte Carlo Simulation; L => Literature; DC => Design value

2) User has the option of using values generated by a Monte Carlo simulation or manually inputting experimental or design values

Table 5-3 – 2-D User Material Model Strength Inputs

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<tr>
<td>• Longitudinal Coefficient, ( b_{t,x} )</td>
<td>Exp</td>
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<td>• Lateral Coefficient, ( a_{t,y} )</td>
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</thead>
<tbody>
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<td>• Longitudinal Coefficient, ( b_{c,x} )</td>
<td>Exp</td>
</tr>
<tr>
<td>• Longitudinal Coefficient, ( c_{c,x} )</td>
<td>Exp</td>
</tr>
<tr>
<td>• Lateral Coefficient, ( a_{c,y} )</td>
<td>Exp</td>
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<tr>
<td>• Lateral Coefficient, ( b_{c,y} )</td>
<td>Exp</td>
</tr>
<tr>
<td>• Lateral Coefficient, ( c_{c,y} )</td>
<td>Exp</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Panel-Shear</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Coefficient, ( a_{s,xy} )</td>
<td>Exp</td>
</tr>
<tr>
<td>• Coefficient, ( b_{s,xy} )</td>
<td>Exp</td>
</tr>
</tbody>
</table>

Table 5-4 – 2-D User Material Model Mechanical Behaviour Inputs
5.6.7.5 Model Validation

Two separate sets of APDL scripts (one each for tension and compression) were written to validate the 2-D version of the user material model. A pair of APDL scripts validated the material model by using it to reproduce experimental observations for mechanical behaviour recorded for a chosen set of test specimens. A second pair APDL scripts validated it for use in conjunction with Monte Carlo simulation. A third set of standard APDL scripts were developed for constructing the geometry and the mesh as discussed in Section 5.6.7.3 above for the tension and compression test specimens. These were stored in a separate location and were made available to all model validation procedures. This simplified the APDL scripts used to validate the 2-D user material model subroutine because the procedures for generating geometry and mesh could be called from within the validation procedure using a single command. This eliminated the need to reproduce the code for generating geometry and mesh in each of the validation procedures. They also provided the added benefit of ensuring that the same mesh and geometry was used for each test piece during validation runs.

5.6.7.5.1 Validation with Experimental Results

The first pair of APDL scripts reproduced the stress-strain curves, elastic moduli and failure loads obtained experimentally for each single-layer, surface material OSB test specimen subject to tension and compression in both directions. This pair of APDL scripts performed the following tasks:

- Imported experimental values for the regression coefficients as defined in Table 5-4 above and substituted them into Equations (5.4) to (5.6) above,
- Imported the experimental results for ultimate strength, ultimate strain and thickness from tension and compression testing in both directions for the single-layer OSB panels,
- Called APDL scripts for generating test specimen geometry and mesh,
- Inputted experimental values for all the strength parameters described in Table 5-3 above and the mechanical behaviour parameters described in Table 5-4 above into the 2-D version of the user material model,
• Applied a displacement to one edge of the test specimens to represent the movement of the cross-head during experimental testing, (the applied displacement was such that it induced a strain at the mid-height of the specimen equal to the experimental ultimate strain value),
• Applied a zero displacement at the opposite end of the test specimen to represent the support during experimental testing,
• Solved the model using the ANSYS non-linear solver,
• Post-processed results, generated a contour plot showing the direct stresses parallel to the direction of loading and two scatter plots showing stress vs strain and load vs displacement respectively,
• Calculated the failure load and the elastic modulus for each test specimen,
• Output the results to text files for comparison with experimental results for each test specimen using an Excel 2010 VBA macro.

Figure 5-13 below shows the ANSYS graphical output for test specimen A-1-SURF-TENS-LAT. A more detailed set of results is presented in Appendix D.
The results presented in Figure 5-13 above show a nearly uniform distribution of the tensile stress (shown in red) in the necked section of the test specimen. The legend shown on the bottom indicates that the tensile stress in this region is between 10.1 N/mm² and 11.5 N/mm². The results presented in Appendix B show that test specimen A-1-SURF-TENS-LAT failed at 11.12 N/mm². This shows that the 2-D user material model accurately predicted the ultimate tensile strength for this test specimen. Similar results were also obtained for the remaining tension test specimens in both directions. The stress vs strain and load vs displacement curves shown in Figure 5-13 above show quadratic behaviour similar to that observed from experimental testing for test specimen A-1-SURF-TENS-LAT. This proves that the 2-D material model accurately represents the mechanical behaviour of single-layer, surface material OSB subject to tension.

Figure 5-14 and Figure 5-15 below show the predicted mechanical behaviour superimposed onto the experimentally observed mechanical behaviour for test specimens A-7-SURF-TENS-LONG and A-11-SURF-TENS-LAT respectively. The results demonstrate that the model accurately represents the non-linear behaviour of OSB subjected to tension in both directions.
Figure 5-15 – Predicted vs Experimental Results for A-11-SURF-TENS-LAT

Figure 5-16 below shows the ANSYS graphical output for test specimen A-3-SURF-COMP-LAT. A more detailed set of results is presented in Appendix D.

Figure 5-16 – 2-D Model Validation ANSYS Output (A-3-SURF-COMP-LONG)
The results presented in Figure 5-16 above show that as was the case with tensile loading, the 2-D material model accurately captured the mechanical behaviour and failure characteristics for test specimen A-1-SURF-COMP-LAT. The stress distribution shows a nearly uniform stress distribution across the entire test specimen. The results summary on the top left hand corner of Figure 5-16 above shows that the maximum stress calculated for this test specimen is 16.4 N/mm². The results presented in Appendix B show that the compressive ultimate strength for this test specimen was 15.97 N/mm². This proves that the 2-D user material model subroutine accurately predicted the ultimate compressive ultimate strength for this test specimen. Similar accuracy was also achieved for the remaining compression test specimens in both directions. The stress vs strain and load vs displacement curves shown in the right-hand side of Figure 5-16 above also show cubic behaviour similar to that observed from experimental testing for test specimen A-3-SURF-COMP-LAT. Figure 5-17 below shows the predicted and the experimentally observed mechanical behaviour for A-20-SURF-COMP-LONG.

![Figure 5-17 – Predicted vs Experimental Results for A-20-SURF-COMP-LONG](image-url)
Figure 5-18 below shows the predicted mechanical behaviour superimposed onto the experimentally observed mechanical behaviour for test specimen A-20-SURF-COMP-LAT.

![Graph showing predicted vs experimental results for A-20-SURF-COMP-LAT](image)

**Figure 5-18 – Predicted vs Experimental Results for A-20-SURF-COMP-LAT**

The results shown in Figure 5-17 and Figure 5-18 above demonstrate that the 2-D version of the user material model accurately represents the non-linear behaviour of OSB subjected to in-plane compression in both material directions.

5.6.7.5.2 **Validation with Monte Carlo Simulation**

The second set of APDL scripts demonstrated the Monte Carlo simulation could be used in conjunction with the 2-D version of the user material model subroutine. They demonstrated that influence of the random variability in ultimate strength, ultimate strain and density on the mechanical behaviour, elastic modulus and failure load of single-layer, surface could be predicted. These APDL scripts verified this for single-layer surface material OSB panels subjected to tension and compression in both material directions. They also accounted for the correlations between parameters. This pair of APDL scripts performed the following tasks:
• Imported the probabilistic data determined from the statistical analysis program as described in Chapter 4 above for the strength parameters defined in Table 5-3 above and global density,

• Built model geometry and generated the mesh,

• Defined the number of Monte Carlo simulation loops,

• Declared global density, ultimate strength and ultimate strain for tension, compression and panel-shear loading as random input variables,

• Defined correlations between random input variables,

• Declared failure load and elastic modulus as random output variables,

• Performed Monte Carlo simulation to generate random values for the input variables (using Cholesky decomposition and the correlation matrix to ensure that the randomly-generated values for the input variables obeyed the correlations observed during experimental assessment),

• Inputted the randomly-generated values for all the strength parameters described in Table 5-3 above and the statistically-determined mechanical behaviour parameters described in Table 5-4 above into the 2-D version of the user material model,

• Applied a displacement to one edge of the test specimens to represent the movement of the cross-head during experimental testing, (the applied displacement was such that it induced a strain at the mid-height of the specimen equal to the simulated ultimate strain value),

• Applied a zero displacement at the opposite end of the test specimen to represent the support during experimental testing,

• Solved the model using the ANSYS non-linear solver,

• Post-processed results, generated a contour plot showing the direct stresses parallel to the direction of loading and two scatter plots showing stress vs strain and load vs displacement respectively,

• Calculated failure load and elastic modulus results for each loop,

• Outputted the results to text files for comparison with experimental results for each test specimen using an Excel 2010 VBA macro.
Similar to the 1-D model validation exercises, these validation exercises did not simulate the panel thickness as a random input variable. They did however include global density as a random input variable. These validation exercises also simulated ultimate strength and ultimate strain of single-layer OSB panels subjected to tension, compression and panel-shear loading accounting for the inter-dependence between these properties and their relationship with global density. The validation run accounted for the relationships between random input parameters using the Pearson’s correlation coefficients as described in Chapter 4.

