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Title	Modelling the hygro-mechanical creep behaviour of FRP reinforced timber elements
Author(s)	O'Ceallaigh, Conan; Sikora, Karol; McPolin, Daniel; Harte, Annette M.
Publication Date	2020-06-20
Publication Information	O'Ceallaigh, Conan, Sikora, Karol, McPolin, Daniel, & Harte, Annette M. (2020). Modelling the hygro-mechanical creep behaviour of FRP reinforced timber elements. <i>Construction and Building Materials</i> , 259, DOI:10.1016/j.conbuildmat.2020.119899
Publisher	Elsevier
Link to publisher's version	<a href="https://doi.org/10.1016/j.conbuildmat.2020.119899">https://doi.org/10.1016/j.conbuildmat.2020.119899</a>
Item record	<a href="http://hdl.handle.net/10379/16042">http://hdl.handle.net/10379/16042</a>
DOI	<a href="http://dx.doi.org/10.1016/j.conbuildmat.2020.119899">http://dx.doi.org/10.1016/j.conbuildmat.2020.119899</a>

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# Modelling the Hygro-Mechanical Creep Behaviour of FRP Reinforced Timber Elements

Conan O’Ceallaigh<sup>1\*</sup>, Karol Sikora<sup>2</sup>, Daniel McPolin<sup>3</sup>, Annette M. Harte<sup>1</sup>

<sup>1</sup> College of Engineering & Informatics, National University of Ireland Galway, University Rd., Galway, Ireland

<sup>2</sup> Faculty of Engineering and Information Sciences, University of Wollongong in Dubai, UAE

<sup>3</sup> School of Planning, Architecture and Civil Engineering, Queen’s University Belfast, University Road, Belfast BT7  
1NN, UK

Email: conan.oceallaigh@nuigalway.ie\*, karolsikora@uowdubai.ac.ae, d.mcpolin@qub.ac.uk,  
annette.harte@nuigalway.ie

## Highlights

- A numerical model has been developed to predict the creep behaviour of timber elements.
- DFLUX and UMAT user subroutines describe the relative humidity and material behaviour.
- Recoverable and irrecoverable mechano-sorptive creep have been characterised.
- The creep behaviour of FRP reinforced beams has been accurately modelled.

**ABSTRACT:** A fully coupled moisture-displacement finite element model has been developed to predict the viscoelastic, mechano-sorptive and swelling/shrinkage behaviour of FRP reinforced timber elements when stressed under long-term load and simultaneously subjected to changes in relative humidity. A DFLUX subroutine, to describe the changes in relative humidity with time, and a UMAT subroutine, implemented to describe the viscoelastic, mechano-sorptive and swelling/shrinkage behaviour, are presented. Additionally, an irrecoverable mechano-sorptive component is presented. This additional irrecoverable component occurs when the timber moisture content increases to a moisture content above levels previously attained. The model is found to be in agreement with experimentally determined deflection and strain results on both unreinforced and FRP reinforced beams subjected to constant and variable climates.

**KEYWORDS:** Basalt fibre, DFLUX, Finite element analysis, Mechano-sorptive creep, Reinforced timber, Sitka spruce, Swelling/shrinkage, Variable climate, Viscoelastic creep, UMAT.

## 1 Introduction

FRP (Fibre Reinforced Polymer) materials are increasingly being used to strengthen and stiffen structural timber products [1–3]. This occurs in both new and existing timber construction and has been used to great effect when retrofitting structures. Changes in use of the building or, indeed, changes in building regulations often require a higher load capacity than that of the existing members. FRP reinforcement has been used successfully to achieve such additional capacity requirements [1–10] but the influence of FRP reinforcement on the long-term or creep behaviour of timber elements has received less attention. [Creep in wood](#) is often separated into two main categories, namely viscoelastic creep and mechano-

32 sorptive creep. Viscoelastic creep is defined as the deformation with time at constant stress under constant environmental  
33 conditions and it has been the subject of many investigations, which have examined the influence of stress [11,12],  
34 temperature [13], moisture content [14] and flexural reinforcement on the long-term viscoelastic behaviour of timber  
35 elements [15–18]. Mechano-sorptive creep behaviour is defined as a deformation due to the interaction between stress and  
36 moisture content change in timber elements. Under variable environmental conditions, the mechano-sorptive effect can  
37 greatly accelerate the creep deflection of a timber element and ultimately lead to failure. The prediction of long-term effects  
38 and the influence of reinforcement on these timber beams are of crucial importance to structural engineers when designing  
39 timber structures.

40 Rheology is the study of the flow of matter and rheological models can be used to describe time-dependent viscoelastic  
41 behaviour in timber elements. The basic elements of these models are known as spring and dashpot elements. When  
42 combining springs and dashpots in series and/or parallel, rheological or viscoelastic models can be created [19]. In practical  
43 applications, generalised models are required to accurately model viscoelastic material behaviour. Generalised models  
44 combine a number of springs and dashpot elements, which increases the number of parameters and gives a better  
45 representation of the behaviour of the material being studied [11,20]. When modelling the long-term behaviour of timber  
46 elements, the surrounding environment must be considered given its significant effect on the material properties and creep  
47 behaviour. Many researchers have attempted to predict the effects of variable humidity and associated moisture fluctuations  
48 on timber elements and to model mechano-sorptive behaviour [21–25]. Leicester [21] and Ranta-Maunus [22,26]  
49 developed some of the first models in an attempt to quantify the mechano-sorptive effect in timber. Leicester [21] produced  
50 a uniaxial model consisting of an elastic component and an irrecoverable mechano-sorptive component. The predicted  
51 results were compared with experimental data from a small sample of Eucalyptus during two weeks of drying. This  
52 rheological model was found to predict 85% of the total deformation recorded during testing. In a later study, Fridley et al.  
53 [27] developed a sophisticated model based on the Burger model, which included mechano-sorptive creep effects, but also  
54 included moisture and temperature dependent variations in stiffness. This adaption provided good agreement between  
55 modelled and experimental strain data. Mohager & Toratti [28] presented a mechano-sorptive model incorporating different  
56 tensile and compressive compliance functions and a model including partially irrecoverable compressive strains was  
57 proposed. Mårtensson [25] developed another model that decomposed the total strain into elastic, viscoelastic,  
58 shrinkage/swelling, and mechano-sorptive creep strain components. Lu & Leicester [29] presented a mechano-sorptive  
59 model coupled with a simple approximate solution for moisture variation within a specimen based on Fick's law of  
60 diffusion and sinusoidal fluctuations in ambient moisture boundary conditions. Hanhijärvi & Mackenzie-Helnwein [30]  
61 presented an orthotropic material model based on a one-dimensional model presented by Hanhijärvi [31] incorporating

62 elastic, viscoelastic, mechano-sorptive and swelling/shrinkage strains. The mechano-sorptive strain component is altered  
63 to incorporate permanent deformations by introducing a hardening type plasticity element. This was found to accurately  
64 describe the deformations associated with high temperature drying in timber elements. Fortino et al. [32] presented a three-  
65 dimensional model for analysing timber structures under variable humidity and stress conditions. The  
66 viscoelastic/mechano-sorptive constitutive model is implemented in the user subroutine UMAT of the finite element  
67 modelling code Abaqus. They used Fick's law to describe moisture flow within the timber element. This Fickian behaviour  
68 was implemented into the Abaqus user-defined DFLUX subroutine. The model was successfully validated against  
69 experimental results by Leivo [33], Toratti & Svensson [34], Svensson & Toratti [35] and Jönsson [36]. Such advanced  
70 models have been used to examine a range of different challenges facing the timber industry and have contributed to  
71 increased knowledge and safer structures. Fragiaco et al. [37] utilised an advanced numerical model to compute the  
72 moisture distribution and corresponding stresses or moisture-induced stresses in timber elements subjected to different  
73 climates which demonstrated that northern European climates can be more severe than southern climates. Massaro et al.  
74 [38,39] applied such models to examine timber elements subjected to compression perpendicular to the grain. This has  
75 been further advanced in recent years to include multi-Fickian transport theory which examines the influence of changes  
76 in both water vapour and bound water on timber structures [24,40]. Huč et al. [40] developed a model to successfully  
77 predict strains in timber elements subjected to sustained compressive loading. Fortino et al. [24] recently presented an  
78 advanced study incorporating a multi-Fickian hygro-thermal model capable of simulating severe changes in relative  
79 humidity and temperature. The study presented the associated moisture fluctuations and moisture-induced stresses on a  
80 bridge in the north of Sweden which is subjected to harsh climatic conditions over a 10-year analysis.

