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1	Evaluation and Analysis of Fracture Modes in single Composite
2	Basalt/Epoxy Fibres by Photoelastic Method and Single Fibre
3	Fragmentation Test
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16	Abstract:
17	In this work, the suitability of basalt fibres for uni-directional composite material
18	applications, and adhesion between the fibres and the matrix they are embedded in
19	have been investigated. A single fibre fragmentation test was carried out on 13µm
20	diameter basalt fibres embedded in a dog-bone epoxy matrix. Photoelastic analysis
21	was used to observe different fracture mechanisms in a single fibre composite
22	sample and fibre breaks during testing. A theoretical model based on a Griffith's
23	fracture mechanics approach was used to determine the fibre-matrix interfacial
24	shear strength, which is a measurement of the level of adhesion between the fibre
25	and the matrix. It was also used to predict the fibre fragment axial stress and the
26	fragment interfacial shear stress, both as functions of axial position on the fibre. A

27	finite element model was developed to simulate the fibre fracture process, and the
28	redistribution of stresses in the fibre and the local region surrounding a fibre break.
29	The developed experimental procedure was successful in that stress-induced
30	birefringence was observed in the tested samples, as well as the characteristic shear
31	stress light fringes that occur in the regions surrounding fibre fractures. Also, there
32	were some similarities between the finite element model results and the theoretical
33	predictions. The critical fibre length, l_c was measured as 0.752 mm, whereas this
34	value was calculated 0.6708 mm from finite element predicted interfacial shear
35	stress distribution for fibre fragment. A combination of all three types of failure
36	modes was recorded across the samples that were tested, while only a single failure
37	mode was observed in the finite element model. According to the theoretical
38	model, for a given set of parameters and constant stress with only the fibre length
39	varying, the axial stress in the fibre reduces as the fibre gets smaller.

40

Keywords: Basalt fibre, Photoelastic, Fracture mode, Single Fibre Fragmentation

41 Test, Finite Element Modeling.

42 1. Introduction

43 Today, basalt fibres can be considered the 'new-comer' to the composite industry. There is a wide range of material properties associated with basalt fibres which make it a desirable 44 composite material. Some research has been done on fracture behaviour of composite 45 materials to characterize their strength and resistance against different loadings [1]. An 46 important characteristic of uni-directional composites is the level of adhesion at the interface 47 between the fibre and the matrix. When uni-directional composites are subjected to a tensile 48 load parallel to the fibre direction, stress is transferred from the matrix to the fibre via shear 49 [2]. As the load increases, the fibre fractures into smaller lengths. At a certain point, the fibres 50 51 are unable to fracture any further, as they essentially lose their load-bearing capacity. This

52 point is called fibre saturation, and the fibre fragment length at this point is known as the critical fibre length. The critical transfer length is required for the interfacial shear stress to 53 load the fibre to its fracture stress. Fibres with a shorter length than this embedded in the matrix 54 will pull out. One interesting feature of composites containing chopped fibres is that they are 55 almost as strong as those containing continuous fibres; providing the fibres exceed a critical 56 length. Fibres shorter than the critical length will not carry their maximum load are thus unable 57 to function effectively. Beyond the critical length, the fibres will carry an increasing fraction 58 of the applied load and may fracture before the matrix especially if the matrix material has 59 some ductility eg. a thermoplastic such as PEEK or a metal matrix. It is therefore necessary to 60 determine what the critical fibre length is. Shear stress is used to transfer the applied load to 61 62 the fibre - so that the fibre can do its job and the tensile stress that results from this in the fibre is not the same along the length of the fibre - in fact, it increases from zero at the free end to 63 some arbitrary value in the middle of the fibre then decreases as towards the other free end. A 64 high level of adhesion is desirable in a composite, as it represents a good stress transfer 65 mechanism from the matrix to the fibre. This allows for a significant portion of the load to be 66 borne by the fibres, which have a much higher tensile strength and modulus than the matrix 67 [2]. Single-fibre fragmentation test (SFFT) is the most widely used to evaluate interface 68 properties in single-fibre composites, due to its ease of testing, relatively simple preparation 69 of samples [3]. Wang et al [4] have carried out an SFFT test on carbon fibre-epoxy single fibre 70 composites. A finite element model of the fibre failure process was also developed. The finite 71 72 element model created was a 2-D planar model of a short section of the fibre and the surrounding matrix, and it was assumed that the fibre and matrix are perfectly bonded. Van 73 der Meer et al. [5] have presented a numerical investigation into one of the tests that has been 74 proposed for measuring interfacial properties between fibre and matrix. They have introduced 75 76 a new cohesive zone model with friction, as well as an original numerical framework for

77 modelling embedded fibres. Their research has generated new insight into the meaning of the single fibre fragmentation test, confirming the applicability of shear lag theory also in presence 78 of multiple cracks, and emphasizing the relevance of matrix plasticity for the development of 79 friction in the test. Sørensen [6] has developed a shear-lag model utilizing the relation for the 80 loss in potential energy of Budiansky, Hutchinson and Evans for the analysis of single fibre 81 fragmentation tests for the characterization of the mechanical properties of the fibre/matrix 82 interface in composite materials. Stojcevski et al. [7] have carried out single fibre 83 fragmentation, Iosipescu and short beam shear testing to evaluate the translatability and 84 sensitivity of interfacial shear strength across micro-, meso- and macro-scale testing protocols. 85 Humbert et al. [8] proposed an exact solution for the characterization of thermal stresses in a 86 87 single-fibre composite of finite length that involves a particular solution that is added to a 88 three-dimensional complementary displacement field which satisfies automatically the Navier's equations. Kant and Penumadu [9] have measured the fracture toughness of single 89 Toray T700 polyacrylonitrile carbon fibres using focused ion beam (FIB) nano-fabrication 90 techniques to induce controlled geometry of end notches with lengths 100 nm to 1 µm. These 91 fibres were subjected to axial loading with a nano-tensile testing system for evaluating mode 92 I fracture behaviour. The influence of the basalt fibre's length and content on the fundamental 93 94 mechanical properties of concrete has been investigated Sun et al. [10] using multi-scale simulation. A damage constitutive model was developed at the mesoscopic scale in accordance 95 with the Mori-Tanaka homogenization theory and progressive damage theory to predict the 96 97 composite material properties of basalt fibre reinforced concrete. At the macroscopic scale, the obtained material properties of basalt fibre reinforced concrete from mesoscopic were input 98 into the finite element specimen model to simulate the mechanical performance of these 99 materials. Sarasini et al., [11] have presented an experimental investigation of the effects of 100 101 temperature and atmosphere on the tensile behaviour of basalt fibres. The properties of basalt