Figure 5-19 below shows a finite element contour plot obtained for a typical Monte Carlo simulation loop showing the stresses presented in a single-layer panel loaded in longitudinal tension.

Figure 5-19 – Typical Tensile Stress Plot for 2-D Material Model

Figure 5-20 below shows the simulated longitudinal tension stress-strain relationships generated by the Monte Carlo simulation for the A-SURF panels.
Figure 5-20 – 2-D Material Model Validation (Simulated Tension Behaviour)

Figure 5-21 below shows the matching set of experimentally-evaluated stress-strain curves obtained for the A-SURF panels.

Figure 5-21 – 2-D Material Model Validation (Experimental Tension Behaviour)

Figure 5-22 below shows the averaged stress vs strain curve superimposed on the corresponding experimental averaged stress-strain curve.
Figure 5-22 – 2-D Material Model Validation (Averaged Stress-Strain Curve)

Figure 5-23 and Figure 5-24 below show the predicted EDF plots for the elastic modulus and failure load respectively obtained from the validation run for A-SURF panels loaded in longitudinal tension.

Figure 5-23 – 2-D Material Model Validation (Predicted EDF Plot for Elastic Modulus)
The plots presented in Figure 5-20 and Figure 5-21 above show that the stress-strain relationships generated by Monte Carlo simulation show similar variation patterns to those obtained from experimental assessment. The results presented Figure 5-22 above show that the averaged stress-strain curve calculated for the simulated data set is almost identical to that calculated for the experimental data set. This reaffirms that the user material subroutine accurately represents the mechanical behaviour while Monte Carlo simulation accurately represents the variability in mechanical behaviour observed during experimental testing.

The EDF plots, shown in Figure 5-23 and Figure 5-24 above, demonstrate that the model correctly predicted the probability distribution models for the elastic modulus and failure load, respectively. For the A-SURF panels, the validation run predicted that the longitudinal elastic tension modulus was normally distributed with a mean of 5662 N/mm$^2$ and a standard deviation of 517.5 N/mm$^2$. The validation run predicted that failure load in tension was normally distributed with a mean of 24.29 kN with a standard deviation of 4.052 kN. Comparing these results with experimental data shows the validation run overestimated the mean longitudinal elastic tension modulus by just 2.23% and overestimated the mean failure load by 7.90%.

![Simulated vs Experimental Failure Load](image)

**Figure 5-24 – 2-D Material Model Validation (Predicted EDF Plot for Failure Load)**
The slightly larger discrepancy between predicted and experimental values for failure load is likely due to the fact that the validation run did not treat the panel thickness as a random input parameter. The experimental results for failure load by their nature include the random variation in the panel thickness. It is likely that re-running the validation run with the panel thickness as a random input parameter will improve this.

5.6.7.6 Remarks

The results of these validation exercises prove that the 2-D version of the model offers much more flexibility and accurate than its 1-D predecessor. It can be used in conjunction with plane and shell elements to accurately model the mechanical behaviour of OSB using actual test specimen geometry under the conditions that exist during a load test. The 2-D model is capable of representing the mechanical behaviour of OSB subjected to panel-shear loading. However, no attempt was made to validate this component of the model because of the complex geometry involved with panel-shear test specimens. The geometry of panel-shear test specimens is three dimensional and cannot be accurately represented in two dimensions.

5.6.8 3-D Model

5.6.8.1 Model Capabilities and Limitations

The 3-D version of the model expanded on the capabilities of the 2-D version by allowing the true geometry of the tension, compression and panel-shear test specimens to be modelled in three dimensions using brick elements. The 3-D version of the model also has the capability of modelling the mechanical behaviour of OSB subjected to planar-shear and plate-shear loading as well as accounting for all Poisson’s effects in three-dimensions. The 3-D version overcomes all the limitations imposed on the 1-D and 2-D versions. The validation runs described in Section 5.6.7 above demonstrate that the 2-D version of the user material subroutine is more than adequate for modelling in-plane tension and compression problems. Although it was not validated, it is likely that the 2-D version of the user material model could be used to represent the panel-
shear behaviour of OSB provided that the geometry of the problem can be accurately represented in two dimensions. Furthermore, many of the 2-D elements available in ANSYS have layered material capabilities, theoretically enabling the 2-D version to be used to model multi-layered OSB based on the properties of individual layers (including accounting for relationships between layer properties, panel thickness and density profile). It is recommended that the 3-D version of the model should only be used to model problems where:

- Complex 3-D geometric configurations exist that cannot be accurately simplified to a 2-D problem,
- OSB is loaded in planar-shear, plate-shear, bending, out-of-plane tension or compression,
- The stress distribution across the thickness of the panel is of a particular interest (e.g. bending problems).

5.6.8.2 Element Technology

The 3-D version of the user material model subroutine used the SOLID186 element. Details of the element geometry are shown in Figure 5-25 below for the solid version and in Figure 5-26 below for the layered version.

---

**Figure 5-25 – SOLID186 Element Geometry, Solid Version (Kohnke, 2009a)**
SOLID186 is a 3-D, 20-node element with three degrees-of-freedom per node. This element is capable of modelling solid and laminated materials (Kohnke, 2009a) and supports non-linear displacement behaviour.

5.6.8.3 **Geometry**

Figure 5-27 below shows the 3-D finite element representations of the tension test specimen using SOLID186 elements.
Keypoints were used to define the vertices of the test specimen in the $x$-$y$ plane. The keypoints were connected together using lines to define the plan area of the tension test specimen. The plan area was extruded along the $z$-axis to produce a volume (Kohnke, 2009a). The mesh geometry used to represent the plan area of tension test specimen in two dimensions (see Figure 5-11 above) was also used to represent the plan area of the tension test specimen in three dimensions. A single element represented the thickness of tension test specimen. The user had the option of inputting a specific thickness or using the Monte Carlo method to randomly generate a thickness.

Figure 3-21 above presents the details of the geometry for the compression test specimen. Figure 5-28 below shows the 3-D finite element representation of the compression test specimen used to evaluate the compression performance of 11 mm thick OSB panels using SOLID186 elements.

Figure 5-28 – 3-D Finite Element Representation of Compression Test Specimen

Keypoints were used to define the vertices of the test specimen in the $x$-$y$ plane. The keypoints were connected together using lines to define the plan area of the compression test specimen. The plan area was extruded along the $z$-axis to
produce a volume (Kohnke, 2009a). The mesh geometry used to represent the
plan area of compression test specimen in two dimensions (see Figure 5-12
above) was also used to represent the plan area of the compression test specimen
in three dimensions. The number of elements used to represent the thickness of
the compression test specimen in the \( z \)-plane equalled the number of strips of
OSB used to construct the specimen (see Figure 3-21 above). The thickness of
each element equalled the thickness of the specimen divided by the number of
layers used to construct it. The user had the option of inputting a specific
thickness or using the Monte Carlo method to randomly generate a thickness.

Figure 5-29 below shows the 3-D finite element representation of the panel-shear
test specimen using SOLID186 elements.

![Figure 5-29 – 3-D Finite Element Representation of Panel-Shear Test Specimen](image)

Keypoints were used to define the vertices of the test specimen in the \( x-y \) plane.
The keypoints were connected together using lines to define areas to represent
the contact area between the C16 rails and the panel-shear test specimen, the
shear area and the instrumented region in centre of the shear area. The areas were
extruded along the positive \( z \)-axis by a distance equal to the specimen thickness
to produce a volume to represent the panel-shear test specimen. The areas representing the contact between the C16 rails and the panel-shear test specimen were extruded by the thickness of the rails. This produced volumes to represent the C16 rails.