81 While many models have been developed to examine the effect of FRP reinforcement on the mechanical properties of  
82 timber elements, the majority of these models focus on the short-term performance and are not concerned with viscoelastic  
83 creep, mechano-sorptive, temperature and moisture effects. A two-dimensional model was developed by Tingley [41] to  
84 examine the stress-strain relationship of FRP reinforced glued laminated beams. This model did not include plasticity,  
85 creep, temperature or moisture effects and solely focused on the short-term elastic response. Serrano [42] modelled timber  
86 connections with bonded-in rods. The timber was modelled as a linear elastic orthotropic material and it was found that the  
87 stress concentrations were greatly influenced by the reinforcement stiffness and thickness. In another study, Alam [35]  
88 implemented anisotropic plasticity in a three-dimensional model to predict flexural properties of LVL beams reinforced  
89 with bonded-in FRP reinforcement. This model compared well with experimental findings. Raftery & Harte [44] also  
90 employed anisotropic plasticity theory in a model to predict the behaviour of unreinforced and glass fibre reinforced glued

91 laminated beams. The model results agreed strongly with experimental results and a parametric study showed that as the  
92 reinforcement percentage is increased, the stiffness and ultimate moment capacity are enhanced.

93 A relatively low number of studies have attempted to predict the long-term performance of FRP reinforced beams under  
94 constant or variable climate conditions and these have been limited to the uniaxial case. In a study by Plevris & Triantafillou  
95 [15], an analytical model is employed to predict the creep behaviour of CFRP reinforced timber beams. The model, based  
96 on a Burger element, was developed to account for moisture effects. The experimental and analytical data showed good  
97 agreement in a constant climate; however, only limited experimental data was available. In Davids et al. [45], a uniaxial  
98 model was developed to model the creep behaviour of GFRP reinforced timber beams in a variable climate. The model,  
99 combining viscoelastic and mechano-sorptive creep strain parameters, was fitted using unreinforced specimen test results  
100 and then shown to accurately predict the relative creep deflection of glass FRP reinforced beams in a variable climate.

101 Numerical modelling can be an important tool when modelling complex materials such as timber. It has also been  
102 shown to adequately model various reinforcement materials in various configurations. These advances in numerical  
103 modelling have increased the reliability of results and as a result can aid future product development. The recent advances  
104 in modelling unreinforced timber by Hanhijärvi & Mackenzie-Helnwein [30] and Fortino et al. [24,32,46] are yet to be  
105 specialised for reinforced timber elements under changing relative humidity conditions.

### 106 1.1 Objectives of the Current Study

107 The objective of the current numerical study is to develop a model to predict the influence of flexural reinforcement on the  
108 long-term creep behaviour of timber beams in constant and variable climates. The numerical model presented is developed  
109 using Abaqus finite element analysis software [47]. As mechano-sorptive creep is not explicitly available in Abaqus, a  
110 user-defined UMAT subroutine is required to define mechano-sorptive behaviour during loading and simultaneous  
111 moisture diffusion within timber. The moisture content distribution within the timber and associated strains are determined  
112 in a fully coupled time-dependent hygro-mechanical analysis. A DFLUX subroutine is utilised to describe the interaction  
113 between the surrounding environment and the surface of the timber in the model. Such models have been shown to  
114 successfully replicate deflection and stress development in fluctuating environments by Mirianon et al. [48] and Fortino et  
115 al. [32]. In this study, the formulation of the UMAT subroutine follows the approach implemented by Santaoja et al. [49],  
116 Mårtensson [50], Mirianon et al. [48] and Fortino et al [32]; however, a significant alteration was made to the irrecoverable  
117 mechano-sorptive creep matrix to include irrecoverable deformations in the longitudinal direction when stressed under  
118 loaded conditions and subject to moisture contents not previously attained. The coupled hygro-mechanical model is  
119 compared to the experimental creep deflection and strain tests results on unreinforced and FRP reinforced elements  
120 subjected to four-point bending tests presented by O’Ceallaigh et al. [17,51–54].

121 2 Materials

122 In this study, timber is modelled as an orthotropic elastic material in Abaqus. The [Sitka spruce material](#) tested  
123 experimentally by O’Ceallaigh et al. [17,51–53] was graded to strength class C16. The standard EN 338 [55] provides a  
124 mean value of 8000 MPa for the elastic modulus of C16 timber in the longitudinal direction; however, the experimentally  
125 determined elastic modulus in the longitudinal direction of 9222 N/mm<sup>2</sup>, [determined from short-term static bending tests,](#)  
126 [is used.](#) The elastic moduli in the radial and tangential directions were not measured experimentally; however, Bodig &  
127 Jayne [56] expressed a general relationship between the elastic modulus,  $E$  and shear modulus,  $G$  in the three material  
128 directions. These ratios are reproduced in Eqs. (1)-(3).

$$E_L : E_R : E_T \approx 20 : 1.6 : 1 \quad (1)$$

$$G_{LR} : G_{LT} : G_{RT} \approx 10 : 9.4 : 1 \quad (2)$$

$$E_L : G_{LR} \approx 14 : 1 \quad (3)$$

129 These ratios are widely accepted for modelling the orthotropic properties of timber. However, it is noted that these ratios  
130 are not without their inaccuracies. The size of a timber element and the location it was cut from a log are factors in the  
131 accuracy of the assumption. More information on the timber material properties is given in **Table 1**. [Additionally, these](#)  
132 [material properties are also dependent on the density, temperature and moisture content of the timber.](#) Equations (4) and  
133 (5) are implemented to adjust the elastic and shear modulus properties when the environmental conditions are different  
134 from the reference conditions [49].

$$E_i = E_{i,ref} \{1 + \alpha_1(\rho - \rho_{ref}) + \alpha_2(T - T_{ref}) + \alpha_3(u - u_{ref})\} \quad (4)$$

$$G_{ij} = G_{ij,ref} \{1 + \alpha_1(\rho - \rho_{ref}) + \alpha_2(T - T_{ref}) + \alpha_3(u - u_{ref})\} \quad (5)$$

136  $E_{i,ref}$  and  $G_{ij,ref}$  are the reference elastic modulus and shear modulus, respectively, which correspond to the reference  
137 density ( $\rho_{ref}$  - kg/m<sup>3</sup>), temperature ( $T_{ref}$  - °C) and moisture content ( $u_{ref}$  - %).  $\rho$ ,  $T$  and  $u$  refer to the current density,  
138 temperature and moisture content, respectively, at any given time step and  $\alpha_1 = 0.0003$ ,  $\alpha_2 = -0.007$  and  $\alpha_3 = -2.6$  are material  
139 constants provided by Santaoja et al. [49] and Mirianon et al. [48].

141 The FRP rod reinforcement and epoxy adhesive in reinforced members are modelled as linear elastic materials.  
142 [Experimental tests have shown that the reinforcement is negligibly affected by swelling and shrinkage or creep and have](#)  
143 [not been considered in the study \[51\].](#) The material properties implemented in the model are presented in **Table 2**.

145 In this section, the constitutive models used to simulate the moisture diffusion and deformation of timber beams in  
 146 both constant and variable climates are described. The formulation presented for deformation follows the approach  
 147 implemented by Santaoja et al. [49], Mårtensson [50], Mirianon et al. [48] and Fortino et al. [32] but is adapted to represent  
 148 Irish-grown Sitka spruce using experimental data. In the fully coupled 3-dimensional finite element model, a UMAT  
 149 subroutine to determine the total strain experienced in timber elements when subjected to mechanical stress and  
 150 simultaneous moisture content changes with time is implemented. This simulated total strain is subdivided into five  
 151 separate strain components. These strain components are solved for in an incremental analysis with time. The total strain  
 152  $\epsilon_{Total}$ , is given in Eq. (6).

$$\epsilon_{Total} = \epsilon_e + \sum_{i=1}^k \epsilon_{ve} + \epsilon_{ms} + \epsilon_{ms,irr} + \epsilon_s \quad (6)$$

153 where  $\epsilon_e$  = Elastic strain component,  $\epsilon_{ve}$  = Viscoelastic strain component,  $\epsilon_{ms}$  = Mechano-sorptive strain component,  $\epsilon_{ms,irr}$   
 154 = Irrecoverable mechano-sorptive strain component and  $\epsilon_s$  = Swelling/shrinkage strain component. The  $k$  term denotes the  
 155 number of viscoelastic Kelvin elements used in the formulation of the viscoelastic creep component. The modelling of  
 156 diffusion moisture through the cross section within a coupled moisture-displacement analysis is presented as is the transfer  
 157 of moisture content from the surrounding environment which is defined through the use of a DFLUX subroutine.