102 fibres range from somewhere between E and S-glass fibres to slightly better than S-glass. It is 103 worth noting that the cost of manufacturing for basalt fibres is less than that for S-glass fibres, 104 making it a potential replacement for S-glass fibres [12]. A study carried out at Leuven 105 University, Belgium, compared unidirectional E-glass and basalt fibre composites with a fibre volume fraction of 40% by subjecting them to a three-point bending test and an interlaminar 106 shear strength test. The basalt fibre composite strength was recorded as 13.7% higher than that 107 of the E-glass fibre composite, while the basalt fibre composite stiffness was 17.5% greater 108 than the stiffness of the E-glass fibre composite [13]. Meng et al [14] conducted a series of 109 110 experiments to develop continuous basalt fibres using two natural forms of basalt. The average 111 tensile strength of the fabricated continuous basalt fibres was 4.1GPa. They revealed that the 112 amount of glass network modifier $(Na_2O + K_2O)$ has a negative correlation with the tensile 113 strength of continuous basalt fibres. Sabet et al. [15] have investigated the tensile strength of 114 basalt fibres at room temperature and also after exposure to 300, 350, 400, 450 and 500 °C in a furnace for durations of 5, 10, 15 and 20 minutes. The results showed that the residual 115 116 strength of basalt fibres drastically decreases after 20 min exposure at 300 and 400 °C and is only about 57% and 35% of that of fibres at room temperature, respectively. Eslami Farsani et 117 al. [16] have studied the effects of thermal cycles on hardness and impact resistance of three 118 types of phenolic-matrix composites, phenolic resin reinforced with (1) woven basalt fibres, 119 120 (2) woven carbon fibres and (3) hybrid of basalt and carbon fibres. Akhlaghi et al. [17] have shown the applicability of basalt fibre as a reinforcing material for metal matrix composites 121 122 through various experimental works for thermal stability and mechanical properties.

In this work, the goal is to determine the tensile load-bearing capability and fracture behaviour of basalt fibres for composite material applications. Whilst the properties and cost of basalt fibres suggest that they are a good choice for composite fibres, more information is required on the quality of adhesion between the fibres and the matrix they are embedded in. 127 In this research, a single fibre fragmentation test was performed on single fibre basalt-epoxy 128 dog-bone samples, with the objective of characterising the interfacial adhesion and critical 129 fibre length in single basalt fibre through observing the different fibre failure modes via 130 photoelastic methods. A theoretical model which uses Griffith's fracture mechanics approach 131 was used to quantify the interfacial adhesion in terms of interfacial shear strength. Finally, a 132 finite element model was created to simulate the fibre failure process, finding critical fibre 133 length, and failure modes.

134 **2. Experimental**

135 2.1. Experimental Testing

136 For the experimental testing in this research, a single fibre fragmentation test was carried 137 out. The photoelastic analysis method is the most common technique used to determine the stresses at which a certain break occurs. The objective of this technique is to observe stress-138 induced birefringence, which occurs in transparent materials which are optically non-isotropic, 139 140 in the region surrounding a fibre break and matching it with the stress at which it occurred. For fibre breaks to be accurately matched with the stresses at which they occur, incremental 141 loading must be implemented [18]. After the application of a load, the gauge length can be 142 143 scanned for the presence of any new fibre breaks before applying the next incremental load. The fibre diameter of each sample also needed to be accurately measured to carry out 144 145 theoretical calculations.

146 **2.2.** Materials

The samples tested in this research were supplied by Comeragh Composites, Northern
Ireland. The samples consist of a single 13 μm diameter basalt fibre embedded in a dog-bone
shape epoxy matrix. The basalt fibres used were manufactured by Mafic, located in Kells, Co.

Meath, Ireland. The epoxy matrix used was a low viscosity, two-part epoxy resin (RS-M135 with a slow hardener, RS-MH137), which is a product of PRF Composite Materials, Poole, Dorset, England (Table 1). In order to embed the single basalt fibres into the epoxy matrix, a dog-bone mould was designed and the single fibres were fixed in the middle of the mould (Figure 1) within a slight tensile load to make sure the fibre does not get bent during adding the epoxy and the hardener to the die ad curing process. Also, the approximate sample dimensions are shown in Figure 1.