The tetrahedral version of the SOLID186 and SOLID185 elements were used to accurately model the complex geometry of the panel-shear test setup. During mesh development, care was taken to ensure that the mesh on the plan area of the panel-shear test specimen was compatible with that used for the rails. This ensured compatibility in the nodal results at the interface between the panel-shear test specimen and the rails. A single element represented the thickness of panel-shear test specimen. The user had the option of inputting a specific thickness or using the Monte Carlo method to randomly generate a thickness. Two elements with a thickness of 22 mm represented the thickness of the C16 timber rails.

Since the C16 timber rails are of no particular interest other than to investigate their influence on stresses in the panel-shear test specimen, they were modelled using the lower-order SOLID185 element. The SOLID185 element has the same basic geometry and capabilities as its higher-order counterpart but does not have the mid-side nodes as shown in Figure 5-25 and Figure 5-26 above for SOLID186 element (Kohnke, 2009a). This reduced the solution time without any loss of accuracy in terms of modelling the panel-shear test specimen.

5.6.8.4 Model Input

Table 5-5 below gives the material strength property inputs required by the 3-D version of the material subroutine. The experimental testing program focused primarily on evaluating the behaviour of OSB under the most common loading conditions to which it would be subjected in service. The testing program did not address the less common loading conditions such as out-of-plane tension and compression, planar-shear, panel-shear or other properties such as Poisson’s ratio. Despite the lack of experimental data, the user material subroutine has the ability to model these load conditions should experimental data become available in the future. For the purpose of this study, the input for these parameters was sourced from a combination of:
• Design values presented in BS EN 12369-1 (BSI, 2001),
• Quality control data supplied by Manufacturer A that included internal bond test results,
• Past literature on evaluating Poisson’s ratio for OSB (Thomas, 2003),
• Estimates based on experimental results for other material properties to produce realistic estimated values of these properties.

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<thead>
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<th>Input</th>
<th>Source^1)</th>
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</tr>
<tr>
<td>• Bearing Ultimate Strain, ( \varepsilon_{u,c,z} )</td>
<td>QC</td>
</tr>
<tr>
<td><strong>Panel-Shear</strong></td>
<td></td>
</tr>
<tr>
<td>• Ultimate Strength^2), ( \tau_{u,s,xy} )</td>
<td>MC/Exp/DC</td>
</tr>
<tr>
<td>• Ultimate Strain^2), ( \gamma_{u,s,xy} )</td>
<td>MC/Exp/DC</td>
</tr>
<tr>
<td><strong>Planar-Shear</strong></td>
<td></td>
</tr>
<tr>
<td>• Ultimate Strength, ( \tau_{u,s,yz} )</td>
<td>DC</td>
</tr>
<tr>
<td>• Ultimate Strain, ( \gamma_{u,s,yz} )</td>
<td>DC</td>
</tr>
<tr>
<td><strong>Plate-Shear</strong></td>
<td></td>
</tr>
<tr>
<td>• Ultimate Strength, ( \tau_{u,s,xz} )</td>
<td>Est</td>
</tr>
<tr>
<td>• Ultimate Strain, ( \gamma_{u,s,xz} )</td>
<td>Est</td>
</tr>
</tbody>
</table>

1) Explanation of symbols: Exp => Experimental data; MC => Generated by Monte Carlo Simulation; DC => Design value; QC => Quality control data from manufacturer
2) User has the option of using values generated by a Monte Carlo simulation or manually inputting experimental or design values

Table 5-5 – 3-D User Material Model Strength Properties Input

The model in its current form has only been validated for load conditions examined by the experimental test program. Further research will be needed to validate it for all remaining loading conditions. Table 5-6 below gives the inputs required to represent mechanical behaviour in the 3-D material model subroutine.
## Poisson’s Ratio
- $v_{xy}$
- $v_{yz}$
- $v_{xz}$

## Tension
- Longitudinal Coefficient, $a_{t,x}$
- Longitudinal Coefficient, $b_{t,x}$
- Lateral Coefficient, $a_{t,y}$
- Lateral Coefficient, $b_{t,y}$
- Internal Bond Elastic Modulus, $E_{I,z}$

## Compression
- Longitudinal Coefficient, $a_{c,x}$
- Longitudinal Coefficient, $b_{c,x}$
- Longitudinal Coefficient, $c_{c,x}$
- Lateral Coefficient, $a_{c,y}$
- Lateral Coefficient, $b_{c,y}$
- Lateral Coefficient, $c_{c,y}$
- Bearing Elastic Modulus, $E_{c,z}$

## Panel-Shear
- Coefficient, $a_{s,xy}$
- Coefficient, $b_{s,xy}$

## Planar-Shear
- Planar-Shear Modulus, $G_{s,yz}$

## Plate-Shear
- Planar-Shear Modulus, $G_{s,zx}$

### Table 5-6 – 3-D User Material Model Mechanical Behaviour Inputs

As was the case with the material strength properties, no experimental data was available to characterise the mechanical behaviour of OSB subjected to out-of-plane tension and compression, planar-shear or plate-shear. As stated in Chapter 1, the primary aim of this study is to develop models for predicting the material response and failure characteristics of OSB under the loading conditions that are of most interest to structural designers. The loading conditions not addressed by the experimental testing program are not regularly encountered in typical structural design problems. Hence, the precise nature of the stress and strain relationships for these loading conditions is of little interest to this study.

---

1) Explanation of symbols: Exp => Experimental data; MC => Generated by Monte Carlo Simulation; L => Literature; DC => Design value; QC => Quality control data from manufacturer
2) User has the option of using values generated by a Monte Carlo simulation or manually inputting experimental or design values
The 3-D version of the model represents the stress-strain relationship for these loading conditions using a simple linear elastic model based on the elastic constants for these loading conditions. These elastic constants have been sourced from design codes, past literature, quality control data supplied by Manufacturer A and estimates based on experimental results for other loading conditions. The user material subroutine has been designed to be easily modified to incorporate the necessary models to represent the mechanical behaviour under these loading conditions should the necessary experimental data become available.

5.6.8.5 Model Validation

Similar to the validation of the 2-D model described in Section 5.6.7.5 above, two separate sets of APDL scripts (one each for tension and compression) were written to validate the 3-D version of the user material model. Additionally, a third set of APDL scripts validated the 3-D version of the user material model to panel-shear loading. The first set of APDL scripts validated the material model by using it to reproduce experimental observations for mechanical behaviour recorded for a chosen set of test specimens. A second set of APDL scripts validated the 3-D version of the user material model for use in conjunction with Monte Carlo simulation.

A fourth set of standard APDL scripts were developed for constructing the geometry and the mesh as discussed in Section 5.6.8.3 above for the tension, compression and panel-shear test specimens. These were stored in a separate location and were made available to all model validation procedures. This simplified the APDL scripts used to validate the 3-D user material model subroutine because the procedures for generating geometry and mesh could be called from within the validation procedure using a single command. This eliminated the need to reproduce the code for generating geometry and mesh in each of the validation procedures.

5.6.8.5.1 Validation with Experimental Results

The first set of APDL scripts validated the 3-D model against experimental observations by inserting experimentally-determined values for ultimate strength and ultimate strain into the material model. The first set of APDL scripts
reproduced the experimental stress-strain curves, elastic moduli and failure loads for the single-layer, surface material OSB tension, compression and panel-shear test specimens in both directions. These APDL scripts performed the following tasks:

- Imported experimental values for the regression coefficients as defined in Table 5-6 above and substituted them into Equations (5.4) to (5.6) above,
- Imported the experimental results for ultimate strength, ultimate strain and thickness from tension, compression and panel-shear testing in both directions for the single-layer OSB panels,
- Called APDL scripts for generating test specimen geometry and mesh,
- Inputted experimental values for all the strength parameters described in Table 5-5 above and the mechanical behaviour parameters described in Table 5-6 above into the 3-D version of the user material model,
- Applied a displacement to one edge of the test specimens to represent the movement of the cross-head during experimental testing, (the applied displacement was such that it induced a strain at the mid-height of the specimen equal to the experimental ultimate strain value),
- Applied a zero displacement at the opposite end of the test specimen to represent the support during experimental testing,
- Solved the model using the ANSYS non-linear solver,
- Post-processed results, generated a contour plot showing the direct stresses parallel to the direction of loading and two scatter plots showing stress vs strain and load vs displacement respectively,
- Calculated the failure load and the elastic modulus for each test specimen,
- Output the results to text files for comparison with experimental results for each test specimen using an Excel 2010 VBA macro.