### 158 3.1 Elastic Strain Component

159 The elastic component ( $\epsilon_e$ ) follows the generalised Hooke's law as seen in Eq. (7) where  $\sigma$  is the stress and  $C_e$  is the  
 160 elastic compliance matrix of an orthotropic material. In 3-dimensional matrix form, this equation defines the orthogonal  
 161 elastic stress-strain behaviour of timber (Eq. (8)).

$$\epsilon_e = C_e \sigma \quad (7)$$

$$C_e = \begin{bmatrix} \frac{1}{E_R} & -\frac{\nu_{TL}}{E_T} & -\frac{\nu_{LR}}{E_L} & 0 & 0 & 0 \\ -\frac{\nu_{RT}}{E_R} & \frac{1}{E_T} & -\frac{\nu_{LT}}{E_L} & 0 & 0 & 0 \\ -\frac{\nu_{RL}}{E_R} & -\frac{\nu_{TL}}{E_T} & \frac{1}{E_L} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{RT}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{RL}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{TL}} \end{bmatrix} \quad (8)$$

163 The elastic compliance matrix is symmetric, and the Poisson's ratios are related according to Eq. (9).

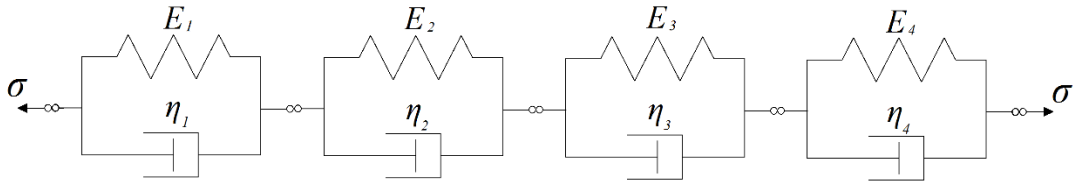
$$v_{RL} = \frac{E_R}{E_R} v_{LR} \quad v_{TL} = \frac{E_T}{E_L} v_{LT} \quad v_{TR} = \frac{E_T}{E_R} v_{RT} \quad (9)$$

164

165 The subscripts  $L$ ,  $R$  and  $T$  refer, respectively, to the directions of assumed elastic symmetry, longitudinal, radial and  
 166 tangential directions.  $E$  and  $G$  represent the elastic modulus and shear modulus, respectively. Bodig & Jayne [56] expressed  
 167 a general relationship between the moduli  $E$  (elastic) and  $G$  (shear) in the three orientations as presented in Eqs. (1)-(3).  
 168 These material properties of timber are dependent on the moisture content, temperature and density of the timber. Eqs. (4)  
 169 and (5) are implemented to adjust the elastic and shear modulus properties when the environmental conditions are different  
 170 from the reference conditions [49].

### 171 3.2 Viscoelastic Strain Component

172 The additional deformation with time in timber elements loaded under constant stress is known as viscoelastic creep. In  
 173 this study, the viscoelastic strain component ( $\varepsilon_{ve}$ ) is an extension of the one-dimensional model presented by Toratti [12]  
 174 consisting of a sum of Kelvin type elements as illustrated in Fig. 1.



175

176 **Fig. 1.** A system of four Kelvin elements connected in series: Each Kelvin element comprises a spring ( $E$ ) and viscous dashpot ( $\eta$ ) in  
 177 parallel.

178 The stress-strain relationship describing the time-dependent behaviour of a Kelvin element is described in Eq. (10)  
 179 [19,30,32].

$$\dot{\varepsilon}_{ve,i} + \frac{1}{\tau_i} \varepsilon_{ve,i} = \frac{1}{\tau_i} C_{ve,i}^{-1} \sigma \quad (10)$$

180 where  $\dot{\varepsilon}_{ve,i}$  = the viscoelastic strain rate =  $\frac{\partial}{\partial t} \varepsilon_{ve,i}$ ,  $C_{ve,i}$  = the viscoelastic compliance matrix of the  $i^{th}$  Kelvin element,  
 181  $\sigma$  = the total stress in the  $i^{th}$  Kelvin element and  $\tau_i$  = the retardation or characteristic time of the  $i^{th}$  Kelvin element. It has  
 182 been shown by Hanhijarvi & Mackenzie-Helnwein [30] and Fortino et al. [32] that for stress-driven problems, the solution  
 183 to the rate equation (Eq. (10)) can be written as,



$$\varepsilon_{ve,i,n+1} = \varepsilon_{ve,i,n} \exp\left(\frac{-\Delta t}{\tau_i}\right) + \int_{t_n}^{t_{n+1}} \frac{C_{ve,i}^{-1} \sigma}{\tau_i} \exp\left(-\frac{(t_{n+1} - t_n)}{\tau_i}\right) dt \quad (11)$$

184 where  $\varepsilon_{ve,i}$  = viscoelastic strain of the  $i^{th}$  Kelvin element and  $\Delta t$  = the time increment ( $t_{n+1} - t_n$ ). By integrating this  
 185 expression for viscoelastic strain (Eq. (11)) over time for the  $i^{th}$  Kelvin element, the following increment of elemental  
 186 viscoelastic strain is obtained [48,57].

$$\Delta\varepsilon_{ve,i,n+1} = C_{ve,i} T_{i,n+1} \left(\frac{\Delta t}{\tau_i}\right) \Delta\sigma_{n+1} - (\varepsilon_{ve,i,n} - C_{ve,i} \sigma_n) \left(1 - \exp\left(-\frac{\Delta t}{\tau_i}\right)\right) \quad (12)$$

187 where:

$$T_{i,n+1} \left(\frac{\Delta t}{\tau_i}\right) = 1 - \frac{\tau_i}{\Delta t} \left(1 - \exp\left(-\frac{\Delta t}{\tau_i}\right)\right) \quad (13)$$

$$C_{ve,i} = J_{ve,i} C_e \quad (14)$$

188 where  $J_{ve,i}$  represents the dimensionless viscoelastic compliance ratio of the  $i^{th}$  Kelvin element.

### 189 3.3 Total Mechano-sorptive Strain Component

190 The total mechano-sorptive strain component ( $\varepsilon_{ms,Total}$ ) consists of two individual components as seen in Eq. (15). Both  
 191 of these components occur under coupled stress and moisture content change associated with relative humidity variations  
 192 in the surrounding environment.

$$\varepsilon_{ms,Total} = \varepsilon_{ms,irr} + \varepsilon_{ms} \quad (15)$$

193 where  $\varepsilon_{ms,irr}$  = irrecoverable mechano-sorptive strain component and  $\varepsilon_{ms}$  = mechano-sorptive strain component.

194 The increment of the irrecoverable component of mechano-sorptive strain is calculated using Eq. (16) [32,35]. It is  
 195 independent of stress rate and is a permanent deformation proportional to the current stress state and change in moisture  
 196 content [58].

$$\Delta\varepsilon_{ms,irr,n+1} = C_{ms,irr} \sigma_n |\Delta U| \quad (16)$$

197 where  $\Delta\varepsilon_{ms,irr}$  = irrecoverable mechano-sorptive strain increment,  $C_{ms,irr}$  = irrecoverable mechano-sorptive compliance  
 198 matrix (Eq. Error! Reference source not found.),  $\sigma_n$  = stress state at time  $t=t_n$  and  $\Delta U$  = increase in moisture content above  
 199 levels attained during previous moisture cycles. The irrecoverable mechano-sorptive matrix previously presented by  
 200 Fortino et al. [32] accounts for irrecoverable deformations in the radial and tangential directions only. [As a novelty of this](#)  
 201 [research project](#), it was shown experimentally that the development of irrecoverable mechano-sorptive creep strains are

202 also observed in the longitudinal direction. As a result, Fortino's formulation has been modified to account for irrecoverable  
 203 strains ( $m_L$ ) in the longitudinal direction as seen in Eq. **Error! Reference source not found.**. The modified terms are  
 204 highlighted in the dashed box in Eq. **Error! Reference source not found.**. The value of the irrecoverable coefficient in the  
 205 radial/tangential direction,  $m_v$  presented by Fortino et al. [32] and the longitudinal direction,  $m_L$  have been determined  
 206 through careful calibration against experimental results on unreinforced beams.

$$C_{ms,irr} = \begin{bmatrix} m_v \frac{E_T}{E_R} & -m_v \frac{E_T}{E_R} \nu_{RT} & -m_v \frac{E_T}{E_R} \nu_{RL} & 0 & 0 & 0 \\ -m_v \frac{E_T}{E_R} \nu_{RT} & m_v & -m_v \frac{E_T}{E_R} \nu_{TL} & 0 & 0 & 0 \\ -m_v \frac{E_T}{E_R} \nu_{RL} & -m_v \frac{E_T}{E_R} \nu_{TL} & m_L & 0 & 0 & 0 \\ 0 & 0 & 0 & m_v \frac{E_T}{G_{RT}} & 0 & 0 \\ 0 & 0 & 0 & 0 & m_v \frac{E_T}{G_{RL}} & 0 \\ 0 & 0 & 0 & 0 & 0 & m_v \frac{E_T}{G_{TL}} \end{bmatrix}$$

207 where  $m_L$  = Longitudinal irrecoverable strain coefficient and  $m_v$  = Radial/tangential Irrecoverable strain coefficient.

