



**QUEEN'S
UNIVERSITY
BELFAST**

An investigation of the viscoelastic creep behaviour of basalt fibre reinforced timber elements

O'Ceallaigh, C., Sikora, K., McPolin, D., & Harte, A. M. (2018). An investigation of the viscoelastic creep behaviour of basalt fibre reinforced timber elements. *Construction and Building Materials, construction and building materials*(187), 220-230. <https://doi.org/10.1016/j.conbuildmat.2018.07.193>

Published in:

Construction and Building Materials

Document Version:

Peer reviewed version

Queen's University Belfast - Research Portal:

[Link to publication record in Queen's University Belfast Research Portal](#)

Publisher rights

© 2018 Elsevier Ltd. All rights reserved.

This work is made available online in accordance with the publisher's policies. Please refer to any applicable terms of use of the publisher.

General rights

Copyright for the publications made accessible via the Queen's University Belfast Research Portal is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy

The Research Portal is Queen's institutional repository that provides access to Queen's research output. Every effort has been made to ensure that content in the Research Portal does not infringe any person's rights, or applicable UK laws. If you discover content in the Research Portal that you believe breaches copyright or violates any law, please contact openaccess@qub.ac.uk.

Open Access

This research has been made openly available by Queen's academics and its Open Research team. We would love to hear how access to this research benefits you. – Share your feedback with us: <http://go.qub.ac.uk/oa-feedback>

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/326781507>

An investigation of the viscoelastic creep behaviour of basalt fibre reinforced timber elements

Article in *Construction and Building Materials* · October 2018

DOI: 10.1016/j.conbuildmat.2018.07.193

CITATION

1

READS

163

4 authors:



Conan O'Ceallaigh
National University of Ireland, Galway

15 PUBLICATIONS 10 CITATIONS

[SEE PROFILE](#)



D.O. Mcpolin
Queen's University Belfast

44 PUBLICATIONS 328 CITATIONS

[SEE PROFILE](#)



Karol S. Sikora
University of Wollongong in Dubai

27 PUBLICATIONS 94 CITATIONS

[SEE PROFILE](#)



A.M. Harte
National University of Ireland Galway

102 PUBLICATIONS 761 CITATIONS

[SEE PROFILE](#)

Some of the authors of this publication are also working on these related projects:



Commercialisation of Irish Cross Laminated Timber (CICLT) [View project](#)



"Polymer Concrete for Timber Composites" [View project](#)

An Investigation of the Viscoelastic Creep Behaviour of Basalt Fibre Reinforced Timber

Elements

Conan O’Ceallaigh¹, Karol Sikora², Daniel McPolin³, Annette M. Harte¹

¹ College of Engineering & Informatics & Ryan Institute, National University of Ireland Galway, University Rd., Galway, Ireland.

² Department of Civil Engineering, Xi’an Jiaotong-Liverpool University, Suzhou Dushu Lake Higher Education Town, Jiangsu Province, P.R. China 215123.

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

Email: conan.oceallaigh@nuigalway.ie, karol.sikora@xjtlu.edu.cn, d.mcpolin@qub.ac.uk, annette.harte@nuigalway.ie

Highlights

- Viscoelastic creep deflection of BFRP reinforced timber beams measured over a 75-week period.
- No significant reduction in relative viscoelastic deflection due to FRP reinforcement.
- Beneficial reduction in strain on the tension face due to reinforcement.
- Eurocode 5 Service Class 1 creep modification factors may be suitable for FRP reinforced beams.

ABSTRACT: An investigation was carried out to examine the effect of flexural reinforcement on the long-term behaviour of timber beams. Creep tests, utilising statistically matched groups, were performed under Service Class 1 conditions on reinforced and unreinforced beams loaded to a common maximum compressive stress of 8 MPa. As flexural reinforcement resulted in a reduction in the timber tensile stresses, the viscoelastic tensile strains in the reinforced members were found to be significantly lower than in the unreinforced beams. It was found that the viscoelastic relative creep deflection was governed by the stress level in the timber and the reinforcement had an insignificant effect. It is concluded that current creep modification factors in Eurocode 5 may be suitable for the design of reinforced timber elements under Service Class 1 conditions.

KEY WORDS: BFRP; Engineered wood products; Reinforced timber; Sitka spruce; Viscoelastic creep.

1 INTRODUCTION

Structural timber products have been shown to have benefitted with regard to stiffness and ultimate load capacity when reinforced with FRP (Fibre Reinforced Polymer) materials of a superior stiffness. The short-term behaviour of these reinforced elements is relatively well understood. The addition of reinforcement can delay tension failure in timber flexural elements and utilise the additional capacity of the timber in the compression zone resulting in much more consistent

32 behaviour as well as a significant increase in flexural stiffness [1–9]. However, the long-term or creep behaviour of such
33 members has received less attention. Accurate prediction of the long-term performance of timber elements is of crucial
34 importance to structural engineers when designing timber structures as timber is particularly susceptible to large creep
35 deformations when stressed for long periods of time.

36 Creep effects in timber elements can be divided into two main categories, namely, viscoelastic creep and mechano-
37 sorptive creep. The viscoelastic creep component is defined as the deformation with time at constant stress and under
38 constant environmental conditions, which is typical of indoor conditions. Under variable environmental conditions,
39 additional mechano-sorptive creep and swelling/shrinkage behaviour occurs. The mechano-sorptive creep effect has been
40 shown to dramatically accelerate the rate of creep in a loaded timber element and is defined as a deformation due to the
41 interaction between stress and moisture content change due to variable environmental conditions [10–13]. Eurocode 5 [14]
42 provides modification factors which allow design engineers to account for both viscoelastic and mechano-sorptive creep
43 behaviour of solid timber members and engineered wood products. Currently, there are no guidelines on how to account
44 for the influence of reinforcement on the creep response of reinforced timber elements. The reasons for this are partly due
45 to a lack of knowledge, particularly related to the long-term performance of such reinforcement systems. To date only a
46 small number of studies have investigated creep behaviour in reinforced timber and further work in this area is required to
47 enable the development of harmonised design rules for structural engineering applications. This paper focuses on
48 establishing the influence of reinforcement on the viscoelastic creep of reinforced timber beams.

49 *1.1 Viscoelastic Creep Behaviour of Timber*

50 For many structural applications, the most important mechanical property of timber is its resistance to deflection, including
51 both elastic and creep deflection. The contribution of creep deflection to the total deflection is generally much more
52 significant in the case of timber structures to those made of steel or concrete. The creep behaviour of timber also more
53 complex as it is a function not only of timber but also environmental conditions, which change the moisture content of the
54 material. When stressed in a constant climate condition, a timber element undergoes an instantaneous elastic deflection
55 followed by viscoelastic creep behaviour with time. Under this constant climate condition, the level of viscoelastic creep
56 depends on the stress level, temperature and moisture content of the timber. Senft & Suddarth [15] examined small
57 specimens (41.3 x 50.8 x 203.2 mm³) of Sitka spruce (*Picea sitchensis*) under compression load at stress levels of 10, 20,
58 40 and 60% of ultimate strength for load durations up to twenty days. The moisture content remained constant throughout
59 to exclude the mechano-sorptive effect and focus solely on viscoelastic creep. They found that the viscoelastic creep
60 behaviour increases with increasing stress levels and significantly, they found that creep deformation can occur at stress

61 levels as low as 10% of ultimate strength. It was also reported that, at higher stress levels (>55%), specimens are susceptible
62 to creep rupture resulting in failure [15,16]. Similarly, an increase in temperature has been shown to result in higher
63 viscoelastic creep deformations. Davidson [17] performed creep tests on three different species at a series of constant
64 temperatures. It was shown that the rate of creep increased slightly with increasing temperature from 20 °C to 50 °C. The
65 magnitude of viscoelastic creep has been also shown to depend on the moisture content of the timber [10,11,18]. In a study
66 by Hering and Niemz [19], the viscoelastic behaviour of European beech timber elements subjected to four-point bending
67 was investigated and the longitudinal creep compliance at three different moisture contents (8.14%, 15.48% and 23.2%)
68 was examined. Each timber specimen was loaded to approximately 25% of the ultimate bending strength for a period of
69 approximately 200 hr and the viscoelastic creep behaviour was found to increase linearly with increasing moisture content.