157

Suggested position for Table 1

158

Suggested position for Figure 1

159 2.3. Sample Preparation

160 A simple sample holder was constructed from match-sticks, small pieces of plywood, foam, and a container to prevent the samples from being damaged or scratched. The first step 161 162 taken at the outset of the experimental testing was to observe the samples under a microscope 163 to view the fibre. While the fibres were visible to the naked eye under certain lighting 164 conditions, and clearly visible using a magnifying glass, when viewed under a microscope the fibre could not be observed. This was due to microscopic imperfections on the epoxy, 165 166 increasing the surface roughness and resulting in the epoxy being too opaque for the lens to penetrate it. Various levels of sample illumination were used to try and overcome this, such as 167 168 cleaning them with isopropyl alcohol, followed by polishing them using a polishing compound, applying Isopropyl alcohol, polishing using a Parkside PABSW B2 10.8V, 1.3Ah 169 electric drill with a mini polishing pad, etc., but the microscope lens was unable to focus on 170 the fibre due to surface imperfections. Finally, the sample preparation procedure which 171 172 resulted in the desired surface finish was carried out in a 'Beuhler Beta Grinder-Polisher'. The polishing compound used with the sample was a 'Beuhler Masterprep 0.05 Micron Diamond
Polishing Suspension'. The samples were polished until the surface observed under the
microscope was considered satisfactory.

176 2.4. Measurement Of Fibre Diameter

The fibre diameters were measured using an Olympus toolmakers microscope. The fibre diameters were measured under an X40 Olympus MSPlan20 lens and an Infinity camera attached, using the ocular crosshairs and stage displacement output. To calibrate the Infinity camera with the Olympus X40 lens, measurements needed to be taken from a stage micrometer of known dimensions. The stage micrometer used consisted of squares with a period of 10µm, which were arranged in multiple arrays, each of which had a period of 500µm. Once an image of the micrometer stage had been captured with the Infinity camera, the 'Calibration' option was chosen in the Infinity Analyse software. The largest length possible was then measured for calibration.

186 2.5. Experimental Setup and Testing

The experimental setup is illustrated in Figure 2, and the experimental protocol was based 187 188 on Hunston et al., n.d [19]. The complete experimental setup consists of: a tensile tester to load the samples in small increments; a white light source to illuminate the samples; two 189 190 linear polarisers to polarise the light from the light source travelling through the sample so 191 that stress-induced birefringence can be observed; an Infinity 2 camera with an X100 lens for monitoring and imaging of the fibre and sample; and a jack device to give the operator 192 193 control over the vertical displacement of the Infinity camera, so that the entire gauge length 194 can be examined. The tensile tester used was a hydraulic Instron 8874 with a 1kN load cell. 195 As suggested by the experimental protocol developed by Hunston et al., n.d. [19], a strain 196 of 0.2% was desired for each step. For a gauge length of 20 mm, this is equivalent to

197 0.04mm. No indication of the ideal crosshead speed is given in the test protocol, but the 198 work of Awal et al. [20] has shown that the best results were obtained at a speed of 0.2mm/min. Once the test was initiated, the displacement reading was monitored until the 199 displacement had increased by 0.04mm, at which point the crosshead was stopped. It is 200 recommended [19] that each load hold increment last 10 minutes. This is to ensure that 201 stresses in the matrix are transferred to fibre before commencing the next step. It is 202 recommended that the sample be left for the first 8 minutes, with the final 2 minutes for 203 204 checking the fibre for the occurrence of any new breaks. Once all samples had been tested, 205 the fibres were analysed using the toolmaker's microscope to capture images of the fibre 206 breaks and to record the fibre fragment lengths.

207

Suggested position for Figure 2

208 This section details how the finite element model was created and refined to generate an accurate simulation of the fibre break in the single fibre fragmentation process. This model 209 210 does not simulate interfacial debonding or matrix damage. The following method is based on Wang et al. work [4] in 2010. The finite element software ABAQUS CAE was used to create 211 212 the model, while the fibre breaks were simulated using the subroutine USDFLD. This stands for User Defined Field and was developed in MS Visual Studio 2013 using the programming 213 language FORTRAN. Fibre and matrix in this research were considered to be homogeneous, 214 215 isotropic, elastic materials [4]. The elastic material properties that were assigned to the fibre and the matrix are shown in Table 1. As modelling of a fibre repeatedly fracturing is non-216 linear, a small increment size was required to ensure that an accurate solution is obtained. 217 218 Once the model and subroutine were running successfully, an increment convergence study 219 was carried out. Using an unbiased mesh of the same size for each job, the increment size was 220 gradually reduced. The Von Mises stress of the same three elements was taken from each job to determine increment convergence. Von Mises stress was used here as it incorporates all the principal stresses for each element. Figure 3 shows the entire mesh used for the increment convergence study.

224

Suggested position for Figure 3

225 The ratio of fibre to matrix elements used was 2:1, as seen in figure 3. From the results of the increment convergence study, it was evident that the solution converges at 226 approximately 8000 increments. This increment size was selected as the final increment size 227 228 and was then used for the mesh convergence study and final solution. Only two boundary conditions were required in the initial step of this model; the upper left and right-hand corners 229 of the upper matrix section were constrained in the U2, or Y, direction. This was to prevent 230 231 vertical displacement during tensile displacement of the model. With respect to loading, a 232 tensile displacement load was applied to both ends of the model to simulate straining. The total displacement loading applied to the model was equivalent to 5% straining of the model. As 233 the application of the displacement load was required at a constant rate, the ABAQUS default 234 amplitude ramp was not suitable. Instead, a tabular amplitude was created, to give a linear 235 application of displacement. Two initial conditions were also required to be defined in the 236 input file to successfully run this model, as they are not supported in ABAQUS CAE. The 237 initial condition types used were 'FIELD' and 'SOLUTION'. FIELD is used to assign initial 238 239 values of predefined field variables. This initial condition was used to set the value of the elastic modulus field variable at each fibre node to 1, representing an un-degraded elastic 240 modulus. SOLUTION allows for the definition of the initial values of solution-dependent state 241 242 variables. This was applied to the fibre elements, with the initial value set to 1. Similar to 243 FIELD, the function of this initial condition was to ensure that the fibre modulus is not 244 degraded prematurely. To increase the accuracy of modelling, meshing of both the fibre and 245 matrix part instances utilised the same element type; a 4-node bilinear plane stress quadrilateral element, with reduced integration, and hourglass control (CPS4R). A mesh of 246 medium fineness was used for the increment study, to achieve a good balance between 247 accuracy and computational time. However, to obtain an accurate final solution, a mesh 248 convergence study was also required. The method by which convergence was verified was 249 slightly different than that used in the increment study, as element sizes will change with 250 different meshes. Instead, the maximum Von Mises stresses for each mesh were compared. 251 Firstly, several unbiased meshes coarser than that shown in figure 3 (4200 elements) were 252 created. For the creation of meshes finer than that in figure 3, edge seed biasing was applied 253 to the vertical matrix edges. The mesh bias direction was set towards the fibre. The minimum 254 255 seed size was gradually reduced until the mesh elements close to the fibre were approximately 256 the same height as the fibre elements. The minimum seed size was not reduced further as a 257 mismatch between fibre and matrix element height was not desired. The results of the mesh convergence study show that mesh convergence occurs at 12750 elements. 258