208 When describing the recoverable mechano-sorptive strain associated with repeating cycles of relative humidity, the  
 209 schemes previously implemented by Santaoja et al. [49] Mårtensson [50] and Ormarsson [59] have been implemented. The  
 210 solution is found using the absolute value of moisture content, which is assumed to be constant over the time increment.

$$\Delta \varepsilon_{ms,n+1} = C_{ms} \sigma_n |\Delta u| \quad (17)$$

211 where:  $\Delta \varepsilon_{ms}$  = mechano-sorptive strain increment,  $C_{ms}$  = mechano-sorptive compliance matrix (Eq. (18))  $\sigma_n$  = stress state  
 212 at time  $t=t_n$  and  $|\Delta u|$  = the moisture increment  $|u_{n+1} - u_n|$ .

213 The elemental mechano-sorptive compliance matrix assumes the form given in Eq. (18) [49,50,59].

$$C_{ms} = \begin{bmatrix} m_{ms,R} & -m_{ms,T} \nu_{ms,RT} & -m_{ms,L} \nu_{ms,LR} & 0 & 0 & 0 \\ -m_{ms,R} \nu_{ms,RL} & m_{ms,T} & -m_{ms,L} \nu_{ms,LT} & 0 & 0 & 0 \\ -m_{ms,R} \nu_{ms,RL} & -m_{ms,T} \nu_{ms,TL} & m_{ms,L} & 0 & 0 & 0 \\ 0 & 0 & 0 & m_{ms,RT} & 0 & 0 \\ 0 & 0 & 0 & 0 & m_{ms,RL} & 0 \\ 0 & 0 & 0 & 0 & 0 & m_{ms,TL} \end{bmatrix} \quad (18)$$

214

215 The coefficients of the matrix ( $C_{ms}$ ) are based on the mechano-sorptive compliance coefficients ( $m_{ms,i}$ ) in the respective  
 216 material directions and, using the ratios  $\nu_{ms,i}$ , to describe the coupling of the mechano-sorptive strain between the different  
 217 directions. The values used have been based on previous research by Santaoja et al. [49] and Ormarsson et al. [60] and  
 218 finally matched to experimental test results.

### 219 3.4 Swelling/shrinkage Strain Component

220 Swelling/shrinkage strains ( $\varepsilon_s$ ) occur within the timber during moisture content change. This change in strain depends on  
221 the material direction and magnitude of the change in moisture content. The increment in  $\varepsilon_s$  due to a moisture content  
222 change,  $\Delta u$ , is described by Eq. (19).

$$\Delta\varepsilon_s = \alpha_u \Delta u \quad (19)$$

223  
224 Where the moisture swelling/shrinkage vector  $\alpha_u$  is described by Eq. (20).

$$\alpha_u = \begin{bmatrix} \alpha_R \\ \alpha_T \\ \alpha_L \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad (20)$$

225 The components of the swelling/shrinkage vector ( $\alpha_u$ ) used in the study were determined experimentally [61]. It has been  
226 found that different loading conditions (tension, compression or bending) result in different longitudinal swelling/shrinkage  
227 behaviour of timber. Wood tends to swell/shrink less when in tension and swell/shrink more in compression [62]. Toratti  
228 [23] implements an adapted formula (Eq.(21)) to account for variations in longitudinal strain when in a state of tension and  
229 compression as is the case in bending.

$$\Delta\varepsilon_{s,L} = (\alpha_L - \beta \varepsilon_{mech,L}) \Delta u \quad (21)$$

230 where  $\beta$  = Material constant = 1.3 (Mirianon et al. [48]) and  $\varepsilon_{mech,L}$  = longitudinal component of the mechanical strain  
231 vector. This is applied to the longitudinal direction in the developed model. A similar approach has been used in Mohager  
232 & Toratti [28], Hanhijarvi [58] and Davids et al. [63].

### 233 3.5 Diffusion modelling

234 Fick's law, which describes the moisture diffusion process, is analogous to Fourier's law of heat transfer. Using this  
235 analogy, the governing equations allow diffusion coefficients and moisture content to replace thermal conductivity and  
236 temperature. This allows coupled temperature-displacement elements in Abaqus to be exploited in a hygro-mechanical  
237 model to simulate coupled moisture diffusion and mechanical behaviour. The environmental load or relative humidity load  
238 is implemented in Abaqus through a DFLUX user subroutine in order to apply a defined time-dependent relative humidity  
239 boundary condition. The transport of moisture across the surface of the timber is proportional to the difference between the  
240 equilibrium moisture content of the surface of the timber and the equilibrium moisture content of the timber corresponding

241 to the relative humidity of the surrounding environment. In the DFLUX subroutine, the rate of moisture transport between  
242 the surface of the timber and the surrounding environment is governed by Eq. (22).

$$q_n = \rho S_u (u_{eq} - u_{surf}) \quad (22)$$

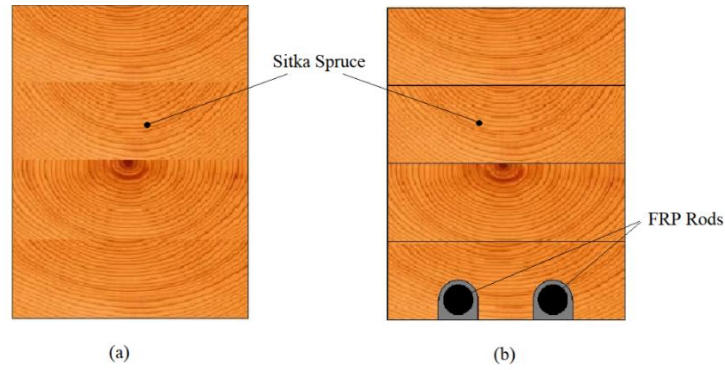
243 where  $q_n$  = rate of moisture flow,  $\rho$  = density at 0% moisture content,  $u_{eq}$  = equilibrium moisture content of timber  
244 corresponding to the relative humidity of the surrounding environment and  $u_{surf}$  = moisture content of the timber surface.  
245 The surface emissivity  $S_u$  defines the rate of moisture content exchange across the boundary and is a function of the  
246 environment, the characteristics of the timber surface and is also dependent on the velocity of the circulating air [58]. The  
247 value used in this model of  $3.2 \times 10^{-8} e^{4.0u}$  m/s was previously reported by Hanhijärvi [58] where  $u$  is moisture content. [More](#)  
248 [information related to the diffusion coefficients and the influence of relative humidity on the equilibrium moisture content](#)  
249 [\( \$u\_{eq}\$ \) of the timber used in this study is provided by O’Ceallaigh et al. \[61\], which focuses on moisture-induced strains in](#)  
250 [fast-grown timber. In the current study, the environmental load is applied to the exposed surfaces of the beam. In line with](#)  
251 [the experimental tests \[17,51–54\], the exposed surfaces include both sides of the glued laminated beam and the top surface](#)  
252 [only. The BFRP reinforcement in the tension zone of the reinforced beams impedes the movement of moisture through the](#)  
253 [bottom and end grain surfaces. As a result, the bottom and end grain surfaces are sealed for unreinforced and reinforced](#)  
254 [beams to ensure all beams are subject to the same exposure conditions.](#)