70 Another study designed to examine if the rate of creep eventually decreases towards a creep limit was performed by Hunt
71 [20]. Experimental creep tests on solid timber elements were carried out in a carefully controlled environment over a 13-
72 week period. Creep functions were matched to these experimental test results and to creep test results by Gressel [21] over
73 a much longer period of time (8 years). The curves were extrapolated to estimate the viscoelastic creep after 50 years under
74 sustained load. No evidence was found to suggest a viscoelastic creep limit exists in timber when stressed in a constant
75 climate condition. This demonstrates the potential for timber elements to deform throughout their service life and
76 demonstrates the importance of understanding its behaviour.

77 *1.2 Viscoelastic Creep Behaviour in Reinforced Timber*

78 When timber elements are reinforced, the behaviour of the elements can be greatly altered. The short-term or instantaneous
79 elastic behaviour of reinforced elements has been investigated by many authors and significant improvements in stiffness
80 and ultimate moment carrying capacity have been demonstrated [1,3,7–9,22]. More ductile behaviour can be achieved
81 when modest proportions of reinforcement are utilised in strategic locations. Reinforcing the tension zone of timber
82 elements can delay tension failure and utilise the additional capacity of the timber in the compression zone. A limited
83 number of studies have focused on the long-term or viscoelastic creep behaviour of FRP reinforced timber elements. Plevris
84 and Triantafillou [23] performed long-term creep tests on carbon fibre reinforced polymer (CFRP) reinforced beams under
85 three-point bending. There was a relatively small sample size of three beams, one unreinforced control beam and two
86 reinforced beams with two different area reinforcement ratios of 1.18% and 1.65%, respectively. The tests were carried out
87 under constant climate conditions and similar loads were applied to each beam. This resulted in different stress levels in
88 the timber. It was determined from the experimental results, that the creep behaviour of the FRP-reinforced timber elements
89 was primarily dominated by stress within the timber.

90 In a study by Yahyaei-Moayyed and Taheri [24], the creep performance of southern yellow pine (SYP) and Douglas fir
91 (DF) timber beams reinforced with aramid fibre reinforced polymer (AFRP) was examined. These creep tests were carried
92 out in an uncontrolled climate over a period of 800 hours and it is noted that the applied loads (P) were not the same for
93 the unreinforced and reinforced beams. When comparing one SYP unreinforced (P = 4.85 kN) with one SYP reinforced
94 beam (P = 4.40 kN) there appeared to be a reduction in creep deflection, but it was not clear if this reduction was due to
95 different stress levels within the timber or the presence of the AFRP reinforcement. The reduced load on the reinforced
96 beam led to a lower stress level within the timber when compared to the unreinforced beam making comparisons difficult.
97 Interestingly when one unreinforced DF beam (P = 5.60 kN) and one reinforced DF beam (P = 5.76 kN) were compared,
98 there was a slightly higher load on the reinforced beam and a similar creep deflection was observed. The timber stress
99 levels in both the unreinforced and reinforced beams were more comparable in this case. There was also an influence of
100 the uncontrolled climate condition in this study and possible swelling/shrinkage or mechano-sorptive creep deformations
101 as a result of the minor fluctuations in moisture content.

102 Davids et al. [25] performed long-term creep tests on six unreinforced and six reinforced 7 m long Douglas fir and
103 western hemlock glulam beams in a sheltered environment with controlled temperature and uncontrolled relative humidity.
104 A proportion of the beams were reinforced with glass fibre reinforced polymer (GFRP) plate with two percentage area
105 reinforcement ratios, namely, 1.1% and 3.3%. While the laboratory tests demonstrated the effectiveness of the GFRP
106 reinforcement in reducing the elastic deformation between the unreinforced beams and the reinforced beams, a difference
107 between the creep deformation of the unreinforced elements and the GFRP reinforced elements is only seen at the higher
108 reinforcement level. It is noted by Davids et al. [25] that the effectiveness of FRP reinforcement on reducing creep cannot
109 be inferred from the test data due to the different load and associated stress levels in the timber in addition to the
110 uncontrolled relative humidity during the test.

111 The creep behaviour of a loaded timber element has been shown to be heavily influenced by the stress level within the
112 timber. When reinforced, the flexural stiffness of the timber beam is altered and stress distribution through the cross-section
113 is affected. In an effort to reduce the difference in stress distribution between unreinforced and reinforced beams, beams
114 should be loaded to a common maximum stress, similar to that performed by Kliger et al. [22] who carried out mechano-
115 sorptive creep tests on beams loaded to a common maximum compressive stress.

116 *1.3 Objectives of the Current Study*

117 The objective of this study is to investigate the influence of flexural reinforcement on the long-term viscoelastic behaviour
118 of timber beams in a constant climate. As has been shown, the viscoelastic behaviour of timber is influenced by many

119 factors such as the timber mechanical properties, moisture content, temperature and the stress level in the timber. To
120 characterise the influence of the reinforcement on the viscoelastic response, a test procedure was designed to minimise the
121 differences in timber properties, environmental conditions and stress level between unreinforced and reinforced beam
122 groups. Groups of beams with statistically matched flexural stiffness were tested in a customised test rig in a constant
123 climate over a 75-week period. Different loads were applied to the reinforced and unreinforced beams to minimise the
124 difference in bending stress levels. This provides a common basis for comparative studies. The findings of this study are
125 intended to contribute to the database of knowledge required to develop future design guidelines for reinforced timber
126 beams.

127 2 EXPERIMENTAL PROCEDURE

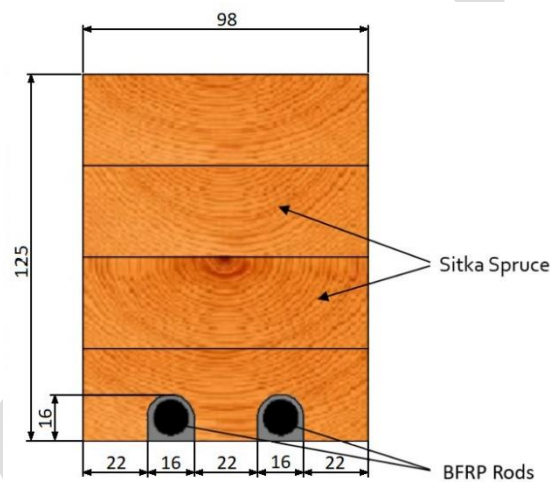
128 2.1 Introduction

129 The glued laminated beams used in the test programme were manufactured using Irish-grown Sitka spruce. The lay-up of
130 each glued laminated beam was designed to allow beams of approximately equal stiffness to be manufactured. A proportion
131 of the beams were reinforced with basalt fibre reinforced polymer (BFRP) rods in the bottom tensile lamination. These
132 unreinforced and reinforced beams were subject to short and long-term flexural testing in a controlled, constant
133 environment.

134 2.2 Glulam Materials and Manufacture

135 The Sitka spruce timber used in this study was grade C16. Sourced in Ireland, this timber has an average rotation length of
136 30 - 40 years [26] and is characterised as a fast-growing, low-density timber which when subjected to flexural loading
137 generally fails in tension due to the presence of knots [3,27]. However, when combined to create a composite element such
138 as a glued laminated beam, the capacity of this softwood timber may be greatly increased [5,7]. Each lamination was
139 strength graded using a mechanical grading machine and ranked in descending order of modulus of elasticity. The lay-up
140 of forty beams was designed using the machine grading results and manufactured in the Timber Engineering Laboratory
141 at the National University of Ireland, Galway. The design process minimised the variation in mean modulus of elasticity
142 of all forty beams. The beams were laminated by applying a 1:1 phenol resorcinol formaldehyde adhesive and clamping to
143 a pressure of 0.6 N/mm² for 24 hours in accordance with EN 14080 [28]. The beams comprise four laminations with each
144 beam measuring approximately 98 mm x 125 mm x 2300 mm. Each beam was conditioned in a constant climate condition
145 at a temperature of 20 ± 2 °C and at a relative humidity of 65 ± 5%, prior to reinforcement.