Figure 5-30 below shows the ANSYS graphical output for test specimen A-1-SURF-TENS-LONG generated by the 3-D version of user material model subroutine. Figure 5-31 below shows the ANSYS graphical output for test specimen A-1-SURF-TENS-LAT generated by the 3-D version of user material model subroutine.
Figure 5-30 – 3-D Model Validation ANSYS Output (A-1-SURF-TENS-LONG)

Figure 5-31 – 3-D Model Validation ANSYS Output (A-1-SURF-TENS-LAT)
The results presented in Figure 5-30 and Figure 5-31 above show a nearly uniform distribution of the tensile stress (shown in red) in the necked section of the test specimen. This is consistent with the findings discussed in Section 5.6.7.5.1 above for the validation of the 2-D version of the user material model. The legend shown on the bottom of Figure 5-30 above indicates that the tensile stress in the necked region in the range of 19.8 N/mm² to 21.2 N/mm². The detailed results presented in Appendix B shows that test specimen A-1-SURF-TENS-LONG failed at 20.11 N/mm². The legend shown on the bottom of Figure 5-31 above indicates that the tensile stress in the necked region in the range of 11.2 N/mm² to 11.9 N/mm². The detailed results presented in Appendix B shows that test specimen A-1-SURF-TENS-LAT failed at 11.12 N/mm². This demonstrates that the 3-D user material model subroutine predicted the ultimate tensile ultimate strength for these test specimens with good accuracy. Similar results were also obtained for the remaining tension test specimens in both directions.

Figure 5-32 and Figure 5-33 below show the predicted mechanical behaviour and load-displacement curves superimposed onto the experimentally-determined curves for A-1-SURF-TENS-LONG and A-1-SURF-TENS-LAT respectively.
Figure 5-33 – Predicted vs Experimental Results for A-1-SURF-TENS-LAT

The results demonstrate that the model accurately represents the non-linear behaviour of OSB subjected to in-plane tension in both directions. Figure 5-34 below shows the ANSYS graphical output for A-1-SURF-COMP-LONG.
Figure 5-35 below shows the graphical output for A-3-SURF-COMP-LAT.

The results presented in Figure 5-34 and Figure 5-35 above show a nearly uniform distribution of the compressive stress (shown in red) over the full height of the test specimen. This is consistent with the findings discussed in Section 5.6.7.5.1 above for the validation of the 2-D version of the user material model. The summary shown at the top of Figure 5-34 above indicates that the maximum compressive stress is in the range of 22.6 N/mm². The detailed results presented in Appendix B shows that test specimen A-1-SURF-COMP-LONG failed at 22.43 N/mm². The summary shown at the top of Figure 5-35 above indicates that the maximum compressive stress is in the range of 15.8 N/mm². The detailed results presented in Appendix B shows that test specimen A-3-SURF-COMP-LAT failed at 15.97 N/mm². This demonstrates that the 3-D model accurately predicted the tensile ultimate strength for these test specimens. Similar results were also obtained for the remaining tension test specimens in both directions.

Figure 5-36 and Figure 5-37 below show the predicted mechanical behaviour and resulting load-displacement curves superimposed onto the experimentally-
determined stress-strain and load displacement curves for test specimens A-11-SURF-COMP-LONG and A-12-SURF-COMP-LAT, respectively.

The results shown in Figure 5-36 and Figure 5-37 above demonstrate that the 3-D version of the user material model accurately represents the non-linear behaviour of OSB subjected to in-plane compression in both material directions.
Figure 5-38 below shows the predicted mechanical behaviour and resulting stress-strain curve superimposed onto the experimentally-determined stress-strain curve for test specimen A-7-SURF-S (PANEL)-LONG.

![Figure 5-38](image)

**Figure 5-38 – 3-D Material Validation (Longitudinal, Panel-Shear Behaviour)**

Figure 5-32 through to Figure 5-38 above demonstrate that the 3-D material model reproduced the experimental mechanical behaviour for single-layer OSB test specimens subjected to tension, compression and panel-shear loading.

5.6.8.5.2 *Validation with Monte Carlo Simulation*

The second set of APDL scripts (one for tension, one for compression and one for panel-shear) validated the 3-D version of the material model subroutine for use with Monte Carlo simulation. They demonstrated that influence of the random variability and the correlations between ultimate strength, ultimate strain, specimen thickness and density on the mechanical behaviour, elastic modulus and failure load of single-layer surface-material OSB panels could be predicted. These APDL scripts verified that this could be achieved using the 3-D user material model subroutine for single-layer surface-material OSB panels subjected to tension, compression and panel-shear loading in both material directions. This set of APDL scripts performed the following tasks:
Imported the probabilistic data determined from the statistical analysis program as described in Chapter 4 above for the strength parameters defined in Table 5-5 above, global density and specimen thickness,

- Built model geometry and generated the mesh,
- Defined the number of Monte Carlo simulation loops,
- Declared global density, thickness, ultimate strength and ultimate strain for tension, compression and panel-shear as random input variables,
- Defined correlations between random input variables,
- Declared failure load and elastic modulus as random output variables,
- Generated values for the input variables using Monte Carlo simulation,
- Inputted the randomly-generated values for strength parameters described in Table 5-5 above and mechanical behaviour parameters described in Table 5-6 above into the 3-D version of the user material model,
- Applied a displacement to one edge of the test specimens to represent the movement of the cross-head during experimental testing, (the applied displacement was such that it induced a strain at the mid-height of the specimen equal to the simulated ultimate strain value),
- Applied a zero displacement at the opposite end of the test specimen to represent the support during experimental testing,
- Solved the model using the ANSYS non-linear solver,
- Post-processed results, generated a contour plot showing the direct stresses parallel to the direction of loading and two scatter plots showing stress vs strain and load vs displacement respectively,
- Calculated failure load and elastic modulus results for each loop,
- Outputted the results to text files for comparison with experimental results for each test specimen using an Excel 2010 VBA macro.

Figure 5-39 below shows the simulated longitudinal compression stress-strain relationships generated by the 3-D material validation run for the A-SURF panels. Figure 5-40 below shows the experimental stress-strain curves obtained for the A-SURF panels loaded in longitudinal compression.
Figure 5-39 – 3-D Material Model Validation (Simulated Compression Behaviour)

Figure 5-40 – 3-D Material Model Validation (Experimental Compression Behaviour)

Figure 5-41 below shows a typical simulated averaged stress-strain curve superimposed into the corresponding experimental averaged stress-strain curve.
Figure 5-41 – 3-D Model Validation (Average Stress Strain Curve)

Figure 5-42 below shows the predicted EDF for the elastic modulus obtained from the validation run for the A-SURF panels in longitudinal compression.
Figure 5-42 and Figure 5-43 below show the predicted EDF plots for the elastic modulus and failure load respectively obtained from the validation run for the A-SURF panels loaded in longitudinal compression.

![Simulated vs Experimental Failure Load](image)

Figure 5-43 – 3-D Material Model Validation (EDF Plot for Compression Failure Load)

Figure 5-39 above demonstrates that the stress-strain curves generated by Monte Carlo simulation for A-SURF OSB panels loaded in longitudinal compression exhibit similar variability to the experimental equivalents shown in Figure 5-40 above up to the ultimate strength. Note that the post-failure behaviour in compression has not been considered as part of this study. Model test specimens were loaded to their ultimate strain in order to ensure the stress behaviour at all possible strain levels could be determined. The results presented in Figure 5-41 above demonstrate that the average of the simulated stress-strain curves matches almost exactly the average of the experimental stress-strain curves. This demonstrates that the 3-D version of the user material model subroutine is suitable for use with Monte Carlo simulation because it captures the random variability without altering the overall average behaviour.