## 255 4 Hygro-Mechanical Creep Model

### 256 4.1 Model Geometry

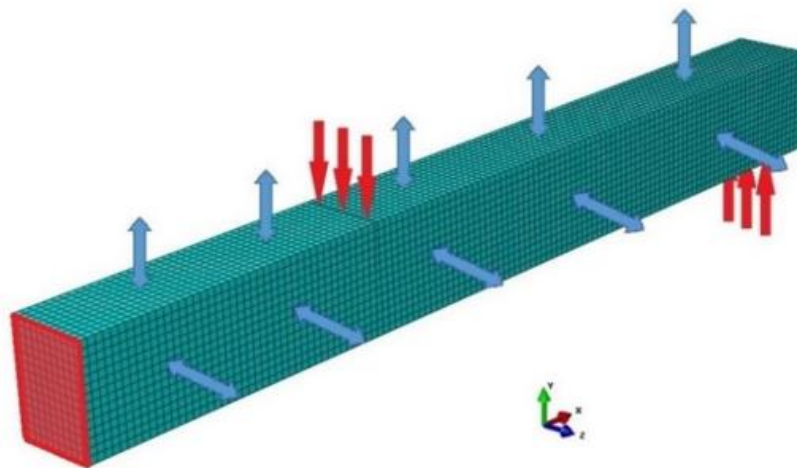
257 The geometry of unreinforced and FRP reinforced beams, which are subjected to a creep test in four-point bending,  
258 [17,51,53] is modelled using Abaqus finite element software. As seen in **Fig. 2**, the 98 x 125 mm<sup>2</sup> unreinforced and  
259 reinforced beams comprise four laminations. Each of the four laminations is assigned material properties in a local  
260 cylindrically orientated coordinate system. [The glue-line between laminations was not modelled in this study due to the](#)  
261 [good performance of the glue-line under variable climates and its limited influence on the moisture diffusion behaviour](#)  
262 [through the cross-section of the timber as shown by Raftery et al. \[64\] and O’Ceallaigh et al. \[61\], respectively. The FRP](#)  
263 [reinforced beam model is similar to that of the unreinforced beam; however, in the bottom tensile lamination, two routed](#)  
264 [grooves are created to accommodate the two 12 mm diameter basalt fibre reinforced polymer \(BFRP\) rods and the 2 mm](#)  
265 [structural epoxy adhesive. Both models use 8-noded coupled thermal-displacement C3D8T elements. As seen in \*\*Fig. 3\*\*,](#)  
266 [symmetry is utilised allowing only half of the 2300 mm long beam to be modelled to reduce the computational time. The](#)  
267 [respective mesh sizes for the unreinforced and reinforced beam models were determined from mesh sensitivity studies to](#)

268 provide accurate results in a reasonable time frame. The beam is simply supported on 80 mm x 100 mm plates which are  
269 free to rotate about their central axis. These plates are modelled using 2-dimensional shell S3 elements. Hard contact is  
270 defined between the surface of the beam and the steel plate with a tangential friction coefficient of 0.4. Similar plates are  
271 used to apply the dead load in tests. These are also modelled using S3 shell elements and the load is applied as a uniform  
272 pressure over the plate area.



273

274 **Fig. 2.** Beam cross-sections: (a) Unreinforced beam, (b) Reinforced beam.



275

276 **Fig. 3.** Finite element coupled hygro-mechanical creep model of the unreinforced glued laminated beam: The plane of symmetry is  
277 highlighted in red at the mid-span of the beam. The red arrows represent the load point and support point on the top and bottom  
278 surface, respectively, and the blue arrows represent the relative humidity load shown on the exposed surfaces (Note: Bottom and end  
279 grain surfaces are sealed on unreinforced and reinforced beams).

280 Regarding the numerical models, a load of 5749 N was applied to the unreinforced beams and a load of 6241 N was  
281 applied to the reinforced beams to induce a common maximum compressive bending stress of 8 MPa in each beam as was  
282 done experimentally by O’Ceallaigh et al. [17,51].

283 4.2 Material Data

284 This section presents the material data for the timber, epoxy adhesive and BFRP implemented in the numerical models.  
 285 The timber material data is summarised in **Table 1**. The BFRP rod reinforcement and epoxy adhesive material data  
 286 implemented into the mechanical model are presented in **Table 2**.

287 **Table 1.** Timber material data

Notation	Description	Property Value	Unit	Source	
$E_R$	Radial elastic modulus	663	MPa	Eqs. (1)-(3) [56]	
$E_T$	Tangential elastic modulus	415	MPa		
$E_L$	Longitudinal elastic modulus	9222	MPa	Experimental test results [51]	
$\nu_{RT}$	Poisson's ratio radial-tangential	0.558	-	[32,48,49]	
$\nu_{RL}$	Poisson's ratio radial-longitudinal	0.038	-		
$\nu_{TL}$	Poisson's ratio tangential-longitudinal	0.015	-		
$G_{RT}$	Shear modulus radial-tangential	66	MPa	Eqs. (1)-(3) [56]	
$G_{RL}$	Shear modulus radial-longitudinal	659	MPa		
$G_{TL}$	Shear modulus tangential-longitudinal	619	MPa		
$\alpha_1$	Alpha density	0.0003	$m^3/kg$	[32,48,49]	
$\alpha_2$	Alpha temp	-0.007	$1/^\circ C$		
$\alpha_3$	Alpha moisture content	-2.6	-		
$\rho_{ref}$	Reference density	400	$kg/m^3$	O'Ceallaigh et al. [61]	
$T_{ref}$	Reference temperature	20	$^\circ C$		
$u_{ref}$	Reference moisture Content	0.12	-		
$u_{FSP}$	Fibre saturation Point	0.28	-		
$\alpha_R$	Radial moisture expansion coefficient	0.1371	-	O'Ceallaigh et al. [61]	
$\alpha_T$	Tangential moisture expansion coefficient	0.2525	-		
$\alpha_L$	Longitudinal moisture expansion coefficient	0.0122	-		
$\tau_1$	Characteristic Time	Kelvin Element No. 1	20	hr	Fortino et al. [32], Mirianon et al. [48] and matched to experimental test results [51]
$J_{ve,1}$	Viscoelastic compliance ratio		0.06	-	
$\tau_2$	Characteristic Time	No. 2	200	hr	
$J_{ve,2}$	Viscoelastic compliance ratio		0.05	-	
$\tau_3$	Characteristic Time	No. 3	2000	hr	
$J_{ve,3}$	Viscoelastic compliance ratio		0.055	-	
$\tau_4$	Characteristic Time	No. 4	20000	hr	
$J_{ve,4}$	Viscoelastic compliance ratio		0.285	-	
$m_L$	Longitudinal irrecoverable mechano-sorptive parameter	0.70	1/GPa	Experimental test results [51]	
$m_V$	Radial/tangential irrecoverable mechano-sorptive parameter	0.13	1/MPa		
$m_{ms,R}$	Mechano-sorptive creep matrix parameters	0.01	1/MPa	Santaoja et al. [49], Ormarsson et al. [60] and matched to experimental test results [51]	
$m_{ms,T}$		0.02	1/MPa		
$m_{ms,L}$		0.40	1/GPa		
$\nu_{ms,RT}$		0.50	-		
$\nu_{ms,RL}$		0.04	-		
$\nu_{ms,TL}$		0.02	-		
$m_{ms,RT}$		0.10	1/MPa		
$m_{ms,RL}$		8.00	1/GPa		
$m_{ms,TL}$		8.00	1/GPa		
$D_L$		Longitudinal diffusion coefficient at $u_{ref}$	$3.3 \times 10^{-10}$		$m^2/s$
$D_R$	Radial diffusion coefficient at $u_{ref}$	$1.6 \times 10^{-11}$	$m^2/s$		
$D_T$	Tangential diffusion coefficient at $u_{ref}$	$1.6 \times 10^{-11}$	$m^2/s$		

288

289 **Table 2.** BFRP and epoxy adhesive material data

Notation	Description	Property Value	Unit	Source
$E_{\text{BFRP}}$	BFRP rod reinforcement elastic modulus	50772	MPa	Experimental test results [51]
$\nu_{\text{BFRP}}$	Poisson's ratio BFRP rod reinforcement	0.3	-	Zachary & Kavan [65]
$E_{\text{EPOXY}}$	Epoxy adhesive elastic modulus	3700	MPa	Manufacturers data sheet [66]
$\nu_{\text{EPOXY}}$	Poisson's ratio Epoxy adhesive	0.29	-	Konnerth et al. [67]