146 BFRP reinforcement was chosen as a suitable material to reinforce the timber beams. This novel material has received
147 less attention in previous studies but has the potential to rival more commonly used fibres in load bearing applications in
148 the construction industry [29–32]. Twenty of the beams were reinforced with two 12 mm BFRP rods positioned in two
149 circular routed grooves in the bottom tensile lamination. The grooves were sized to accommodate the BFRP rod plus a 2
150 mm glue line, as seen in **Fig. 1**. A two-part structural epoxy adhesive was used to bond the reinforcement to the timber.
151 The BFRP rod manufacturer reported a tensile strength of 1000+ N/mm² and a modulus of elasticity of 45+ GPa [33] but
152 experimental tensile tests on six test specimens in accordance with ISO 10406-1 [34] demonstrated a mean tensile strength
153 of 905 N/mm² and a mean modulus of elasticity of 50.7 GPa. The beams were placed a conditioning chamber with a
154 temperature of 20 ± 2 °C and with a relative humidity of 65 ± 5%, where they remained to cure for a period of 3 weeks
155 prior to flexural testing.



156
157 **Fig. 1.** Cross-section of a Sitka spruce manufactured beam reinforced with two BFRP rods in the tensile lamination.

158 2.3 Short-term Testing

159 Each beam underwent a short-term four-point bending test in accordance with EN 408 [35] to evaluate the flexural stiffness.
160 The load was applied through a hydraulic actuator at a rate of 0.15 mm/s to a maximum load of approximately 40% of the
161 ultimate failure load to ensure that the elastic limit was not exceeded. The deflection at the midspan of the beam was
162 measured using two LVDTs, one for determining the local stiffness and the other for the global stiffness.

163 This short-term test was performed on all beams in their unreinforced state to determine their initial flexural stiffness.
164 The test results allowed two groups, statistically equal in terms of bending stiffness, to be created. One group was
165 subsequently reinforced. The creation of matched groups reduces the difference in the beams due to the variability inherent
166 within timber and provides a reliable basis for comparative studies. Once reinforced, the four-point flexural test was

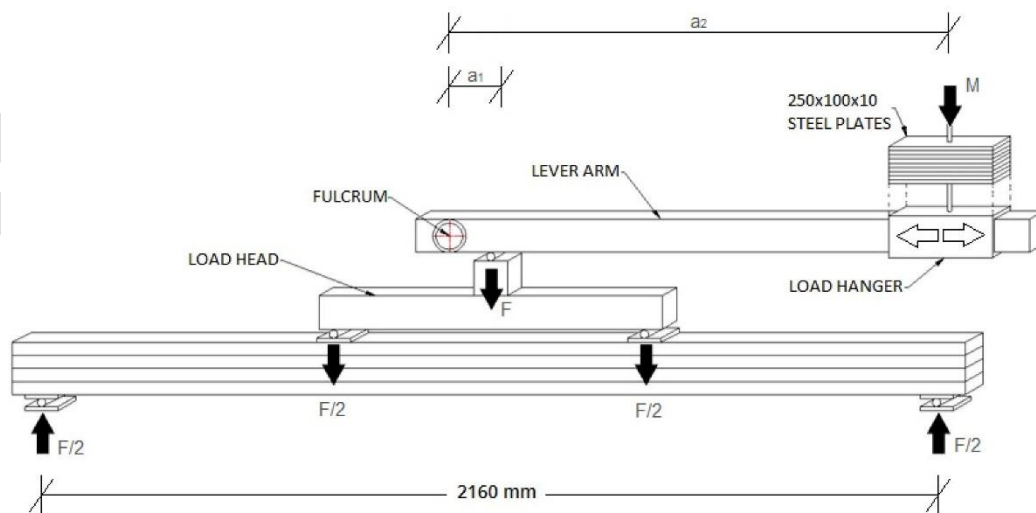
167 repeated. The test set-up remained the same throughout allowing the percentage increase in bending stiffness to be
168 calculated.

169 2.4 Long-term Testing

170 2.4.1 Test Frame Design and Instrumentation

171 There is no standardised method for examining the creep behaviour of timber beams. As a result, different test methods
172 and test frames have been reported in the literature. The majority of authors implement a four-point bending test set-up
173 [13,22,24,25,27]; however, in some cases, a three-point bending test set-up [23] or a uniformly distributed load across the
174 whole length of the member have been used [36].

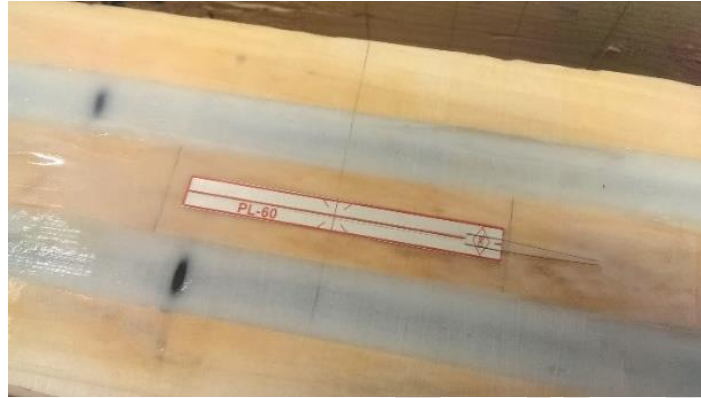
175 In this study, the creep test frame was designed to implement a four-point flexural test set-up. The geometrical constraints
176 of this set-up were in accordance with the short-term flexural test prescribed in EN 408 [35]. The creep test frame was
177 designed to accommodate eighteen beams simultaneously loaded to a constant bending stress to induce viscoelastic creep
178 behaviour with time. The constant bending stress is achieved by applying a dead load, M (steel plates $250 \times 100 \times 10 \text{ mm}^3$),
179 through a lever-arm mechanism. An example of this mechanism on a single beam can be seen in **Fig. 2**. The lever-arm is
180 free to rotate about the fulcrum. The lever-arm length, a_2 (distance from the load to the fulcrum), is adjustable and dead
181 load, M , can be added or subtracted as necessary to achieve a desired bending stress. The flexural load, F , applied at a
182 distance a_1 from the fulcrum is equal to the dead load, M , multiplied by the ratio a_2/a_1 .



183
184 **Fig. 2.** Creep test beam loaded in four-point bending using an adjustable lever-arm mechanism.

185 The beam mid-span deflection was measured using a Mitutoyo displacement dial gauge with an accuracy of 0.01mm and
186 the mid-span longitudinal strain on the tension and compression faces was measured using electrical resistance strain

187 gauges (TML type PLW-60-11) specially designed for long-term use on timber elements. The strain gauges on the tension
188 face of the reinforced beams were adhered to the timber surface of the beam situated between two routed grooves which
189 house the BFRP rods as seen in **Fig. 3**.



190
191 **Fig. 3.** Strain gauge orientated longitudinally between two BFRP rods on the tension face of a reinforced beam.

192 These long-term strains were monitored using a Campbell Scientific data acquisition system, which recorded strains every
193 five minutes during the early stages of the test. This frequency was slowly reduced with time to its current frequency of
194 one hour. The beams are tested in a controlled climate chamber at a temperature of 20 ± 2 °C and at a relative humidity of
195 $65 \pm 5\%$ throughout, which coincides with Service Class 1 conditions as defined in Eurocode 5 [14].

196 2.4.2 Loading Procedure

197 As the aim of the tests is to determine the influence of the reinforcement on the creep performance, the applied loading for
198 the tests was chosen to minimise the difference in the timber stress levels between the unreinforced and reinforced beams.
199 Two different loading scenarios were investigated: the beams are loaded to the same maximum compressive stress level
200 (Case A) or to the same load level (Case B). Analytical modelling of the stress distribution in the unreinforced and
201 reinforced beams was undertaken assuming linear elastic behaviour. For the analysis, it was assumed that elastic moduli
202 of the timber laminations and the BFRF rods were 8000 N/mm^2 and 50000 N/mm^2 , respectively.