The chosen theoretical model was that of Limin Zhou et al. [21], which is Griffith's fracture mechanics approach to the problem. This model is simplified slightly in this research, as the complete model requires knowledge of friction coefficients and residual clamping stresses due to matrix contraction and thermal shrinkage, which could not be determined. The procedure to determine the fibre tensile stress at the critical length and hence the interfacial shear strength from the SFFT is relatively simple and is outlined below. For a certain applied stress, σ_a , the fibre tensile stress, σ_f , as a function of fibre fragment axial position is determined from the following relationship [22]:

$$\sigma_{\rm f}(z) = \eta \left(\sigma_{\rm a} - \sigma_{\rm a} \frac{\cosh \sqrt{A_1} z}{\cosh \sqrt{A_1} L} \right) \tag{1}$$

For fibre fragments of critical length, $2L = l_c$. As $\sigma_f(z)$ is maximised at the centre of the fibre fragment (z = 0, the fibre midpoint), the value for σ_f at this point is regarded as the fibre fragment tensile strength. A_1 and η are defined as [22] (Figure 4):

$$A_{1} = \frac{2[\alpha + \gamma - 2k(\alpha v_{\rm f} + \gamma v_{\rm m})]}{(1 + v_{\rm m})\left[2\gamma R^{2}\ln\left(\frac{R}{a}\right) - a^{2}\right]}$$
(2)

$$\eta = \frac{1 - 2k\nu_{\rm m}}{\alpha + \gamma - 2k(\alpha\nu_{\rm f} + \gamma\nu_{\rm m})} \tag{3}$$

270 Where *R* is the radius of the matrix region affected by the fibre break and is measured from 271 experimental images, and *k*, γ , and α are defined as [22]:

$$k = \frac{\alpha v_{\rm f} + \gamma v_{\rm m}}{\alpha (1 - v_{\rm f}) + 2\gamma + v_{\rm m} + 1} \tag{4}$$

$$\gamma = \frac{a^2}{R^2 - a^2} \tag{5}$$

$$\alpha = \frac{E_{\rm m}}{E_{\rm f}} \tag{6}$$

Suggested position for Figure 4

273 The interfacial shear strength, τ_i , is then determined using a modified Kelly-Tyson formula.

$$\tau_{\rm i} = K \frac{\sigma_{\rm f}(l_{\rm c})d}{2l_{\rm c}} \tag{7}$$

274 Where K is a constant with a value of 0.75 as suggested by Ohsawa et al. [23].

275 The interfacial shear stress distribution along the fibre length Assuming a perfectly bonded

276 interface after fibre fracture as a function of axial position, $\tau_f(z)$, is defined as [22]:

$$\tau_{\rm f}(z) = \frac{a\sqrt{A_1}}{2} (\eta\sigma_{\rm a}) \frac{\sinh\sqrt{A_1}z}{\cosh\sqrt{A_1}(L)}$$
(8)

277 5. Results and Discussion

272

278 5.1. Experimental Preparation Results

Table 2 shows the fibre diameter measurements taken using the Infinity 2 camera. Note that samples 4 and 5 contained two fibres. As there was no single fibre for measurement in these samples, they are marked n/a.

282

Suggested position for Table 2

From Table 2, it can be seen that of the nine samples that were prepared for incremental load testing, three samples were not suitable (samples 3, 4, and 5). Of the remaining six samples, two were not suitable for testing as the fibres contained within them had a diameter of ~15 μ m (samples 8 and 9). A further sample (sample 1) was deemed unsuitable due to internal imperfections in the matrix which made it impossible to clearly view the fibre under polarised light. This left three samples remaining for incremental load testing (samples 2, 6, and 7). The samples which were not considered suitable for testing were subjected to a tensile test with continuous loading (samples 1, 4, 8, and 9).

291 5.2. Testing Results

Figure 5 displays the force and displacement values that were recorded after the completion of each incremental loading step along with the total number of fibre breaks that were observed after the completion of each loading step (Table 3).

295

Suggested position for Figure 5

The load and displacement values were recorded from the Instron control interface. The lower values for sample 6 relative to samples 2 and 7 is a result of a software issue during testing which resulted in the loss of data for the first few incremental loads. For this reason, as well as no fibre fractures being observed during testing or when using the toolmaker's microscope to measure fibre fragment lengths, sample 6 was excluded from further analysis.