290

291 

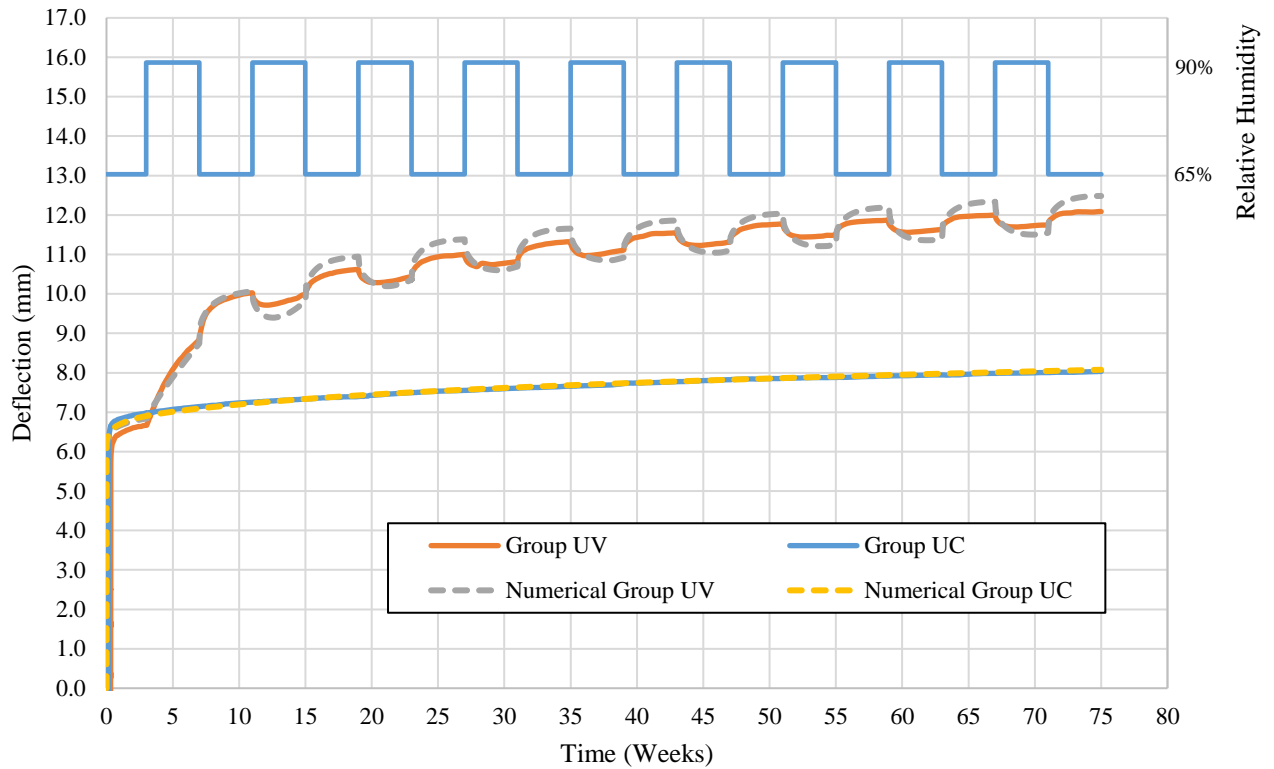
### 4.3 Climate Conditions

292 The numerical model is compared to experimental creep results on beams in both a constant and variable climate [17,51–  
 293 53]. The constant climate remains at a relative humidity of 65% and a temperature of 20 °C for the duration of the test. The  
 294 variable climate condition induces mechano-sorptive creep and swelling/shrinkage strains due to hygro-expansion. This  
 295 occurs due to the change in the relative humidity and subsequent change in the moisture content of the beams. Testing  
 296 commenced at a relative humidity of 65% and at a temperature of 20 °C for a period of three weeks, after which, the relative  
 297 humidity in the variable climate chamber was changed to 90%. After three weeks, the variable relative humidity cycle  
 298 commenced with an increase in the relative humidity to 90% for four weeks followed by four weeks at a relative humidity  
 299 of 65%.

300 

### 4.4 Unreinforced Beam Model Results

301 In this section, the results of the long-term numerical simulation of the unreinforced beam model in constant and variable  
 302 climates are compared to the mean experimental result presented by O’Ceallaigh [51]. [The experimental groups presented](#)  
 303 [comprised of nine beams each \[51\]](#). The predicted total vertical deflection is compared to the experimental results in **Fig.**  
 304 **4**. The predicted initial elastic deflection of 6.09 mm compares well with the mean measured values of 6.27 mm (Group  
 305 UC) and 5.95 mm (Group UV). Over the 75-week test period, it can be seen that the total mean long-term vertical deflection  
 306 of Group UC beams is simulated accurately with a final predicted deflection of 8.08 mm compared to a measured mean  
 307 value of 8.03 mm. This is to be expected as the viscoelastic compliance coefficients defined in **Table 1** and used in this  
 308 unreinforced model have been calibrated against the mean experimental deflection data from the unreinforced beams. It  
 309 was important to accurately define the viscoelastic compliance coefficients of the unreinforced beams prior to simulating  
 310 creep in reinforced beams.



311

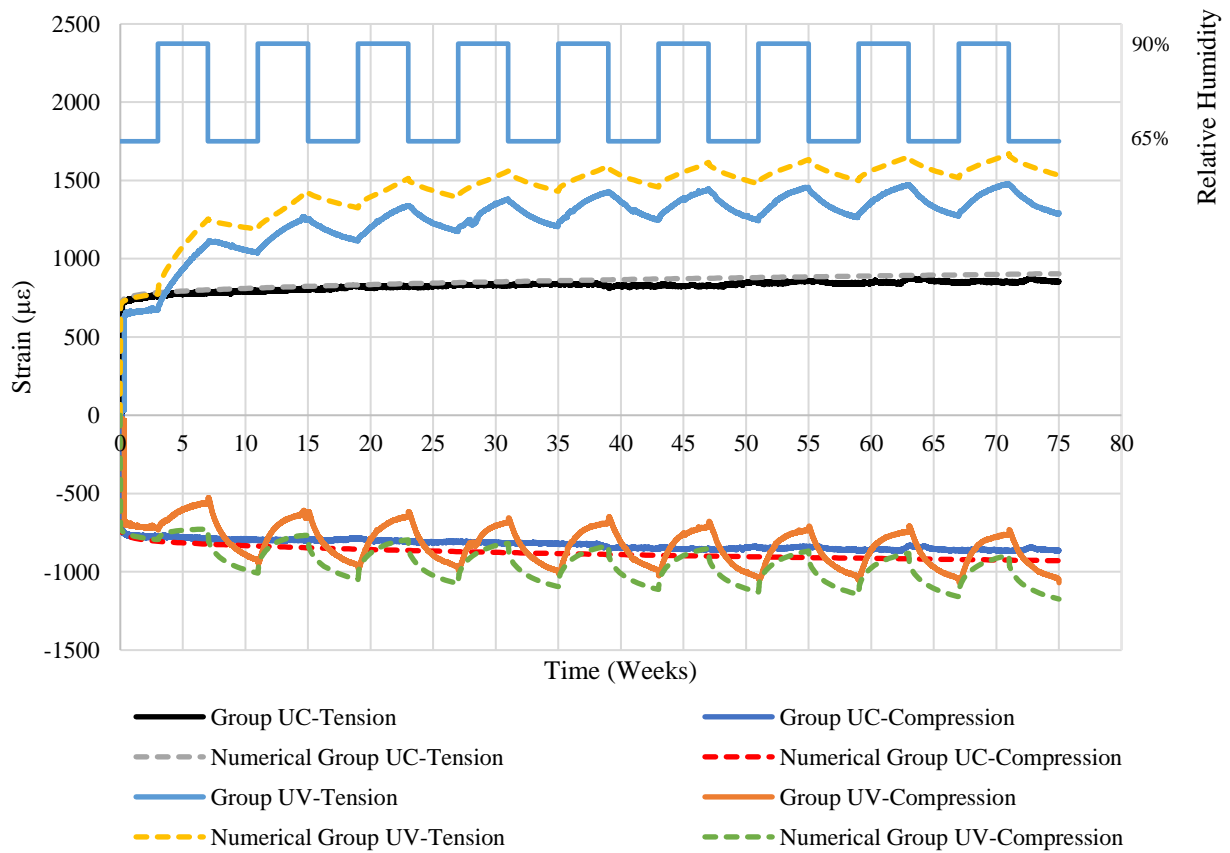
312 **Fig. 4.** Mean deflection result of Group UC (Constant climate) and Group UV (Variable climate) vs the numerical result.