Figure 5-42 and Figure 5-43 above show that the combination of the 3-D version of the material model and Monte Carlo simulation correctly predicted the
probability distribution for global elastic modulus and failure load, respectively. For single-layer OSB, the validation run predicted that the longitudinal compressive elastic modulus was lognormally distributed with a mean of 3296 N/mm\(^2\) and a standard deviation of 267 N/mm\(^2\). The model predicted the mean failure load 53.5 kN with a standard deviation of 3.55 kN. Comparison with the experimental values shows that the model overestimated the mean longitudinal compressive elastic modulus by 3.94% and underestimated the mean failure load by 2.55%.

The error in the failure load predictions obtained from the validation runs of the 2-D version of the user material model showed a higher margin of error when compared to experimental values. However, unlike the validation runs of the 3-D version, the validation runs of the 2-D version did not include the variability in panel thickness. It is likely that this improvement can be at least partially attributed to treating the variation in panel thickness as a random input parameter in the Monte Carlo simulation.

5.6.8.6 Remarks

The results of these validation exercises prove that the 3-D version of the model can be used to predict the in-plane tension and compression properties with similar degrees of accuracy as the 2-D version. The improvement in terms of failure load prediction accuracy is more likely due to treating the variation in panel thickness as a random input variable.

The 3-D version of the model is capable of representing the mechanical behaviour of all loading conditions and Poisson’s effects. Any loading conditions, whose mechanical behaviour has not been assessed in the experimental programme, have been represented using linear models. Elastic properties for these loading conditions as well as Poisson’s effects have been obtained from a variety of sources as detailed in Table 5-5 and Table 5-6 above and have been treated as constants throughout the model validation exercises. However, the 3-D material model subroutine can be upgraded to represent these loading conditions once the necessary experimental data becomes available. The variability of these properties could also be represented using knowledge of the
probability distribution models they are known to follow and Monte Carlo simulation using the same approach.

The most significant improvement the 3-D version of the model offers over the 2-D version is that it could be validated for panel-shear loading. Section 5.6.7.1 above mentions that the 2-D version of the model can represent the panel-shear behaviour of OSB provided the geometry of the system can be accurately represented in two dimensions. However, the 2-D version could not be validated for panel-shear because the geometry of the panel-shear test specimen is a three-dimensional shape. Section 5.6.7.1 above also indicates that the 2-D version of the model uses the identical equation as the 3-D version to represent the panel-shear behaviour. The results show that the 3-D version of the model is suitable for representing the mechanical behaviour of single-layer OSB loaded in panel-shear. Therefore, it is possible to state that the 2-D version can also be considered to be validated.

5.7 18 mm Thick Three-Layered Commercial OSB/3 Panels

5.7.1 Introduction

The user material model subroutines discussed in Section 5.6 above have been shown to be effective at representing the mechanical behaviour and random variability of single-ply OSB panels. The discussion of laminated plate theory presented in Section 5.3 above describes how the properties of a single ply of an anisotropic material can be used to calculate the resultant properties of a multiply laminate of the same material.

The next phase of the modelling study was to use the user material model in conjunction with Monte Carlo simulation and laminated plate theory to predict the properties of typical commercial OSB/3 panels. Chapter 3 describes how the single-layer OSB panels were made using commercial 18 mm thick OSB/3 panels produced by Manufacturer A. Since there is no guarantee that the layer properties of the other materials are the same as those determined from single-layer OSB panel tests, this phase of the modelling study has been limited to the 18 mm thick panels produced Manufacturer A. Further testing is required to
assess the layer properties of a range of OSB products to allow for comparisons between materials to be made. The 3-D version of the user material model subroutine has been used for this part of the study.

5.7.2 Panel Structure Model

The structure of the single-layer OSB panels used in the validation runs described in Section 5.6 above is relatively straightforward. It can be accurately defined using two parameters (i.e. density and thickness). The structure of a standard three-layered commercial OSB panel is more complex and has a significant influence over the structural performance of typical commercial OSB/3 panels. Chapter 2 outlines how past research has identified that the density profile, the flake orientations and relative thicknesses of the constituent layers have a significant impact on the behaviour of these materials. It is therefore incorrect to ignore the board structure when attempting to model such materials.

Typical commercial OSB/3 panels are typically described as a three-layered material because they are manufactured using three discrete layers of wood strands stacked in a 0-90-0 stacking sequence (see Chapter 1). Closer examination, however, reveals that the structure of OSB is far more complex. OSB can be more accurately described as being a multi-layered material where the layers are defined not only by the orientation of the wood strands but also by variations in density, thickness and mechanical properties. The results from experimental testing of single-layer OSB panels, described in Chapter 3, demonstrated the difference in mechanical performance between the surface and core-layers of OSB. A study by Steidl et al. (2003) made similar findings on commercially-available OSB panels. The results from the experimental testing program and by Steidl et al. showed that the structural properties through the thickness of commercial OSB/3 panels are strongly correlated with the density, thickness of the layer and strand orientation.

The approach adopted by this study was to discretise standard three-layered OSB panels into a finite number of layers. Figure 5-44 below shows multi-layer discretisation approach applied to a typical commercial OSB/3 panel. Each layer
is defined by a thickness, a density and a strand orientation. The mechanical properties for each layer can be determined empirically based on the thickness, density and flake orientation. Figure 5-44 below demonstrates how discretising commercial OSB/3 panels into several layers of varying thickness, density and flake orientation can be used to model the true panel structure. Reducing the layer thicknesses will improve the accuracy of the model but will add significantly to the complexity resulting in longer model runs. A balance must therefore be struck in order to ensure the panel structure model is reasonably accurate but can still be solved in a reasonable time with the equipment available.

For the purposes of this study, the panel structure has been simplified to a symmetric seven-layer structure shown in Figure 5-45 below.

Figure 5-44 – Layer Discretisation of Commercial OSB Panel

Figure 5-45 – Seven Layer Panel Structure Model
Note that this seven-layer model was used by the algorithm to calculate the vertical density profile properties as discussed in Section 3.6.2.4 above. Table 5-7 below summarises the inputs for randomly generating panel structures.

<table>
<thead>
<tr>
<th>Property</th>
<th>Symbol</th>
<th>Probability Distribution</th>
<th>First Moment</th>
<th>Second Moment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Density (kg/m³)</td>
<td>$\rho_s$</td>
<td>Lognormal</td>
<td>686</td>
<td>56.7</td>
</tr>
<tr>
<td>Core Density (kg/m³)</td>
<td>$\rho_c$</td>
<td>Lognormal</td>
<td>499</td>
<td>32.2</td>
</tr>
<tr>
<td>Surface thickness (mm)</td>
<td>$t_s$</td>
<td>Lognormal</td>
<td>3.49</td>
<td>0.45</td>
</tr>
<tr>
<td>Core thickness (mm)</td>
<td>$t_c$</td>
<td>Normal</td>
<td>10.9</td>
<td>0.82</td>
</tr>
<tr>
<td>Surface Damage (mm)</td>
<td>$t_{s,\text{dam}}$</td>
<td>Uniform</td>
<td>$4.04 \times 10^{-3}$</td>
<td>$6.87 \times 10^{-1}$</td>
</tr>
</tbody>
</table>

**Table 5-7 – 18 mm Panel Structure Model Inputs**

The Monte Carlo method generated values for layer density, thickness and mechanical properties for each of the seven layers in the panel structure. The layers could then be assembled to form a laminate that could in turn be implemented in a finite element model. The global density and total thickness of the simulated panel structures were defined as response variables. Figure 5-46 and Figure 5-47 below show the simulated overlaid onto the experimental EDF for global density and specimen thickness respectively.

![Simulated vs Experimental Global Density](image)

**Figure 5-46 – EDF Plot of Simulated vs Experimental Global Density**
The results show that the model predicted the correct probability distribution for the global density and the specimen thickness. The model predicted that the global density was normally distributed with a mean of 569.5 kg/m$^3$ and a standard deviation of 41.5 kg/m$^3$ and that the total thickness was normally distributed with a mean of 18.33 mm and a standard deviation of 0.82 mm. When compared to the experimental results, the model predicted the mean global density with no significant error while the model overestimated the total thickness by just 1.3%. The model overestimated the standard deviation of the global density by 9.6% and overestimated the standard deviation of the total thickness by 13.6%. The results demonstrate that the Monte Carlo simulation routine was capable of accurately representing the structure of commercial 18 mm thick OSB/3 panels.