13

Suggested position for Table 3

302 Figure 6 shows images taken of sample 2 during progressive stages of the increment 303 loading. As the images obtained during loading are similar for all samples, only sample 304 2 will be presented in detail. The average width of this sample was 3.917 mm, and this is 305 marked in Figure 6 as a reference measurement. As different wavelengths/colours of light 306 have different refractive indices, and due to the out-of-phase nature of the two light 307 components, the colours of light in the components will undergo both destructive and 308 constructive interference, resulting in the observed interference pattern. Figure 7 309 illustrates a uniform birefringent colour (stress-induced birefringence) in the gauge 310 length, representing a single stress state (tensile stress) of sample 2 at various loading 311 stages. Figure 8 shows samples 1, 4, 8, and 9 (continuous loading) after failure. As 312 mentioned previously, there were imperfections present in sample 1. In fact, of the nine 313 samples, five (including sample 1) contained similar imperfections that made monitoring 314 of the fibre during testing virtually impossible. The continuous loading of sample 1 was 315 monitored using the Infinity camera and recorded to observe what occurs to these 316 imperfections under loading. Several still images from the video are presented below in 317 Figure 9.

318Suggested position for Figure 6319Suggested position for Figure 7320Suggested position for Figure 8321Suggested position for Figure 9

14

Transverse microcracks were observed on the surfaces of the samples after testing, which is indicative of the occurrence of fracture failure mode I (Figure 10) which was expected due to the nature of the tensile test. The presence of these microcracks, which were not present before testing, made it significantly more difficult to locate the fibre in the sample.

327

Suggested position for Figure 10

328 As mentioned above, there were micro imperfections present in numerous samples. 329 Sample 1 was observed to see what happened to these imperfections under loading. It appeared that they grew in size and became more birefringent as the load increased. This is 330 331 illustrated in Figure 9. These imperfections were even in samples where the fibre was 332 monitored (Figure 6), although not to the same extent as other samples. Voids may form during the curing process. Polymerisation increases the mechanical properties of the resin, 333 which coincides with volumetric shrinking. If a resin is cured in a constrained mould, which 334 335 is likely the case with the samples used in this testing, it can adhere to the walls of the mould, which induces tensile stresses. If these tensile stresses exceed the epoxy resin 336 strength at a given stage of curing, voids will form [24]. This is a possible explanation for 337 the presence of micro imperfections. The presence of white spots under polarised light is 338 akin to crazing in polymers. The fact that when monitored under increasing load and 339 340 polarised light they increase in size suggests that they are indeed voids. This could also explain why numerous samples failed near or at the end of the gauge length. Failure in these 341 342 regions is not thought to be due to a combination of stress states in these areas, as Figure 7 343 shows a uniform birefringent colour in the gauge length, representing a single stress state 344 (tensile stress). As it can be seen, the colour diffraction trend has changed from load 345 increment 14 (Figure 6 -D) to increment 18 (Figure 6 -E), a reason for this complies with 346 local shear stresses which occur in the interface of fibre and matrix surrounding. There are a number of stresses present at the ends of the gauge length, which is evident by the multiple 347 light fringes visible in Figure 9 (Right). These fringes can be used to determine the principal 348 stresses and their directions, however doing so would have no benefit to this research as the 349 350 region of interest is the gauge length. It is postulated that failure in these regions surrounding the end of the gauge length may be due to the coalescing of these voids which 351 introduces a weak spot in the sample for failure to initiate. The fact that several samples 352 353 fail in the region at or very close to the gauge length marker (Figure 8) could suggest that 354 there is some feature in one of the moulds used which facilitates the formation of these 355 voids in this particular region.

356 5.3. Fibre Fracture Results

357 Table 4 presents the number of breaks that were found using the toolmaker's microscope, as well as the fragment length. Table 5 then displays the failure mode associated with each 358 break. Mode (a) represents a strong interface, with the fibre break propagating into the matrix 359 and creating a disc-shaped transverse crack with little or no interfacial debonding. Mode (b) 360 also represents a strong interface, but for a matrix that has a relatively lower shear strength 361 capability than tensile strength. This mode may also be accompanied by interfacial debonding. 362 Mode (c) is the result of a weak interface, with the fibre fracture accompanied by interfacial 363 364 debonding in the region surrounding the break. Mode (a) is the desirable failure mode, as it 365 represents the highest level of adhesion between the fibre and matrix, and hence the most 366 efficient stress transfer from the matrix to the fibre.

367

Suggested position for Table 4

368

Suggested position for Table 5

369 Figure 11 illustrates the different fractures that were recorded in the samples. Not every fracture is presented here as some are quite similar. Table 5 and Figure 11 show that a 370 combination of all three types of failure modes was recorded across the samples that were 371 372 tested, with sample 9 presenting all three failure modes. This was an unexpected observation as it indicates a significant variation in fibre-matrix adhesion in a small area. 373 This would be undesirable in a composite material, as it would result in certain regions 374 pertaining to good stress transfer from the matrix to the fibre, whereas other regions in close 375 proximity may be characterised by poor stress transfer. In these regions of poor stress 376 transfer, the fibre is debonded from the matrix, and the fibre load-bearing capacity is 377 dramatically reduced [22]. This increases the load carried by the matrix in that region. This 378 379 variation in the level of adhesion may lead to the concentration of stress in certain areas of the matrix, which would result in premature failure of the composite in those areas, where 380 the failure is governed mainly by the properties of the matrix material. However, except for 381 sample 9, fibre failure mode (c) was not observed in any other samples. Failure modes (a) 382 and (b) were distributed almost equally across all samples, which suggests a good 383 interfacial bonding between the fibre and the matrix. It is worth noting that of the samples 384 which were tested under polarising light (samples 2 and 7) with two fibre breaks observed 385 386 visually, upon examination under a microscope three and four fractures were detected in 387 samples 2 and 7, respectively. By comparing the failure modes of each break in these samples and the length of the fragments between them with the length between the breaks 388 observed experimentally, it was concluded that all breaks that were observed 389 390 experimentally were of failure mode (b).