203 For Case A, it was assumed that each beam was loaded to a maximum compressive bending stress of 8.0 N/mm^2 . For the
204 reinforced beam, the load required to achieve this maximum compressive stress was 6333 N as seen in **Table 1**. For this
205 load, the maximum timber tensile stress is 7.08 N/mm^2 . The maximum tensile stress in the unreinforced beam is 8.00
206 N/mm^2 , which is 13% higher than the reinforced beam. For Case B, a load of 6333 N applied to the unreinforced beam
207 results in maximum tensile and compressive timber stresses of 8.75 N/mm^2 , which are higher by 23.6% and 9.3%,
208 respectively, than the corresponding stresses in the reinforced beam, as shown in **Table 1**. As the differences in the stress
209 distributions is smaller for Case A, it was decided to apply a maximum bending stress of 8 MPa on the compression face
210 of each beam in the test programme. The applied load chosen corresponds to approximately 25-30% of the ultimate load

211 of the unreinforced glued laminated beam which was chosen to produce measurable deflections in a reasonable time scale
 212 without causing failure in the specimen. This common maximum stress level is an essential component of this test
 213 procedure as it minimises the influence of stress distribution on the long-term response of both the unreinforced and
 214 reinforced beams. This allows for comparisons to be made between creep in unreinforced and reinforced beams and the
 215 influence of the BFRP reinforcement to be quantified. To achieve this common maximum stress level, different loads were
 216 required for each beam with greater loads on average required on the reinforced beams.

217 **Table 1.** Comparison between maximum tensile and compressive timber stresses

Beam State	Load (N)	Max. Tensile Stress (N/mm ²)	Percentage Increase (%)	Max. Compressive Stress (N/mm ²)	Percentage Increase (%)
Reinforced	6333	7.08	0.0%	8.00	0.0%
Unreinforced (Case A)	5792	8.00	13.0%	8.00	0.0%
Unreinforced (Case B)	6333	8.75	23.6%	8.75	9.3%

218

219

220



221

222 **Fig. 4.** Creep test frame: (a) Loaded creep test frame in a constant climate condition at a temperature of 20 ± 2 °C and at a relative
 223 humidity of $65 \pm 5\%$, (b) Creep test beam loaded in four-point bending.

224 The short-term flexural test results provided stiffness values for each beam and the required load for each beam was
 225 determined using the linear elastic model. Mean vertical loads of approximately 6241 N and 5748 N were applied to the
 226 reinforced and unreinforced beams, respectively. Each beam is loaded in four-point bending separately through individual
 227 lever arms as seen in **Fig. 4(a)** and **Fig. 4(b)**. The instantaneous elastic deformation is recorded for each beam and the creep
 228 deflection results are then recorded at regular intervals with time.

229 **2.5 Statistical Methods**

230 Statistical methods have been implemented to create the matched groups described above using the test results for all beams
 231 prior to reinforcement. Once reinforced, similar statistical methods were utilised to examine the influence of the

232 reinforcement on both the short- and long-term behaviour of the reinforced beams. Student's t-tests were carried out to
 233 compare the means of each matched group to one another. When performing a Student's t-test, each sample or group being
 234 compared should follow a normal distribution and the variance of each sample or group must be considered. Shapiro-Wilk
 235 tests were performed on each group to assess normality. The null hypothesis of this test assumes the sample is normally
 236 distributed and a p-value greater than the chosen significance level indicates that the hypothesis that the data came from a
 237 normally distributed sample cannot be rejected. Once normality or a normally distributed sample cannot be rejected,
 238 Levene's test was performed to examine the homogeneity of the group or sample variances. Levene's test is an inferential
 239 test statistic implemented to assess the equality of variances for two or more groups or samples. The null hypothesis of this
 240 test assumes the sample variances are equal. If the p-value is greater than the chosen significance level, the null hypothesis
 241 is accepted and it is concluded that there is an insignificant difference between the variances of all samples tested. In this
 242 study, all statistical tests are carried out to a significance level of 0.95 ($\alpha = 0.5$). In each sample studied, normality could
 243 not be rejected and each group was assumed to follow a normal distribution. When comparing groups using Levene's test,
 244 a proportion of the groups had equal variances and a proportion had unequal variances. For equal variances, Student's t-
 245 test was implemented as it assumes equal variances. In the case of unequal variances, an adapted version of Student's t-
 246 test known as Welch's t-test or unequal variances t-test was used to compare the means of both groups.

247 3 EXPERIMENTAL TEST RESULTS

248 3.1 Short-term Test Results

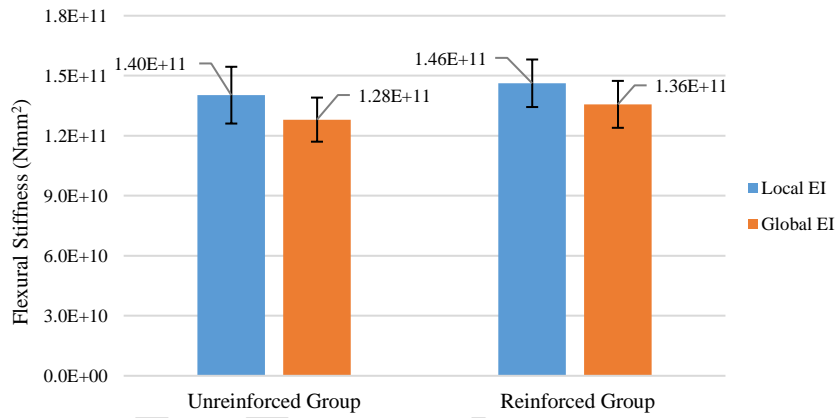
249 The mean flexural stiffness results and associated standard deviation for beams in their respective groups in an unreinforced
 250 state are presented in **Table 2** and **Fig. 5**. The mean local and global flexural stiffness of the Unreinforced Group are
 251 1.40×10^{11} Nmm² and 1.28×10^{11} Nmm², respectively, and the mean local and global flexural stiffness of the Reinforced
 252 Group are 1.46×10^{11} Nmm² and 1.36×10^{11} Nmm², respectively. Statistical Student's t-tests have demonstrated that there is
 253 no evidence to suggest the mean of each group is not equal. The reinforced group was then reinforced and the short-term
 254 test results for the reinforced beam group are presented in **Table 3**. The mean local and global bending stiffnesses for
 255 beams in their unreinforced and reinforced states are given together with the associated standard deviations. The percentage
 256 increase in stiffness is also determined. A mean increase in local bending stiffness of 16.30% for a moderate percentage
 257 reinforcement ratio of 1.85% was observed. There was a mean increase of 8.8% in global bending stiffness. There is a
 258 significant standard deviation of 5.9% associated with this global stiffness measurement.

259 **Table 2.** Mean flexural stiffness results and associated standard deviation for beams in their respective groups in an unreinforced state

Unreinforced Group	Reinforced Group
--------------------	------------------

Beam No.	Global Stiffness, EI_{Global} (Nmm ²)	Local Stiffness, EI_{Local} (Nmm ²)	Beam No.	Global Stiffness, EI_{Global} (Nmm ²)	Local Stiffness, EI_{Local} (Nmm ²)
Beam 5	1.29E+11	1.57E+11	Beam 1	1.32E+11	1.52E+11
Beam 6	1.27E+11	1.31E+11	Beam 2	1.20E+11	1.44E+11
Beam 9	1.39E+11	1.45E+11	Beam 3	1.40E+11	1.61E+11
Beam 11	1.32E+11	1.38E+11	Beam 4	1.62E+11	1.62E+11
Beam 15	1.03E+11	1.14E+11	Beam 7	1.48E+11	1.67E+11
Beam 16	1.30E+11	1.41E+11	Beam 8	1.26E+11	1.53E+11
Beam 17	1.24E+11	1.48E+11	Beam 10	1.38E+11	1.38E+11
Beam 18	1.28E+11	1.31E+11	Beam 12	1.37E+11	1.39E+11
Beam 21	1.52E+11	1.65E+11	Beam 13	1.20E+11	1.44E+11
Beam 22	1.28E+11	1.43E+11	Beam 14	1.57E+11	1.68E+11
Beam 23	1.46E+11	1.59E+11	Beam 19	1.25E+11	1.33E+11
Beam 27	1.15E+11	1.13E+11	Beam 24	1.52E+11	1.40E+11
Beam 29	1.33E+11	1.49E+11	Beam 26	1.42E+11	1.51E+11
Beam 33	1.16E+11	1.33E+11	Beam 28	1.40E+11	1.51E+11
Beam 34	1.42E+11	1.58E+11	Beam 30	1.21E+11	1.31E+11
Beam 35	1.26E+11	1.40E+11	Beam 31	1.20E+11	1.35E+11
Beam 39	1.22E+11	1.24E+11	Beam 32	1.35E+11	1.35E+11
Beam 40	1.13E+11	1.35E+11	Beam 36	1.27E+11	1.27E+11
Mean	1.28E+11	1.40E+11		1.36E+11	1.46E+11
Std. Dev.	1.18E+10	1.42E+10		1.27E+10	1.22E+10

260



261

262 **Fig. 5.** Mean and standard deviation short-term local and global flexural stiffness (Nmm²) results of beam groups in their unreinforced
263 state.