5.7.3 Material Model Inputs

5.7.3.1 Mechanical Behaviour

Table 5-8 below gives the values for the mechanical behaviour coefficients used to model the 18 mm thick commercial OSB/3 panels.
<table>
<thead>
<tr>
<th>Load Condition</th>
<th>Coefficient</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal Tension</td>
<td>$\hat{a}_{t,x}$</td>
<td>-0.2592</td>
</tr>
<tr>
<td></td>
<td>$\hat{b}_{t,x}$</td>
<td>1.2655</td>
</tr>
<tr>
<td>Longitudinal Compression</td>
<td>$\hat{a}_{c,x}$</td>
<td>-0.7808</td>
</tr>
<tr>
<td></td>
<td>$\hat{b}_{c,x}$</td>
<td>-0.7058</td>
</tr>
<tr>
<td></td>
<td>$\hat{c}_{t,x}$</td>
<td>1.0813</td>
</tr>
<tr>
<td>Lateral Tension</td>
<td>$\hat{a}_{t,y}$</td>
<td>-0.4037</td>
</tr>
<tr>
<td></td>
<td>$\hat{b}_{t,y}$</td>
<td>1.4209</td>
</tr>
<tr>
<td>Lateral Compression</td>
<td>$\hat{a}_{c,y}$</td>
<td>-0.9109</td>
</tr>
<tr>
<td></td>
<td>$\hat{b}_{c,y}$</td>
<td>-0.6583</td>
</tr>
<tr>
<td></td>
<td>$\hat{c}_{c,y}$</td>
<td>1.2429</td>
</tr>
<tr>
<td>Panel-Shear$^1)$</td>
<td>$\hat{a}_{s,xy}$</td>
<td>-0.3461</td>
</tr>
<tr>
<td></td>
<td>$\hat{b}_{s,xy}$</td>
<td>1.3453</td>
</tr>
</tbody>
</table>

1) Regression coefficients for panel-shear loading have been taken as the average of those obtained for the longitudinal and lateral experimental data.

Table 5-8 – Mechanical Behaviour Coefficients

Figure 5-48 below shows the stress-strain relationships for tension and compression loading in both material directions on which the values in Table 5-8 above are based.
Figure 5-49 below shows the stress-strain relationships for panel-shear loading in both material directions on which the values in Table 5-8 above are based.

![Stress-Strain Relationship](image)

Figure 5-49 – Normalised Stress-Strain Relationships (Panel-Shear)

### 5.7.3.2 Strength Properties

The seven-layer panel structure model shown in Figure 5-45 above is accompanied by two material models (one for low density layers and one for high density layers). The 3-D version of the user material subroutine represented the mechanical behaviour for both the high density and low density layers in commercial OSB/3 panels. The Monte Carlo method simulated the random variability in the mechanical behaviour, layer thickness and layer density. The simulated values property accounted for the correlation between each property within layers and using the correlation matrix. The simulated values for each layer were assembled and input to the section data table for the layered version of the SOLID186 element to represent the commercial 18 mm thick OSB panel.

Table 5-9 below provides details of the inputs used to generate random values for ultimate strength and ultimate strain for each loading condition and material directions for the high density layers.
Table 5-9 – High-Density Layer Material Strength Properties

As mentioned in Chapter 4, the limited sample size meant that many of the statistical analysis techniques could not be applied to the results from A-CORE panels with any degree of confidence. However, the seven-layer model requires the same information about the mechanical behaviour and variability of the core-layer as described in Table 5-8 and Table 5-9 above for the surface-layer. To overcome this difficulty, the core-layer mechanical behaviour and variability properties were estimated based on the results of the A-SURF OSB panel results and the density profile results from the commercial 18 mm thick OSB/3 panels based on the following assumptions:

1) The normalised stress-strain relationships for the surface-layer and core-layer materials are identical,
2) The relationship between material strength properties and layer density for the surface-layer remains the same in the core-layer material,
3) The coefficient of variation for the core-layer strength properties remain the same as their surface-layer strength properties,
4) The core-layer strength properties follow the same probability distributions as their surface-layer counterparts.

The first assumption implies that the mechanical behaviour coefficients presented in Table 5-8 above for the high-density layers can also be used for low-density layers. Figure 5-50 below shows the normalised stress-strain curves for all OSB materials loaded in longitudinal tension superimposed onto each other.

![Normalised Stress-Strain Relationships](image)

**Figure 5-50 – Comparison of Normalised Stress-Strain Relationships**

The results shown in Figure 5-50 above show that the normalised stress-strain relationships for all the materials tested remain constant. It is therefore valid to assume that this holds true for the A-CORE OSB panels. The second and third assumptions allow the first and second statistical moments for the low-density layers to be estimated based on the results of the surface-layers.

Figure 5-51 below shows a plot of tensile ultimate strength versus layer density. Note that the plot shown in Figure 5-51 below includes the four results obtained from the A-CORE OSB panel tests.
Figure 5-51 – Tensile Ultimate Strength vs Layer Density

The results show that the same relationship can provide a reasonably good description of the relationship between ultimate strength and average density regardless of layer. The core-layer density of 18 mm thick commercial panels produced by Manufacturer A has been extensively evaluated as described in Chapter 4. This means that the regression equations shown in Figure 5-51 above (and similarly for other loading conditions) can be used to estimate the first statistical moments of the core-layer strength properties. The third assumption allows the second statistical moments of the core-layer strength properties to be estimated based on the second statistical moments of the surface-layer strength properties using Equation (5.7) below.

\[ \sigma_c = \mu_c \times CV_s \]  

(5.7)

where:  
\( \sigma_c \) = Second statistical moment of core-layer strength property;  
\( \mu_c \) = First statistical moment of core-layer strength property (estimated based on average core density);  
\( CV_s \) = Coefficient of variation of corresponding surface-layer strength property.
Table 5-10 below gives details of the inputs used by the Monte Carlo simulation routine to generate random values for ultimate strength and ultimate strain for each loading condition and material direction for the low density layers.

<table>
<thead>
<tr>
<th>Property</th>
<th>Symbol</th>
<th>Probability Distribution</th>
<th>First Moment</th>
<th>Second Moment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Longitudinal Tension</strong></td>
<td>( \sigma_{ut,x} )</td>
<td>Normal</td>
<td>8.87</td>
<td>1.31</td>
</tr>
<tr>
<td></td>
<td>( \varepsilon_{ut,x} )</td>
<td>Normal</td>
<td>2.63 \times 10^{-3}</td>
<td>3.64 \times 10^{-4}</td>
</tr>
<tr>
<td><strong>Longitudinal Compression</strong></td>
<td>( \sigma_{uc,x} )</td>
<td>Lognormal</td>
<td>3.57</td>
<td>0.354</td>
</tr>
<tr>
<td></td>
<td>( \varepsilon_{uc,x} )</td>
<td>Lognormal</td>
<td>3.13 \times 10^{-3}</td>
<td>4.04 \times 10^{-4}</td>
</tr>
<tr>
<td><strong>Lateral Tension</strong></td>
<td>( \sigma_{ut,y} )</td>
<td>Lognormal</td>
<td>12.2</td>
<td>0.966</td>
</tr>
<tr>
<td></td>
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<td>Normal</td>
<td>6.53 \times 10^{-3}</td>
<td>5.44 \times 10^{-4}</td>
</tr>
<tr>
<td><strong>Lateral Compression</strong></td>
<td>( \sigma_{uc,y} )</td>
<td>Lognormal</td>
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<td>0.679</td>
</tr>
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<td>( \varepsilon_{uc,y} )</td>
<td>Lognormal</td>
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<td>9.07 \times 10^{-4}</td>
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<td><strong>Longitudinal Panel-Shear</strong></td>
<td>( \sigma_{us,xy} )</td>
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<td>0.752</td>
</tr>
<tr>
<td></td>
<td>( \varepsilon_{us,xy} )</td>
<td>Normal</td>
<td>7.78 \times 10^{-3}</td>
<td>1.22 \times 10^{-3}</td>
</tr>
<tr>
<td><strong>Longitudinal Panel-Shear</strong></td>
<td>( \sigma_{us,yx} )</td>
<td>Normal</td>
<td>6.93</td>
<td>0.612</td>
</tr>
<tr>
<td></td>
<td>( \varepsilon_{us,yx} )</td>
<td>Lognormal</td>
<td>8.59 \times 10^{-3}</td>
<td>1.09 \times 10^{-3}</td>
</tr>
</tbody>
</table>