391

Suggested position for Figure 11

392 This observation can be explained as follows. According to [24], failure mode (b) is 393 characterised by a matrix that has a relatively lower shear than tensile strength capability. When a fibre fractures and strain energy is released and propagates through the local matrix 394 395 region, the matrix is subject to local shear deformation as a result of failure mode (b). Failure mode (b) is often accompanied by a 'butterfly' shaped fracture as a result of this shear failure. 396 397 Local shearing of the matrix about the fracture deforms the polymeric chains, which gives rise to multiple refractive indices as a result of molecular directional anisotropy. This is reinforced 398 399 by the examination of Figure 6 (H), which shows a close-up image of the fracture shear stress birefringent patterns. It is observed in this figure that, if the fibre is taken as an axis at 0° , the 400 birefringent shear stresses act approximately in the area from 315° to 45° (anti-clockwise direction) 401 and 135° to 225° (anti-clockwise direction). This shows alignment with shear bands which suggests 402 403 local shear yielding has occurred. However, in failure mode (a), there is a greater level of 404 adhesion between the fibre and matrix. As strain energy is released after fracture, it results in 405 a transverse crack that propagates perpendicular to the fibre axial direction. As the polymeric chains are broken by the crack, rather than deformed, this significantly reduces the 406 407 deformation of the polymeric chains, hence the lack of stress-induced birefringence. With respect to samples 4 and 6 where no fibre breaks were observed, it is thought that the presence 408 409 of two fibres in sample 4 influenced the fracture response. With sample 6, it is believed that the malfunction of the software had an impact on the loading of the sample. The formation of 410 each failure mode depends on the interfacial properties of fibre and matrix, the presence of 411 412 voids in the vicinity of the fibres, manufacturing quality, and consequently shear properties.

413 5.4. Processed Results

414 Table 6 gives information on testing temperature, and mechanical properties relating to415 each test.

417 Stress-strain experimental results for samples loaded incrementally (samples 2 and 7) are
418 derived, while samples 1, 4, 8, and 9 are subjected to continuous loading.

419 5.5. Finite Element Model Results

420 Figure 12 to Figure 15 (Left) show the S11 stress component in the FE model before and after each break event, while Figure 12 to Figure 15 (Right) plot the axial stress state in the 421 fibre/fibre fragments against the length of the fibre before and after each fibre break event. 422 The regions where the curves dip are the locations of fibre breaks. The line colours used in the 423 graphs to represent the fibre stresses after fibre fracture for a certain break event are also used 424 to represent the fibre stresses before fibre fracture for the following break event. This allows 425 426 for an easy comparison of fibre stresses in different break events. As evident from the right side of Figure 12 to Figure 15 when a fibre fractures into two fragments, the maximum stresses 427 428 in these fragments are reduced. Once one of these fragments fractures into a further two fragments, the maximum stresses in these two fragments are less than any other fragments 429 previously. This is analogous to the reduction of the fibre tensile strength with decreasing 430 431 fragment length. At what point the fibres stop fracturing in the FE model, this could be taken 432 as an estimate of the critical length.

433	Suggested position for Figure 12
434	Suggested position for Figure 13
435	Suggested position for Figure 14
436	Suggested position for Figure 15

437 There are several limitations associated with model, which are a result of some assumptions made during the modelling process. The only failure mode observed in the model is (b), 438 because: a perfectly bonded interface was assumed with no relative motion between the fibre 439 and matrix, which does not allow for interfacial debonding (failure mode (c)); no damage 440 441 model for the matrix was developed, and therefore no transverse cracks could propagate into the matrix (failure mode (a)). The shear stresses present in the entire model are shown in Figure 442 16. The interfacial shear stress at the fibre fragment interface was determined by creating a 443 444 node path along one edge of a fibre fragment. The shear stress distribution along the fragment 445 interface is plotted in Figure 17. The model accurately captures the shear stress distribution 446 into the matrix about a fibre break, which is clearly evident when Figure 16 is compared with 447 the experimental fracture shear stress distribution in Figure 6 (D). A butterfly-shaped distribution is observed, which is characteristic of failure mode (b). The model has also been 448 449 able to successfully plot the shear stress distribution along a fibre fragment interface.

- 450 Suggested position for Figure 16
- 451 Suggested position for Figure 17

452 These findings show that the shear stress along the interface is zero at the fragment ends 453 and is maximised a short distance from the fragment end before gradually decaying to zero at the fibre fragment midpoint. Using eq. (7), the interfacial shear strength for the fibre fragment 454 shown in Figure 17 can be determined. Fibres shorter than the critical length will not carry 455 456 their maximum load are thus unable to function effectively. Beyond the critical length, the fibres will carry an increasing fraction of the applied load and may fracture before the matrix 457 especially if the matrix material has some ductility eg. a thermoplastic such as peek or a metal 458 459 matrix. It is therefore necessary to determine what the critical fibre length is. The critical fibre 460 length is defined as the shortest fibre fragment which can fracture with the application of stress