264 **Table 3.** Short-term local and global flexural stiffness results of the reinforced group beams in their unreinforced and reinforced state.

Stiffness (Nmm ²)	No.	Unreinforced	Reinforced	Percentage Increase (%)
EI_{Local} ($\times 10^{11}$)	20	1.46 (.120)*	1.69 (.119)	16.30 (3.66)
EI_{Global} ($\times 10^{11}$)	20	1.36 (.123)	1.47 (.113)	8.80 (5.90)

265

*Mean Values (Std. Deviation)

266 3.2 Long-term Test Results

267 The long-term deflection and strain measurements over a 75-week test period are presented. Eighteen beams (nine
268 reinforced and nine unreinforced) were tested under a common maximum compression stress in a controlled constant
269 climate. The long-term deflection test results are expressed in terms of both total deflection and relative creep (C_R)
270 deflection, which is defined as the deflection at time t , expressed as a proportion of the instantaneous elastic deflection as
271 seen in Equation (1) [37].

$$C_R(t) = \frac{w(t)}{w_0} \quad (1)$$

272
 273 where C_R = relative creep, w_0 = instantaneous deflection and $w(t)$ = deflection at time, t .

274 As mentioned previously, for serviceability limit state design, Eurocode 5 [14] provides deformation modification factors
 275 (k_{def}) for different service classes in order to account for creep effects. The service classes correspond to predefined
 276 environmental conditions and the k_{def} factor is used to increase the instantaneous elastic deflection of the designed element
 277 to account for creep effects. Equation (2) describes the relationship between k_{def} and relative creep.

$$k_{def}(t-t_0) = \frac{w(t) - w(t_0)}{w(t_0)} = C_R(t) - 1 \quad (2)$$

278
 279 The total measured long-term strain results comprise the instantaneous elastic strain due to the application of the dead load
 280 and the viscoelastic creep strain with time as shown in Equation (3).

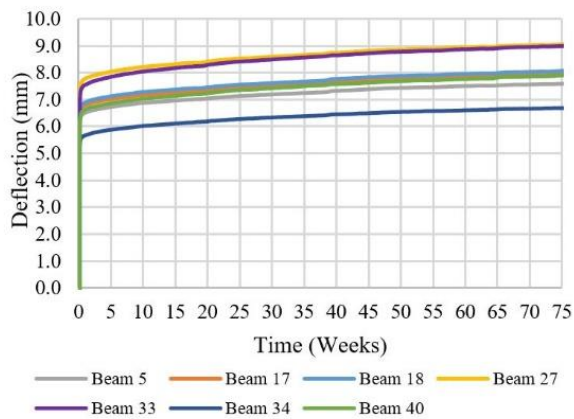
$$\varepsilon_T = \varepsilon_e + \varepsilon_{ve} \quad (3)$$

281
 282 where ε_T = total measured strain, ε_e = elastic strain and ε_{ve} = viscoelastic strain.

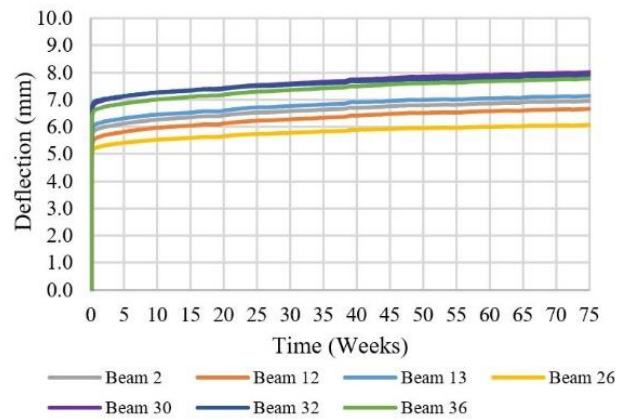
283 Assuming linear behaviour, the viscoelastic strain component is found by subtracting the instantaneous elastic strain
 284 component from the total measured strain. The mean total measured strain data and viscoelastic strain data for the
 285 unreinforced and reinforced beams over the 75-week test period are presented.

286 3.2.1 Long-term Deflection Results

287 The unreinforced beam group consists of nine beams, seven of which, are monitored with displacement dial gauges. The
 288 mid-span deflection for these seven beams are given in **Fig. 6**. Beam 27 (9.068 mm) and Beam 34 (6.674 mm) have the
 289 highest and lowest total deformation (instantaneous elastic deformation + viscoelastic creep deflection) after 75 weeks,
 290 respectively. This is as expected as they have the lowest and highest bending stiffness, respectively, when measured during
 291 short-term flexural tests.



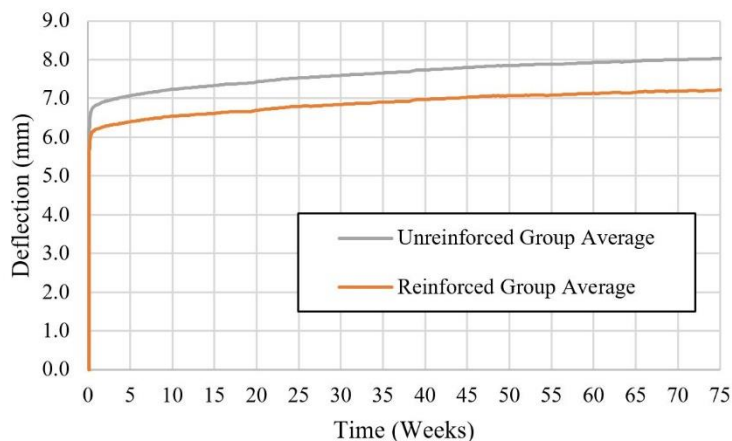
292 **Fig. 6.** Unreinforced deflection results.



293 **Fig. 7.** Reinforced deflection results.

294

295 The reinforced beam group consists of nine beams. Seven of these beams are monitored with displacement dial gauges.
 296 The mid-span deflection for these seven beams are given in **Fig. 7**. Beam 30 (8.022 mm) and Beam 26 (6.072 mm) have
 297 the highest and lowest total deflection after 75 weeks, respectively. Beam 30 and Beam 26 also had the lowest and highest
 298 bending stiffness, respectively, when measured during short-term flexural tests. The variability in the total deflection results
 299 within each matched group can be seen in **Fig. 6** and **Fig. 7**. The average unreinforced bending stiffness of each group was
 300 shown to be statistically equal from short-term test data. To compare the deflection results of the unreinforced and
 301 reinforced groups and observe the effect of reinforcement, the average deflection for each beam group is shown in **Fig. 8**.
 After 75 weeks, the mean total deflection in the unreinforced beam group (8.032 mm) is 10.69% greater than the reinforced
 beams group (7.219 mm).