Table 5-10 – Low-Density Layer Material Strength Properties

5.7.3.3 Poisson’s Ratio

The literature review highlighted that little or no work has been done on evaluating the Poisson’s ratio of OSB. A paper by Thomas (2003) contains the only documented research uncovered by this study on this topic. Thomas’ method used only on a very small sample size (10 replications) to evaluate the in-plane Poisson’s ratios of a commercial OSB using a Demec gauge to record displacements in two directions at three gauge points. Despite the crudeness of the instrumentation combined with the limited sample size, Thomas demonstrated that OSB has principle Poisson’s ratios that fall within the range of the principle Poisson’s ratios in the longitudinal-tangential plane of solid-round wood. This led him to conclude that his estimated values of 0.23 and 0.16 for \( \nu_{xy} \)
and $\nu_{yx}$ respectively were reasonably accurate. This study relied on the assumption that $\nu_{xy} = \nu_{yz} = \nu_{xz}$ and used Thomas’ mean value of 0.23 throughout. The remaining Poisson’s ratios have been estimated using the same reciprocal relationship as Clouston (2001, 2001) given in Equation (5.8) below.

$$\frac{\nu_{ij}}{E_i} = \frac{\nu_{ji}}{E_j} \quad (5.8)$$

### 5.7.4 Results

#### 5.7.4.1 Tension Behaviour

Figure 5-52 below shows the model predictions for load-displacement behaviour obtained for 18 mm commercial OSB/3 panels produced by Manufacturer A loaded in longitudinal tension.

![Load vs Displacement](image)

**Figure 5-52 – Simulated Load-Displacement Curves (18 mm, Longitudinal Tension)**

Figure 5-53 below shows the resultant stress-strain curves calculated from the load-displacement curves shown above in Figure 5-52.
Figure 5-53 – Simulated Stress-Strain Curves (18 mm, Longitudinal Tension)

Figure 5-54 below shows the experimental stress-strain curves for 18 mm thick OSB/3 panels produced by Manufacturer A loaded in longitudinal tension.

Figure 5-54 – Experimental Stress-Strain Curves (18 mm, Long. Tension)

Figure 5-55 below shows the simulated and experimental averaged stress-strain curves for the A-18 mm OSB/3 panels in longitudinal tension.

Figure 5-55 – Stress-Strain Relationships
Manufacturer A, 18mm, Longitudinal

Figure 5-55 – Experimental Stress-Strain Curves (18 mm, Long. Tension)
Figure 5-55 – Averaged Stress-Strain Curves (18 mm, Longitudinal Tension)

Figure 5-56 below shows the model’s prediction for the EDF plot compared against the experimental EDF for elastic modulus in longitudinal tension.
The results presented in Figure 5-52 to Figure 5-56 above suggest that the approach of discretising commercial three-layered OSB/3 panels is a valid approach. The load-displacement and the stress-strain curves shown in Figure 5-52 and Figure 5-53 above respectively show that this approach is capable of capturing the variability of the mechanical behaviour of the material. However, Figure 5-54 above demonstrates that the simulated and experimental stress-strain curves are practically identical. This suggests that the simulated mechanical behaviour represents the experimental mechanical behaviour with good accuracy.

It is noted that the simulated stress-strain curves shown in Figure 5-53 above appear to be clustered together more closely than their experimental counterparts shown in Figure 5-54 above. This suggests that discretising the internal structure of the panel using seven layers loses a certain amount of accuracy in terms of fully capturing the degree-of-variability. This is reflected in the EDF plot for elastic modulus shown in Figure 5-56 above. The model correctly predicted that the elastic modulus in longitudinal tension is normally distributed with a mean of 3755 N/mm². However, the model predicted that a standard deviation of 221 N/mm² whereas the experimental value is almost double that with a value of 433 N/mm². This confirms that discretising the panel into seven layers loses some of the sensitivity in terms of capturing the variability of the material. A more rigorous discretisation such as the schematic shown in Figure 5-44 above is likely to greatly enhance the accuracy of this aspect of the model. The experimental data discussed in Chapter 3 showed that many of the OSB specimens had asymmetric density profiles. This means that the surface density on one face is significantly different than the other. This density profile is modelled assuming that the density profile is perfectly symmetric in all cases. This is unlikely to be the case with all real OSB panels. Expanding the model capabilities to cope with asymmetric density profiles is likely to improve the ability of the model to capture the variability in mechanical behaviour.

5.7.4.2 Compression Behaviour

Figure 5-57 below shows the model predictions for the stress-strain curves for 18 mm thick commercial OSB/3 panels produced by Manufacturer A.
Figure 5-57 – Simulated Stress-Strain Curves (18 mm, Longitudinal Compression)

Figure 5-58 below shows the equivalent experimental stress-strain curves for 18 mm thick commercial OSB/3 panels produced by Manufacturer A.

Figure 5-58 – Experimental Stress-Strain Curves (18 mm, Longitudinal Compression)
Figure 5-59 below shows the simulated and experimental averaged stress-strain curves for 18 mm thick commercial OSB/3 panels in longitudinal compression.

![Graph of Average Stress V's Strain](image)

**Figure 5-59 – Averaged Stress-Strain Curves (18 mm, Longitudinal Compression)**

Figure 5-60 below shows the model prediction for the EDF plot compared against the experimental EDF for elastic modulus in longitudinal compression.

![Graph of Simulated vs Experimental Elastic Modulus](image)

**Figure 5-60 – Predicted vs Experimental EDF Plot, Elastic Modulus**
The results presented in Figure 5-57 through to Figure 5-60 above suggest that the approach of discretising commercial three-layered OSB panels into layers works reasonably well but not as well as it did for the tension case. The stress-strain curves shown in Figure 5-57 above show that the resultant stress-strain curves predicted by the model show a similar degree of scatter to those obtained by experimental testing as seen in Figure 5-58 above. Figure 5-59 above shows that the model accurately represents the mechanical behaviour of the material in the linear elastic range but that significant differences occur at high strains. The model predictions would likely be improved by using a more rigorous layer discretisation scheme like shown schematically in Figure 5-44 above.

The model correctly predicted the correct probability distribution for the elastic modulus in longitudinal compression. The model predicted that the elastic modulus was lognormally distributed with a mean of 2299 N/mm² with a standard deviation of 193 N/mm². The model overestimated the mean by 6.8% and predicted the standard deviation almost exactly. This proves that the model accurately captures the variability of the system.

5.8 Concluding Remarks

The results presented in this chapter demonstrate that it is possible to accurately predict the resultant material properties and mechanical behaviour of commercial OSB/3 panels using the stochastic finite element method. Discretising commercial OSB/3 panels into multi-layered materials based on the vertical density profile and strand orientation and treating them in a similar manner to laminate fibre-reinforced polymers proved efficient. It enabled the material’s internal structure to be accurately modelling using the build in lamination theory available in ANSYS without using an excessive number of elements thus producing favourable solution times. The custom-developed user material model also proved highly effective at reproducing the orthotropic, non-linear material behaviour observed in the experimental testing program. The Monte Carlo method proved to be an effective tool for reproducing the variability in the physical properties, the material properties and mechanical behaviour observed in the experimental testing program.
6 Conclusions

6.1 Introduction

The wood-based composites industry produces quality construction materials that are environmentally-friendly, sustainable, renewable and economically viable. Despite this, engineered wood products pose a unique set of challenges to producers and designers alike due to their orthotropic, non-linear behaviour and due to the variability in the properties.

In the present work, OSB, a wood-based panel product has been studied with a view to:

- Developing a sound understanding of the parameters that influence the behaviour of OSB,
- Using this knowledge, to develop a probability-based tool capable of predicting the influence of changes in these parameters on the OBS performance.

The methodology used to achieve these objectives involved:

- Developing a database of mechanical and physical properties of OSB,
- Characterising the variability in these properties by identifying appropriate probability distributions and determining the co-relations between these properties,
- Developing a stochastic finite element model that can accurately capture the variability in the behaviour of OSB under a variety of loading scenarios.

The outcomes offer significant potential to OSB producers in terms of new product development and to designers seeking to use OSB in structural applications.