461 [25]. In other words, it is defined as the minimum length at which the centre of the fibre reaches 462 the ultimate (tensile) strength σ_f , when the matrix achieves the maximum shear strength τ_m . The critical fibre length, l_c , therefore, was taken as the distance spanned by the curve in Figure 463 17, which is 0.6708 mm, and $\sigma_f(l_c)$ is the maximum value of the third green peak from the 464 right in Figure 15, which is 2620 MPa. The resulting interfacial shear strength is presented in 465 table 7 to allow for comparison with theoretical predictions. The FE model developed was 466 considered successful in almost all aspects, based on the objective of the model and the 467 assumptions made. It successfully models the fracture of the fibre into successively smaller 468 fragments through the application of a displacement load to the matrix only, where internal 469 matrix stresses are transferred to the fibre via shear. The maximum fibre tensile stress is 470 471 located at the centre of the fibres, which is the point of fracture once the failure criterion is 472 reached. This is shown in the plots of fibre axial stress in this section. This is the expected 473 fracture location in experimental testing in the absence of fibre imperfections. However, in reality this is not always observed. In basalt fibres imperfections can occur as a result of 474 cooling due to thermal contraction [12]. Some of the minerals that constitute basalt have 475 different melting temperatures [26], which can also influence the uniformity of fibres when 476 cooling. 477

478 **5.6. Theoretical Results**

479 Generation of results using the chosen theoretical model required knowledge of the 480 following parameters: l_c , the critical fibre length, a, the fibre radius, R, the radius of the 481 matrix region affected by the fibre fracture, and σ_a , the applied stress. Only results for 482 samples 2 and 7 are presented here, as they were the only samples where fibre fractures 483 were observed during experimental testing. As it could not be determined if either sample 484 2 or 7 reached saturation as only two fibre fractures were observed experimentally, l_c was 485 taken as the minimum fibre fragment length that was recorded during single fibre 486 fragment test. a was determined from the measurements given in table 2. σ_a was taken as 487 the applied stress at the end of the step at which the second fibre fracture was observed.

488 *R* was determined by measuring the images taken of samples 2 and 7. As *R* is defined as 489 the radius of the matrix region which is affected by the fibre break, this can be taken as 490 the radius of sheared region surrounding the fibre break. The diameter of each shear 491 region was measured, and average value was determined to use in the calculations. With 492 these parameters determined, eqs. (1) through (7) can be used to determine the interfacial 493 shear strength and to plot the tensile and shear stress distribution along a fibre fragment 494 for samples 2 and 7, assuming a critical length of 0.752 mm in both cases from 495 experimental work (table 4).

Table 7 gives the calculated interfacial shear strengths for the theoretical model and the FE model, while Figure 18 plots the tensile and shear stress distributions along a fibre fragment for samples 2 and 7. Figure 19 plots the axial stress distribution of the sample 7 fragment shown in Figure 18 (C), along with the stress distributions for fibre of decreasing length that are otherwise of the same dimensions as sample 7 and are subject to the same loading conditions.

502

Suggested position for Table 7

503 Suggested position for Figure 18

504 The FE model assumes that the tensile strength of the fibre is constant, when in fact it 505 decreases as the fibre length decreases, as illustrated in Figure 19. Figure 19 plots the 506 theoretical axial stress distribution of the sample 7 fragment shown in figure 18-C, along with the stress distributions for fibre of decreasing length that are otherwise of the same dimensions 507 508 as sample 7 and are subject to the same loading conditions. The initial opening displacement 509 is also quite large for the first break and is not considered representative of actual fibre failure. 510 This is a result of the failure criterion and the initial length of the fibre. Before fibre fracture, the fibre is quite long. As load is transferred to the fibre, the load increases, with the maximum 511 512 load at the centre of the fibre. However, due to the length of the fibre, several elements at the 513 centre have very similar stresses and exceed the failure criterion simultaneously. The model 514 also fails to capture the decay of the fibre fragment axial stress to zero at the fragment ends.

515 This is because when the elastic modulus is degraded for certain elements, it does not go to 516 zero, and hence the degraded elements still pertain some load-bearing capacity. Based on a comparison of Figure 18, it is evident that this model is able to determine the fibre axial stress 517 as a function of axial position for different fibres and matrices. Figure 19 illustrates that for a 518 given set of parameters and constant stress with only the fibre length varying, the axial stress 519 520 in the fibre reduces as the fibre gets smaller. This model can capture the decaying of the fragment interfacial shear stress to zero as the axial position approaches the midpoint of the 521 fibre. Unlike the FE model, and similar to many other theoretical models, the chosen model 522 does not predict zero shear stress at the fibre ends, but rather maximises it. However, 523 similarities between the values for shear stress in the FE model and those predicted by the 524 525 theoretical model for similar fragment lengths are evident. The same cannot be said for the 526 comparison between the theoretical fibre fragment axial stress and that in the FE model, due to limitations of the FE model, which were discussed in the previous section. 527

528

Suggested position for Figure 19

529 7. CONCLUSION

530 A SFFT test was carried out on 13 µm basalt fibre-epoxy composite samples, and fracture behaviour (mode) of different samples were indicated. A Griffith's fracture mechanics 531 532 approach was used to predict the interfacial shear strength, and the axial and shear stress 533 distribution in a fibre fragment as a function of fragment axial position. The developed experimental procedure in this work was considered a success, although there were challenges 534 with obtaining the desired results, in that stress-induced birefringence was observed in the 535 536 tested samples, as well as the characteristic shear stress light fringes that occur in the regions surrounding fibre fractures. A 2-D planar FE model was also created to simulate the problem. 537 The primary conclusions of the study are: 538

- From experimental tests, the critical fibre length, lc, was measured as 0.752 mm,
 whereas this value was calculated 0.6708 mm from FE predicted interfacial
 shear stress distribution for fibre fragment.
- It appeared that micro imperfections in the matrix surrounding fibres grew in
 size and became more birefringent as the load increased.
- A combination of all three types of failure modes (mode a, mode b, and mode
 c), were recorded across the samples. In contrast, only a single failure mode was
 observed in the model, failure mode (b), due to the lack of interface properties
 in the model or a damage model for the matrix.
- The FE model created was able to capture the transfer of stress from the matrix
 to the fibre via shear. The interfacial shear stress distribution along the fragment
 length was correctly predicted, with zero shear stress observed at both ends of
 the fragment, and at the midpoint.
- Theoretical fibre fragment interfacial shear stress as a function of fibre fragment
 axial position correctly captured the decay of shear stress to zero at the fibre
 fragment midpoint, but failed to predict zero shear stress at the fragment ends,
 instead maximising it.
- Some similarities between the FE model results and the theoretical predictions
 were observed.
-

559 **Declarations**

560 **Conflict of interest**: The authors declare that they have no known competing financial 561 interests or personal relationships that could have appeared to influence the work reported 562 in this paper.