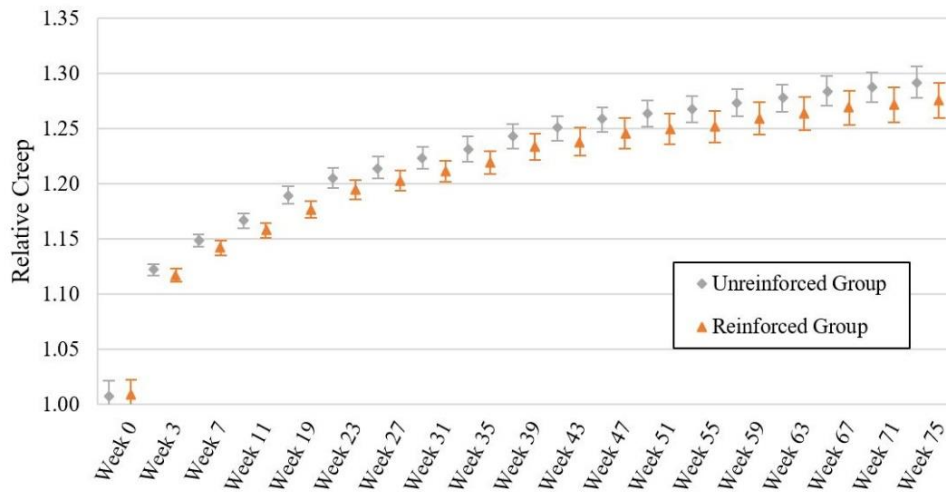


302

303 **Fig. 8.** Unreinforced and Reinforced group average deflection results.

304 **Fig. 9** presents the average relative creep deflection results with time for the unreinforced and reinforced groups. Although
 305 there is a reduction in the overall deflection in the reinforced beam group due to the FRP reinforcement (10.69%), very
 306 similar creep behaviour is observed between the measured relative creep deflections of both groups. This indicates that the

307 reduction in total deflection observed in the reinforced group is primarily due to the lower instantaneous elastic deflection
 308 due to the increased stiffness provided by the reinforcement. The mean relative creep deflections and corresponding
 309 standard deviations of both groups are also plotted in **Fig. 9** at a series of time points over the test period. For clarity, the
 310 results of the unreinforced and reinforced groups at the similar time points are offset from one another. Statistical Student's
 311 t-tests were performed at a series of time points throughout the test and the results are presented in **Table 4**.
 312



313
 314 **Fig. 9.** Unreinforced and Reinforced average and standard deviation results at a series of time points throughout the 75-week test
 315 period.

316 The percentage difference between the mean relative creep results of the unreinforced and reinforced group show that this
 317 difference is increasing with time. During the initial weeks (Week 0 to Week 19) the trend indicated a significant difference
 318 in the creep behaviour of unreinforced and reinforced beams was developing as seen in **Table 4**; however, this period was
 319 associated with a relatively high rate of creep deformation and after this point the statistical tests indicate an insignificant
 320 difference between the mean results of both groups. Although after 75 weeks of creep testing there is a reduction in the
 321 total deflection (10.69%) in the reinforced group, there is less than 1.30% difference between the mean relative creep
 322 deflections of both groups at the same time point. A statistical analysis of the group means has shown that there is no
 323 statistically significant reduction in viscoelastic creep deflection in FRP reinforced beams when compared to unreinforced
 324 beams under similar bending stresses and constant climate conditions.

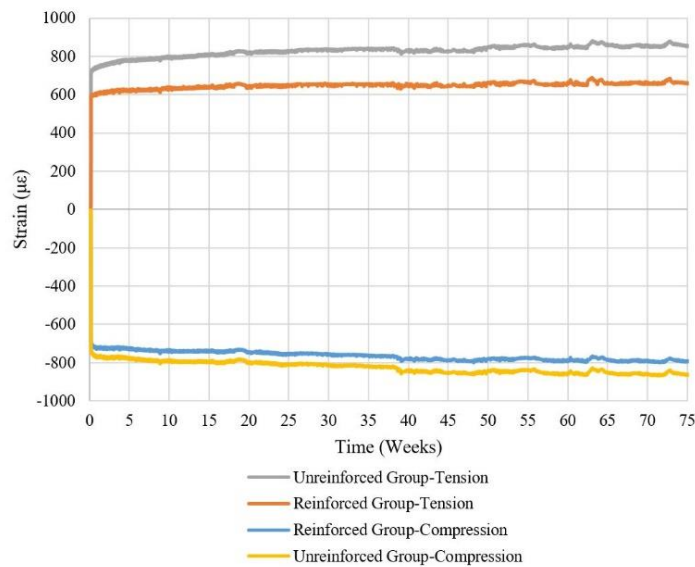
325 **Table 4.** Average relative creep deflection (standard deviation) of the unreinforced and reinforced groups at a series of time points.

Group	Week 0	Week 3	Week 11	Week 19	Week 35	Week 51	Week 75
Unreinforced	1.008 (0.014)	1.122 (0.005)	1.166 (0.007)	1.190 (0.008)	1.231 (0.011)	1.263 (0.012)	1.292 (0.014)
Reinforced	1.009 (0.014)	1.117 (0.006)	1.158 (0.007)	1.177 (0.007)	1.219 (0.010)	1.250 (0.014)	1.275 (0.016)
Percentage Diff.	0.07%	0.43%	0.76%	1.10%	1.00%	1.08%	1.27%
Student's t-test	Not Sig.	Not Sig.	Sig.	Sig.	Not Sig.	Not Sig.	Not Sig.
p-Value	0.9222	0.1330	0.0337	0.0085	0.0560	0.0702	0.0663

326

3.2.2 Long-term Strain Results

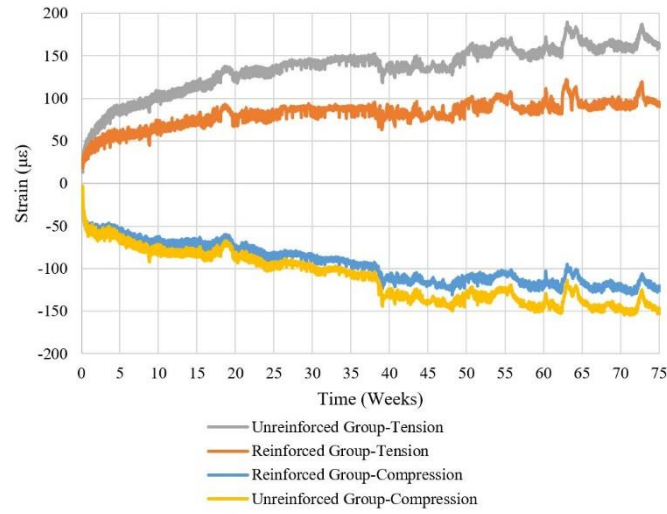
The longitudinal strain has been measured on the tension and compression faces of seven unreinforced and seven reinforced beams. The mean total strain measurements from the tension and compression faces of the unreinforced and reinforced beam groups are presented in **Fig. 10**. The strain gauge measurements on the compression faces are similar when both beam groups are compared. The reinforced beam group experiences slightly less strain than the unreinforced beam group. In contrast, the difference between the strains measured on the tension face of each beam group is more significant. The reinforced beams experience 24.5% less strain on average after 75 weeks. This difference is as a result of the rod reinforcement and its position within the tensile lamination of each reinforced beam.



335

336 **Fig. 10.** Mean total strain results on the tension and compression face of the unreinforced and reinforced beam groups ($\epsilon_T = \epsilon_e + \epsilon_{ve}$).