313 In the variable climate condition, during the first three weeks, the relative humidity remains constant and, as a result, this  
 314 period is solely associated with elastic and viscoelastic creep. Consequently, the numerical result for Group UV produced  
 315 the same elastic deformation and viscoelastic creep as the constant climate model during this three-week period. After the  
 316 first three weeks, the relative humidity increased resulting in an increase in moisture content which in turn leads to a  
 317 significant increase in deflection due to irrecoverable mechano-sorptive creep (**Fig. 4.**) Significant increases in deflection  
 318 and strain in the first relative humidity cycle have been previously reported due to changes in moisture content higher than  
 319 that previously attained under a loaded condition [68]. After week 7 the relative humidity reverts to 65% from 90% and  
 320 the relative humidity continues this 8 week cycle for 75 weeks. The numerical deflection result after 75 weeks of 12.48  
 321 mm agreed well with the mean experimentally determined Group UV deflection of 12.09 mm demonstrating the  
 322 effectiveness of the numerical model in the prediction of the creep deflection of timber elements in both constant and  
 323 variable climates.

324 The mean total longitudinal strain measured on the tension and compression faces of the unreinforced Group UC  
 325 and Group UV beams are presented and compared to the numerical model predictions in **Fig. 5.** The results of the numerical  
 326 model agree well with the mean experimental strain results measured on the tension and compression faces. In a constant  
 327 climate, the model accurately predicts the initial elastic strain and viscoelastic creep strain on the tension and compression



328 faces. After 75 weeks, on the tension face, the experimental result of 853  $\mu\epsilon$  compared well to the numerical result of 904  
 329  $\mu\epsilon$  and on the compression face the experimental result of -864  $\mu\epsilon$  compared well to the numerical result of -929  $\mu\epsilon$ . The  
 330 total mean strains measured on the tension and compression faces of Group UV in a variable climate have also been  
 331 measured and are compared to the numerical model results in Fig. 5. The mean initial elastic strain has been slightly over  
 332 estimated on both the tension and compression faces of the Group UV beams. After the initial elastic component, the model  
 333 appears to adequately predict the total strain on the tension and compression face of the Group UV beams in a variable  
 334 climate. The large increase in longitudinal strain during the first moisture content change attributed to the irrecoverable  
 335 mechano-sorptive component has been simulated.



336

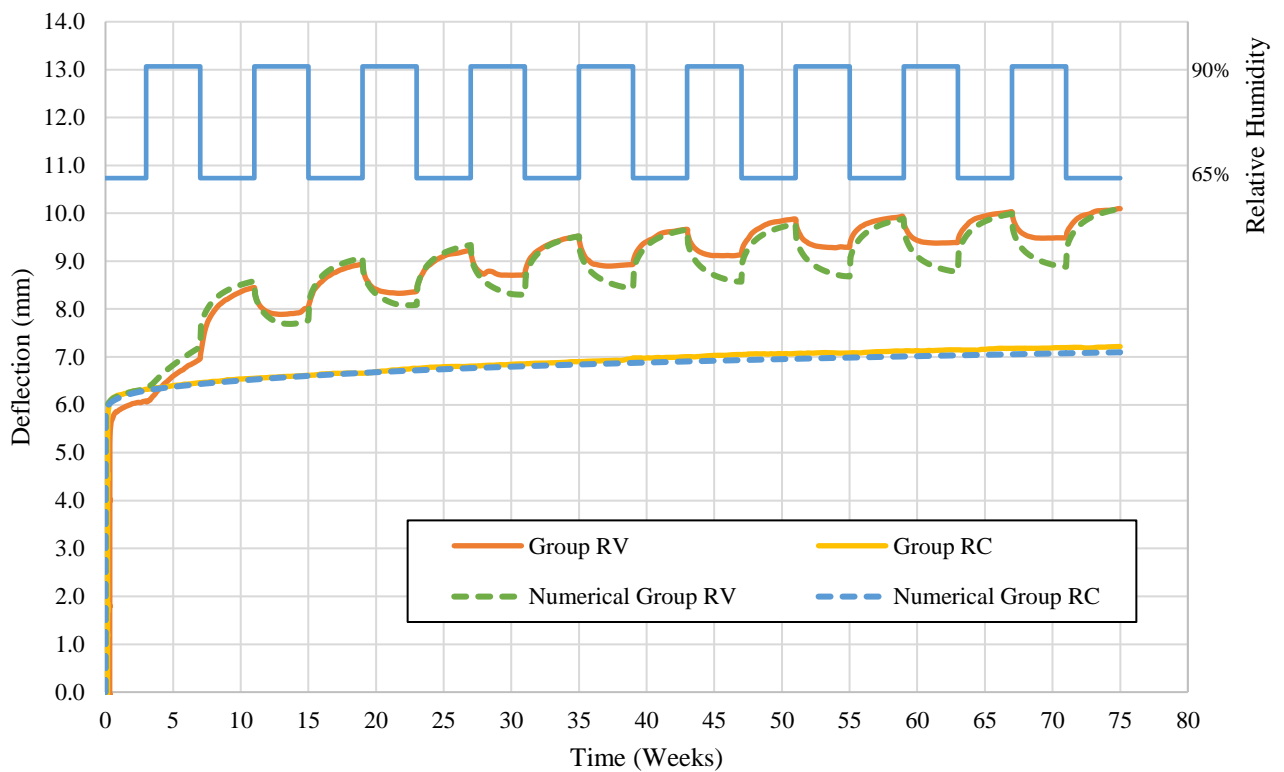
337 **Fig. 5.** Mean unreinforced Group UC (Constant climate) and Group UV (Variable climate) experimental vs numerical longitudinal  
 338 strain results.

339 The fluctuation in strain with repeated cycles has been successfully simulated with the numerical model. On the tension  
 340 face, the change in strain with each relative humidity cycle is more gradual than that experienced on the compression face.  
 341 This is a result of the different exposure conditions of the tension and compression faces. The bottom (tension) face is  
 342 sealed from the surrounding environment resulting in a reduced rate of moisture content change and more steadily  
 343 increasing and decreasing rate of strain development in the tension face. After 75 weeks, the experimental tensile strain of

344 1294  $\mu\epsilon$  compared reasonably well to the numerical result of 1535  $\mu\epsilon$  and the experimental compressive strain of -1069  $\mu\epsilon$   
 345 compared well to the numerical result of -1174  $\mu\epsilon$ . It can be seen that the results of the numerical model slightly over  
 346 predict the mean experimental strain results measured on the tension and compression faces of the unreinforced beams.  
 347 This over prediction is partially due to initial differences in the elastic strain.

#### 348 4.5 Reinforced Beam Model Results

349 The simulated numerical deflection for the reinforced beam model in constant and variable climates is compared to the  
 350 mean experimental result of Group RC and Group RV, respectively in **Fig. 6. Group RC and Group RV comprised nine**  
 351 **beams each [51].** The addition of the BFRP reinforcement has resulted in a reduced initial elastic deflection and reduced  
 352 long-term deflection after 75 weeks when compared to the unreinforced Groups UC and UV. The reduction in initial elastic  
 353 deflection has been accurately predicted using the model. In the constant climate condition, the mean experimental elastic  
 354 deflection of Group RC was 5.72 mm and the numerical model predicted a value of 5.76 mm. Thereafter, the numerical  
 355 model closely matches the experimental creep deflection up to 75 weeks.