The findings of the research are presented under three headings corresponding to the three approaches used: experimental testing, statistical analysis and numerical modelling.
6.2 **Experimental Testing**

The experimental testing program established the necessary data to properly characterise the physical structure and the mechanical properties of existing commercially-available OSB products. All OSB products used throughout this study conformed to BS EN 300 (BSI, 2006). Additional experimental work assessed the mechanical properties of individual layers of OSB.

The experimental testing program assessed a total of five different OSB/3 products in three different thicknesses made by three different manufacturers. This approach allowed comparisons to be made between panels made with different raw materials, producers and in different thicknesses. In addition, single OSB plies taken from the surfaces and the core of 18 mm thick commercial OSB/3 panels were tested. The test programme involved testing full commercial OSB/3 panels and the single-layer OSB panels in tension, compression, bending and panel-shear. The sample size in most cases was 15. Strength and elastic modulus properties were determined for each loading scenario. In general, a comparison of the test results and the code values showed that the measured elastic moduli exceeded the code values for all load cases. Some of the panels had 5\textsuperscript{th} percentile strength values lower than the code values when loaded in tension, compression and panel-shear.

The global density and the vertical (or through-thickness) density profile were established for each case. The density profile results showed that the core density was significantly lower than the surface density. The mean core thickness varied between 55.8\% and 59.4\% of the total sample depth for all 997 samples tested. A simplified stepped model was developed to represent the variation of density through the depth.

6.3 **Statistical Analysis**

A variety of statistical analysis methods have been successfully adapted to develop probabilistic models for different properties of OSB.

The Anderson-Darling test successfully identified appropriate probability distribution models to describe the variability for most parameters. Probability
plots provided a visual aid to compliment the Anderson Darling test by allowing users to make visual comparisons between EDF plots of experimental data and CDF plots for different probability distributions. The results show that, for the majority of cases, either normal or log-normal probability distribution models are suitable for describing the variability observed in the experimental data.

Using polynomial regression analysis, empirical stress-strain relationships were established for each loading condition. Quadratic polynomial models were established for tension, bending and panel-shear loading but a cubic model was required for the compression loading. A unified stress-strain curve was developed for each loading condition by normalising the stress and strain with respect to the ultimate strength and ultimate strain, respectively. The empirical equations derived from the regression analyses formed the basis for the development of the user material model subroutine implemented in the stochastic finite element model.

The Pearson’s correlation coefficient identified correlations between different input parameters and played a key role during Monte Carlo simulation by ensuring that the simulated system accurately represented the actual system. Therefore, it can be concluded that the statistical analysis program successfully provided all necessary information regarding the variability of the system, the mechanical behaviour and the relationships between the various input parameters.

A larger sample size would allow for more rigorous statistical analyses including non-stationary stochastic processes. The computer program developed during this study to perform the statistical analyses is capable of automatically updating itself to include additional test results as they become available. Therefore, it will be very easy to update the database in the future as more experimental data become available. The software could then be upgraded to conduct more rigorous statistical analyses including non-stationary effects.
6.4 Numerical Modelling

A stochastic finite element model has been developed, which incorporates a user material model to account for the orthotropic nonlinear mechanical behaviour of OSB. The results of the numerical modelling demonstrate that the user material model subroutines represented the mechanical behaviour of single-layer OSB panels with excellent agreement with experimental results.

The results demonstrated the effective implementation of the statistical information gathered by the statistical analysis program in a stochastic finite element model. Not only did the model accurately represent the mechanical behaviour of OSB but also accurately represented the natural variability of the material.

The layer discretisation approach used in the model showed that lamination theory can be effectively used to predict the resultant properties of multi-ply cross-laminated OSB panels by splitting the panel into a finite number of layers. This approach could theoretically be used in optimisation studies to determine optimum panel layups and density profiles targeted at specific applications.

For the particular layer discretisation scheme used in this study, some of the variability observed for the three-layered OSB panels was lost. A schematic alternative layer discretisation scheme that more accurately represents the density profile and consequently, the variation in mechanical properties through the thickness of the commercial OSB/3 panels should improve the predicted response.

Another simplification that is likely to be partly responsible for discrepancies in variability between experimental and simulated mechanical properties is that the in-plane variation of the density profile has not been included. All elements in the models are assumed to have the same density profile and consequently, the same mechanical properties. The results of the density profile tests showed that the density profile can vary quite considerably within panels and even within test specimens. Excluding the in-plane variability of the density profile is naturally
going to result in the model underestimating the variability of the output variables.

Given the simplicity of the seven-layered model adopted for this study, the model predicted the probability distribution of the elastic modulus in tension and compression with remarkable accuracy. The accuracy achieved using such a simple discretisation scheme demonstrates that applying laminated plate theory can potentially be extremely useful for estimating the resultant properties of commercial OSB products based on their density profile.

### 6.5 Further Research

Despite the significant advances that have been made in this work in providing a probabilistic basis for advancing the design and development of OSB, the current research could only take into account certain aspects of OSB. Care was taken to ensure that the primary focus of the project was to develop a unified approach to predicting the behaviour of OSB subjected to the most common loading conditions to which it will be subjected in service. However, there are several other loading conditions that have not been directly addressed including internal bond, bearing, plate-shear and planar-shear. The behaviour of OSB when loaded in these loading conditions could be better represented in the 3-D version of the user material model with the availability of the necessary experimental data.

Other improvements that could be made in terms of the experimental testing program include increasing the sample sizes by testing additional specimens. Large sample sizes facilitate the use of large-sample statistical analysis methods, which are inherently more accurate than small-sample statistical analysis methods. The computer program developed during this study to perform the statistical analyses is capable of automatically updating itself to include additional test results as they become available. Therefore, it will be very easy to update the database in the future as more experimental data becomes available. The software could then be upgraded to conduct more rigorous statistical analyses including analysis-of-variance (ANOVA) and non-stationary analysis.
Furthermore, there are several other parameters that are known to impact on the mechanical performance of OSB such as flake size and geometry, degree-of-strand orientation, moisture content and resin content that have now been addressed by this research. These parameters could be experimentally determined and their probability distributions could be assessed using the same methods used in the current work.

### 6.6 Concluding Remarks

There is significant potential to broaden the scope and functionality of the stochastic finite element model. Despite reporting good results, the model has only been validated for relative simple geometry subject to major assumptions in terms of the variability of the density profile. The model as presented here can easily be modified to include the effects of all other physical parameters mentioned above.

Despite the limitations in the scope of the current work, the approach taken has proved highly effective at experimentally evaluating the physical properties and mechanical performance of commercial and custom-produced OSB panels. The custom-developed software and statistical analysis techniques proved highly effective at:

- Extracting the necessary probabilistic information from an experimental results database to describe the variability of OSB,
- Producing mathematical models to accurately describe the true non-linear behaviour of OSB under tension, compression, bending and panel-shear loading,
- Establishing relationships between physical properties and mechanical behaviour under different loading conditions.

The modelling methods developed here have proved that user material model subroutines are highly effective at representing the orthotropic, non-linear mechanical behaviour of OSB for the loading conditions examined by the experimental testing program. It is likely that the user material subroutine developed for this study could also be used to accurately represent the
mechanical behaviour of OSB under plate-shear, planar-shear, internal bond and bearing loading. The user material model subroutine also proved highly effective at representing the different mechanical behaviour characteristics between the different types of loading conditions. The Monte Carlo method proved highly effective at accurately representing the variability of the mechanical behaviour of OSB in a finite element model. This study also demonstrated that it is possible to adapt laminated plate theory to accurately predict the mechanical behaviour of multi-layered, cross-laminated OSB products based on the stacking sequence and mechanical properties of the constituent layers. This study also showed that the combination of laminated plate theory, Monte Carlo simulation, finite element analysis and user material models can also predict the natural variability of multi-layered, cross-laminated OSB products.

In conclusion, this study has developed the necessary methodology and tools to predict the mechanical behaviour and natural variability of multi-layered, cross-laminated OSB panels based on the internal structure of the constituent layers. The template used for this study could easily be implemented on much larger scale studies seeking to develop a fully scientific approach for OSB production control and to assist designers to develop new OSB products.
7 References


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Appendix A– Cutting Patterns

Refer to enclosed DVD for Appendix A
Appendix B– Experimental Results

Refer to enclosed DVD for Appendix B
Appendix C– Statistical Analysis Results

Refer to enclosed DVD for Appendix C
Appendix D– Numerical Model Results

Refer to enclosed DVD for Appendix D