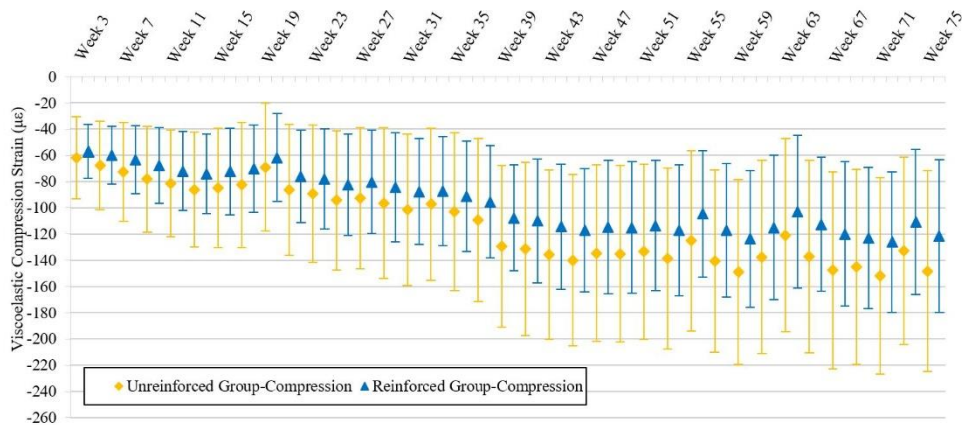
337 To isolate the viscoelastic strain, the instantaneous elastic strain component has been subtracted from the total strain
338 component of each individual beam. The mean viscoelastic strain results are presented in **Fig. 11**. Similar mean strains are
339 observed on the compression faces of both the unreinforced and reinforced beams groups indicating a similar stress and
340 creep rate within both beam groups. In comparison, the mean strains on the tension face are larger for the unreinforced
341 group than the reinforced group. The presence of the reinforcement causes a reduction in the timber tensile stresses as seen
342 in and therefore a lower creep rate is expected (**Table 1**). It is important to note that the controlled climate chamber
343 remained at a constant temperature of 20 ± 2 °C and at a constant relative humidity of 65 ± 5 % throughout the duration of
344 the test and that there was no additional effects due to mechano-sorptive creep or swelling/shrinkage of the timber.



346

347 **Fig. 11.** Mean viscoelastic strain ($\mu\epsilon$) results on the tension and compression face of the unreinforced and reinforced beam groups (ϵ_{ve}).

348 To examine the significance of differences in viscoelastic strain on the compression face, the values at a series of time
 349 points are presented in **Fig. 12** and **Table 5**. The mean viscoelastic strain results in **Fig. 12** show similar trends in both the
 350 unreinforced and reinforced groups. Again, there is a slightly higher standard deviation associated with the unreinforced
 351 group beams. In **Table 5**, the difference between the mean of each group is not statistically significant at any point
 352 throughout the test. The percentage difference ranges from 8.23% at week 3 to a maximum of 20.80% at week 67. The
 353 trend is generally increasing throughout the test; however, there is no evidence to suggest the mean viscoelastic strain
 354 measured on the compression face of the unreinforced and reinforced groups is different. This shows that a similar bending
 355 stress on the compression face results in a similar creep rate within the timber.



356

357 **Fig. 12.** Mean and standard deviation of the viscoelastic strain ($\mu\epsilon$) measured on the compression face of the unreinforced and reinforced
 358 groups at a series of time points (ϵ_{ve}).

359

360
361

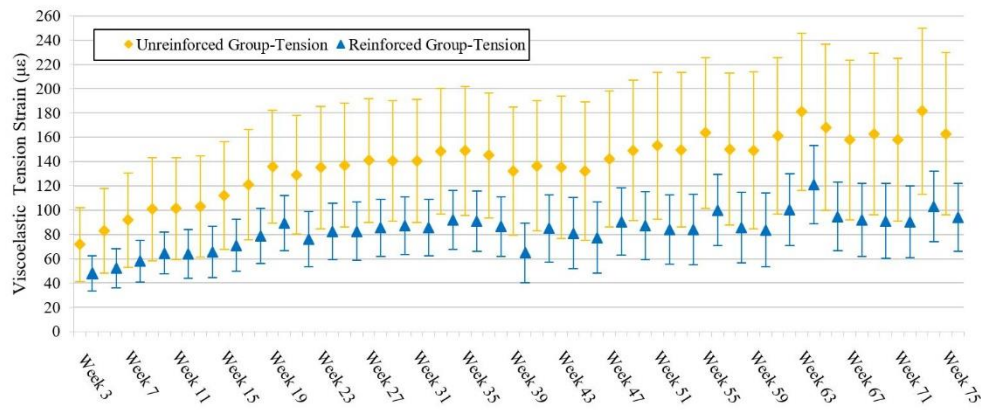
Table 5. Average viscoelastic strain (standard deviation) on compression face of unreinforced and reinforced groups at a series of time points (ϵ_{ve}).

Group-Compression	Week 3	Week 11	Week 19	Week 35	Week 51	Week 67	Week 75
Unreinforced	-61.94 (31.19)	-83.69 (42.60)	-69.02 (48.70)	-102.95 (60.41)	-133.48 (66.80)	-147.71 (75.05)	-148.23 (76.71)
Reinforced	-57.05 (20.66)	-73.42 (30.39)	-61.81 (33.53)	-91.24 (42.06)	-113.66 (49.66)	-119.87 (55.11)	-121.71 (58.21)
Percentage Diff.	8.23%	13.07%	11.02%	12.06%	16.03%	20.80%	19.64%
Students t-test	Not Sig.	Not Sig.	Not Sig.	Not Sig.	Not Sig.	Not Sig.	Not Sig.
p-Value	0.735	0.613	0.753	0.681	0.541	0.444	0.480

362

363 The standard deviation associated with the viscoelastic strain measurement on the tension face at a series of time points
 364 can be seen in **Fig. 13**. The reinforced beams experience much more consistent viscoelastic behaviour and there is a greater
 365 standard deviation observed within unreinforced beams. In **Table 6**, a comparison is made between the mean viscoelastic
 366 strain component on the tension face of unreinforced and reinforced beam groups. It can be seen that even after 3 weeks of
 367 testing, a percentage difference of 39.84% exists between the viscoelastic strain measured on the tension faces of
 368 unreinforced and reinforced beams. Statistical Student's t-tests have shown that, at this point, the percentage difference is
 369 not statically significant. The difference is not statistically significant until after week 15 with a percentage difference of
 370 44.90%. This percentage difference continues to increase to a maximum of 54.33% at week 71 as seen in **Table 6** and is
 371 still increasing with time. This indicates a reduced creep rate on the tension faces of reinforced beams as a result of the
 372 reinforcement.

373



374

Fig. 13. Mean and standard deviation of the viscoelastic strain ($\mu\epsilon$) measured on the tension faces of the unreinforced and reinforced groups at a series of time points (ϵ_{ve}).

376
377

Table 6. Average viscoelastic strain (standard deviation) on tension face of the unreinforced and reinforced groups at a series of time points (ϵ_{ve}).

Group-Tension	Week 3	Week 7	Week 15	Week 31	Week 47	Week 55	Week 71
Unreinforced	71.77 (30.43)	91.79 (38.90)	112.08 (44.44)	140.56 (50.56)	142.33 (56.07)	163.72 (62.00)	157.94 (67.22)
Reinforced	47.93 (14.43)	58.02 (17.06)	70.98 (21.29)	85.66 (23.47)	90.56 (27.77)	100.03 (29.30)	90.47 (29.50)
Percentage Diff.	39.84%	45.08%	44.90%	48.54%	44.46%	48.30%	54.33%

378
379

Students t-test	Not Sig.	Not Sig.	Sig.	Sig.	Sig.	Sig.	Sig.
p-Value	0.086	0.057	0.048	0.023	0.049	0.030	0.032

380

381 **4 SUMMARY AND CONCLUSIONS**

382 The short-term behaviour of FRP-reinforced timber beams has been widely investigated. This study focuses on the long-
383 term behaviour of these elements and investigates the influence of the reinforcement on the viscoelastic creep response. A
384 test procedure has been designed to ensure that other factors known to influence the creep behaviour of timber elements
385 do not prevent valid comparisons between the response of reinforced and unreinforced beams. These factors are the
386 differences in mechanical properties of the timber due to the natural variability in timber properties, differences in moisture
387 content and temperature due to the climatic conditions and differences in the stress level due to the applied loads.

388 The variability in the timber properties has been minimised by creating matched groups, statistically equal in terms of
389 unreinforced bending stiffness. The climate conditions throughout the test remained at a constant temperature and relative
390 humidity. As a result, additional moisture content, temperature, mechano-sorptive creep and swelling/shrinkage effects
391 were avoided. Each beam was subjected to a specific applied load to induce a bending stress of 8 MPa on the compression
392 face. This ensured that the timber stress levels in both the unreinforced and reinforced beam groups were closely matched.

393 Preliminary short-term flexural tests on twenty glued laminated beams demonstrated that the addition of BFRP rod
394 reinforcement in modest quantities can greatly increase the short-term flexural stiffness of glued laminated beams. An
395 average increase in local bending stiffness of 16.3% was observed for a moderate percentage reinforcement of 1.85%. The
396 results demonstrated the suitability of this material for timber reinforcement applications.