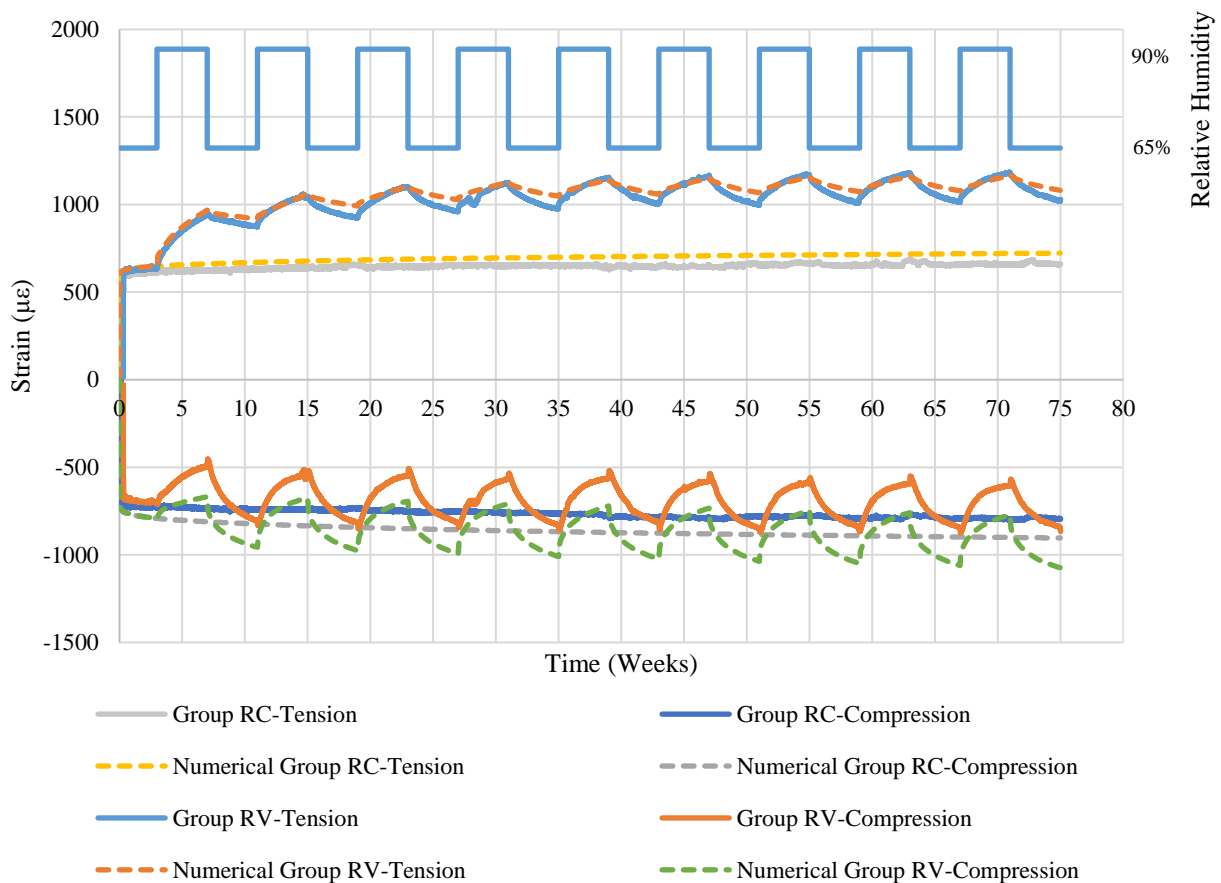
356

357 **Fig. 6. Mean deflection result of Group RC (Constant climate) and Group RV (Variable climate) vs the numerical result.**

358 For Group RV, the measured elastic deflection of 5.44 mm compared well with the numerical prediction of 5.76 mm. Once  
 359 the relative humidity was increased, the deflection increased rapidly. Experimentally, the initial increase in creep deflection  
 360 was less in the reinforced than the unreinforced beams and this is also predicted numerically. With additional relative

361 humidity cycles, the fluctuations in deflection have been successfully predicted; however, greater fluctuations in the  
 362 predicted numerical deflections have been observed. After 75 weeks, the mean experimental Group RV deflection result  
 363 of 10.10 mm has been accurately predicted by the numerical model with a simulated deflection result of 10.09 mm. It is  
 364 noted that the peak deflection of each cycle matches the numerical model well, but the troughs are under predicted but the  
 365 general trend of increasing deflection with repeated cycles has been accurately modelled.

366 The total measured and predicted mean longitudinal strains on the tension and compression faces of the reinforced beams  
 367 are shown in **Fig. 7**. In the constant climate, the maximum tensile and compressive strains in the reinforced beams are  
 368 significantly lower than in the unreinforced beams, demonstrating the beneficial effect of the reinforcement. For the  
 369 reinforced Group RV, the elastic tensile strain of 597  $\mu\epsilon$  predicted by the model is slightly higher than the mean  
 370 experimental tensile strain of 577  $\mu\epsilon$ . On the compression face, the predicted elastic strain of -718  $\mu\epsilon$  is larger than the  
 371 experimental result of -643  $\mu\epsilon$ . Although the elastic strain on the compression face is larger than that measured  
 372 experimentally, the difference is not deemed significant.



373

374 **Fig. 7.** Mean reinforced Group RC (Constant climate) and Group RV (Variable climate) experimental vs numerical longitudinal strain  
 375 results.

376 A large increase in longitudinal strain during the first moisture content change can be seen. This irrecoverable mechano-  
377 sorptive component has been simulated accurately in the reinforced beam. The reduction in irrecoverable mechano-sorptive  
378 creep due to the reinforcement, observed experimentally, is also predicted by the numerical model. The fluctuations in  
379 strain with repeated cycles simulated using the numerical model match well on the tension face but are overpredicted on  
380 the compression face. After 75 weeks, the measured maximum compressive strain was  $-866 \mu\epsilon$  while the model predicts a  
381 conservative value of  $-1068 \mu\epsilon$ .

382 The reinforced beam model has adequately simulated the mean experimentally measured deflection and strain behaviour  
383 in a variable climate condition. The addition of the BFRP rod reinforcement into the model has been shown to simulate the  
384 beneficial reduction of vertical deflection in reinforced beams and has been shown to adequately predict the total  
385 longitudinal creep strain which comprises the viscoelastic, mechano-sorptive and the swelling/shrinkage strain, on both the  
386 tension and compression faces of the reinforced beams.

## 387 5 Summary and Conclusion

388 Unreinforced and reinforced glued laminated beams have been subjected to long-term creep tests in a variable climate  
389 condition [51]. The experimental creep tests confirm that reinforcing timber with a material of superior properties has a  
390 positive effect on the mean deflection and longitudinal strain results in a variable climate. This reduction is currently not  
391 accounted for in the design of timber structures. A coupled hygro-mechanical finite element model has been developed to  
392 predict the behaviour of FRP reinforced timber elements when stressed under long-term load and simultaneously subjected  
393 to changes in relative humidity. The model incorporates elastic, viscoelastic, mechano-sorptive and swelling/shrinkage  
394 behaviour described using a UMAT user-subroutine in Abaqus finite elements software. Included in the formulation is an  
395 irrecoverable mechano-sorptive component. This irrecoverable component characterises the creep behaviour of stressed  
396 timber elements when the moisture content increases to a moisture content not previously attained. The climate conditions  
397 are implemented using a DFLUX subroutine and can be easily adapted to mimic other environmental conditions.

398 The following conclusions can be formulated based on the investigations presented on the long-term behaviour of FRP  
399 reinforced timber elements loaded in a constant or variable climate.

- 400 • The hygro-mechanical creep model has been shown to accurately predict the creep deflection of unreinforced and  
401 reinforced beams in both constant and variable climates. The model has also accurately predicted the reduced creep  
402 deflection behaviour of reinforced members in both constant and variable climates due to the addition of FRP  
403 reinforcement in the tension zone of the beams.

- 404 • The hygro-mechanical model has also accurately predicted the longitudinal creep strain measured on the tension  
405 and compression face of unreinforced and reinforced members. A beneficial reduction in longitudinal creep strain  
406 on the tension face of reinforced members, which was observed experimentally in both a constant and variable  
407 climate, has been simulated by the model.
- 408 • The irrecoverable mechano-sorptive creep matrix proposed by Fortino et al. [32] has been modified here to include  
409 the effects of irrecoverable creep in the longitudinal direction. This greatly improves the accuracy of the  
410 predictions of the long-term deflection and strain in both the unreinforced and reinforced beams in variable  
411 climates. It is recommended to include this modification in future studies, but it is noted that the parameters  
412 provided in this study have been calibrated against experimental test results on fast-grown Sitka spruce and should  
413 be checked when implemented on different species of timber.
- 414 • Long-term testing can be expensive and time-consuming. This validated hygro-mechanical model can now be used  
415 to examine other engineered wood products in different climates more quickly and at a significantly lower cost. In  
416 relation to reinforced elements, this model will be used in future parametric studies to investigate the influence of  
417 FRP type, percentage reinforcement area, and stress level on the creep behaviour of FRP reinforced beams with a  
418 view to determining creep modification factors for design.

419

#### 420 Acknowledgements

421 This work has been carried out as part of the project entitled ‘Innovation in Irish timber Usage’ (project ref. 11/C/207)  
422 funded by the Department of Agriculture, Food and the Marine of the Republic of Ireland under the FIRM/RSF/COFORD  
423 scheme. The authors would also like to thank ECC Ltd. (Earrai Coillte Chonnacht Teoranta) for supplying all the timber  
424 used in this project. The contribution of the technical staff of the College of Engineering and Informatics, NUIG, in  
425 particular, Peter Fahy, Colm Walsh and Gerard Hynes, is acknowledged.

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