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Property	13 μm Basalt Fibre	Epoxy Resin
Elastic Modulus (MPa)	90,000	3,400
Tensile Strength (MPa)	3,100	75
Poisson's Ratio	0.26	0.33
Elongation at break (%)	3.5	5 - 6.5

Table 1: Material properties of basalt fibre and epoxy (material data sheets).

Table 2: Results of fibre diameter measurements using Infinity 2 camera.

Sample No.	Avg. (µm)	Sample No.	Avg. (µm)	Sample No.	Avg. (µm)
1	13.20	4	n/a	7	12.31
2	13.09	5	n/a	8	15.27
3	damaged	6	13.40	9	15.07

Table 3: Fibre breaks vs load increment (F= failure occurred).

Load Increment	21	22	23	24	25	26	27	28	29	30	31	32
Fibre Breaks for sample 2	1	2	2	F								
Fibre Breaks for sample 6	0	F										
Fibre Breaks for sample 7	0	1	1	1	1	1	1	2	2	2	2	F

Table 4: Number of breaks and fibre fragment lengths in each sample.

Sampla No	No. of Prople	Fragment Length (mm)						
Sample No.	INO. OF DECARS	Break 1-2	Break 2-3	Break 3-4	Break 4-5			
1	3	1.695	5.384	n/a	n/a			
2	3	1.190	0.752	n/a	n/a			
7	4	1.305	2.015	1.650	n/a			
8	6	1.110	1.420	1.531	3.325			
9	4	0.752	1.882	1.101	n/a			

Sample No	Fibre Break Failure Mode Type								
Sample 140.	Break 1	Break 2	Break 3	Break 4	Break 5				
1	(b)	(b)	(a)	n/a	n/a				
2	(a)	(b)	(b)	n/a	n/a				
7	(b)	(a)	(b)	(a)	n/a				
8	(b)	(a)	(a)	(a)	(a)				
9	(c)	(a)	(b)	(b)	n/a				

Table 5: Different failure modes of each break observed.

Table 6: Test temperatures and other testing values determined from data files.

	Test Temp.	Max Load	Max Disp.	U.T.S.	Failure	Elastic Modulus
Sample No.	(° C)	(N)	(mm)	(MPa)	Strain (%)	(MPa)
1	20	402.67	1.31	72.93	6.56	1510.3
2	20	444.55	1.04	61.80	5.18	1455.4
4	19	419.58	1.06	68.39	5.32	1638.5
7	19	474.35	1.27	74.80	6.37	1670.0
8	20	484.82	1.28	82.45	6.39	1720.3
9	20	469.52	1.29	81.57	6.43	1740.6

Table 7: Theoretical interfacial shear strength values.

Sample No.	2	7	FE model
$ au_{i}$ (MPa)	9.0451	9.7708	19.0407





Figure 1: Sample manufacturing and approximate dimensions of samples.



Figure 2: Experimental testing diagram and setup.



Figure 3: The increment convergence study.



Figure 4: Schematic diagram of parameters required for theoretical model.



Figure 5: Recorded force and displacement values after each incremental loading step



Figure 6: Sample 2 images in different loading steps.



Figure 7: Stress-induced birefringence of sample 2 after different loading increments.



Figure 8: samples 1, 4, 8, and 9 (continuous loading) after failure



Figure 9: Sample 1 imperfections under different loads (Left), Stress-induced birefringent patterns in grip region of sample 2 (Right).



Figure 10: Sample surface before (left) and after (right) testing.



Figure 11: A) Failure mode (b) in sample 1 with some interfacial debonding, B) Failure mode (b) in sample 1 with small amount of interfacial debonding and slight transverse matrix crack, C) Failure mode (b) in sample 2, D) Failure mode (a) in sample 7, E) Failure mode (a) in sample 8 with crack propagation towards microscope lens, F) Failure mode (c) in sample 9, G) Failure mode (a) in sample 9, H) Failure mode (b) in sample 9 with moderate interfacial debonding.





Figure 12: S11 stress in FE model (Left), FE predicted fibre axial stress (Right) before and after the first fibre break.

Figure 13: S11 stress in FE model (Left), FE predicted fibre axial stress (Right) before and after the second and third fibre breaks.



Figure 14: S11 stress in FE model (Left), FE predicted fibre axial stress (Right) before and after the fourth and fifth fibre breaks.



Figure 15: S11 stress in FE model (Left), FE predicted fibre axial stress (Right) before and after the sixth and seventh fibre breaks.



Figure 16: Close-up image of shear stresses about fibre fractures in FE model.



Figure 17: FE predicted interfacial shear stress distribution for fibre fragment.



Figure 18: Theoretical prediction of fibre fragment tensile stress as a function of fibre axial position for sample 2 (A), sample 2 (B), sample 7 (C) and sample 7 (D).



Figure 19: Axial stress distribution for fibres of various lengths.