397 The long-term deflection results have shown an overall decrease in the total deflection (elastic deflection + viscoelastic
398 deflection) of reinforced beams due to the FRP reinforcement. However, when examining the long-term creep deflections,
399 it has been shown that there is no statistically significant reduction in relative viscoelastic creep deflection when comparing
400 both the unreinforced and reinforced beam groups loaded to a common maximum compressive bending stress. The
401 influence of the reinforcement on the total creep response is indirect and is due to an increase in elastic stiffness. This
402 indicates that the current creep modification factors provided for solid or engineered wood products in Eurocode 5 [14]
403 may be adequate in describing the creep behaviour of FRP reinforced beams under Service Class 1 conditions. The final
404 deflection of FRP-reinforced timber beams may be calculated using the current Eurocode 5 procedures using the composite
405 elastic stiffness of the reinforced beam. While this finding is valid for the current test programme, additional work is
406 required to determine its validity in general. The influence of the timber species, FRP material and reinforcement
407 percentage on the creep deflection behaviour requires further study. For other service class conditions, the influence of

408 different timber moisture contents also requires investigation. Additionally, the applied stress level requires attention and
409 the creep response at higher stress levels should be examined so that the cut-off point in relation to tertiary creep can be
410 determined. The viscoelastic behaviour of unreinforced timber elements has been shown to be susceptible to tertiary creep
411 or creep rupture at stress levels in excess of 55% [15,16]. The use of FRP materials may delay the onset of creep rupture
412 and should be examined.

413 The viscoelastic mid-span longitudinal strains on the compression faces of both the unreinforced and reinforced beams
414 were similar and no statistically significant difference was observed, as expected from the experimental design. In
415 comparison, on the tension face, a statistically significant reduction in viscoelastic strain in the reinforced group relative to
416 the unreinforced group was found. This reduction in strain rate is due to the change in the stress distribution within the
417 timber when reinforced.

418 The methodology described in this paper is being used to investigate the influence of other climatic conditions. Two
419 matched groups (one unreinforced and one reinforced) are under creep testing in a controlled variable climate condition to
420 examine and quantify the effect of FRP reinforcement on mechano-sorptive and swelling/shrinkage behaviour of timber
421 elements, which occurs under Service Class 2/Service Class 3 conditions with changing moisture content. This will be
422 reported in a future publication.

423 ACKNOWLEDGEMENT

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

429 REFERENCES

- 430 [1] J.R. Gilfillan, S.G. Gilbert, G.R.H. Patrick, The improved performance of home grown timber glulam beams using
431 fibre reinforcement, *J. Inst. Wood Sci.* 15 (2001) 307–317.
- 432 [2] H.R. Valipour, K. Crews, Efficient finite element modelling of timber beams strengthened with bonded fibre
433 reinforced polymers, *Constr. Build. Mater.* 25 (2011) 3291–3300. doi:10.1016/j.conbuildmat.2011.03.017.
- 434 [3] G. Raftery, A. Harte, Low-grade glued laminated timber reinforced with FRP plate, *Compos. Part B Eng.* 42 (2011)
435 724–735. doi:10.1016/j.compositesb.2011.01.029.

- 436 [4] J.F. Brady, A.M. Harte, Prestressed FRP flexural strengthening of softwood glue-laminated timber beams, World
437 Conf. Timber Eng. 2008. (2008).
- 438 [5] A.M. Harte, P. Dietsch, Reinforcement of timber structures: A state-of-the-art report., Shaker Verlag GmbH,
439 Germany, 2015.
- 440 [6] W. Lu, Z. Ling, Q. Geng, W. Liu, H. Yang, K. Yue, Study on flexural behaviour of glulam beams reinforced by
441 Near Surface Mounted (NSM) CFRP laminates, Constr. Build. Mater. 91 (2015) 23–31.
442 doi:10.1016/j.conbuildmat.2015.04.050.
- 443 [7] K.-U. Schober, A.M. Harte, R. Kliger, R. Jockwer, Q. Xu, J.-F. Chen, FRP reinforcement of timber structures,
444 Constr. Build. Mater. 97 (2015) 106–118. doi:10.1016/j.conbuildmat.2015.06.020.
- 445 [8] S. Franke, B. Franke, A.M. Harte, Failure modes and reinforcement techniques for timber beams – State of the art,
446 Constr. Build. Mater. 97 (2015) 2–13. doi:10.1016/j.conbuildmat.2015.06.021.
- 447 [9] I.R. Kliger, R. Haghani, M. Brunner, A.M. Harte, K.U. Schober, Wood-based beams strengthened with FRP
448 laminates: improved performance with pre-stressed systems, Eur. J. Wood Wood Prod. 74 (2016) 319–330.
449 doi:10.1007/s00107-015-0970-5.
- 450 [10] L.D. Armstrong, R.S. Kingston, Effect of moisture changes on creep in wood, Nature, London. 185 (1960) 862–
451 863. doi:10.1038/185862c0.
- 452 [11] L.D. Armstrong, R.S.T. Kingston, The effect of moisture content changes on the deformation of wood under stress,
453 Aust. J. Appl. Sci. 13 (1962) 257–276.
- 454 [12] A. Mårtensson, Creep behavior of structural timber under varying humidity conditions, J. Struct. Eng. 120 (1994)
455 2565–2582.
- 456 [13] C. Bengtsson, R. Kliger, Bending creep of high-temperature dried spruce timber, Holzforschung. 57 (2003) 95–
457 100. doi:10.1515/hf.2003.015.
- 458 [14] CEN, EN 1995-1-1. Eurocode 5: Design of timber structures - Part 1-1: General - Common rules and rules for
459 buildings, Comité Européen de Normalisation, Brussels, Belgium, 2009.
- 460 [15] J. Senft, S. Suddarth, An analysis of creep-inducing stress in Sitka spruce, Wood Fiber Sci. 2 (1971) 321–327.
- 461 [16] T. Toratti, Creep of timber beams in a variable environment, Laboratory of Structural Engineering and Building
462 Physics, Helsinki University of Technology, Finland, 1992.

- 463 [17] R.W. Davidson, The influence of temperature on creep in wood, *For. Prod. J.* 12 (1962) 377–381.
- 464 [18] L.D. Armstrong, Deformation of wood in compression during moisture movement, *Wood Sci.* 5 (1972) 81–86.
- 465 [19] S. Hering, P. Niemz, Moisture-dependent, viscoelastic creep of European beech wood in longitudinal direction,
466 *Eur. J. Wood Wood Prod.* 70 (2012) 667–670. doi:10.1007/s00107-012-0600-4.
- 467 [20] D.G. Hunt, The prediction of long-time viscoelastic creep from short-time data, *Wood Sci. Technol.* 38 (2004)
468 479–492. doi:10.1007/s00226-004-0244-6.
- 469 [21] P. Gressel, Prediction of long-term deformation behaviour from short-term creep experiments, *Holz Als Roh-Und*
470 *Werkst.* 42 (1984) 293–301. doi:10.1007/BF02608938.
- 471 [22] R. Kligler, M. Al-Emrani, M. Johansson, R. Crocetti, Strengthening timber with CFRP or steel plates - Short and
472 long-term performance, in: *Proc. 10th World Conf. Timber Eng. 2008, June 2, 2008 - June 5, 2008, Miyazaki,*
473 *Japan, 2008: pp. 414–421.*
- 474 [23] N. Plevris, T. Triantafillou, Creep behavior of FRP-reinforced wood members, *J. Struct. Eng.* 121 (1995) 174–186.
475 doi:10.1061/(ASCE)0733-9445(1995)121:2(174).
- 476 [24] M. Yahyaei-Moayyed, F. Taheri, Experimental and computational investigations into creep response of AFRP
477 reinforced timber beams, *Compos. Struct.* 93 (2011) 616–628. doi:10.1016/j.compstruct.2010.08.017.
- 478 [25] W.G. Davids, H.J. Dagher, J.M. Breton, Modeling creep deformations of FRP-reinforced glulam beams, *Wood*
479 *Fiber Sci.* 32 (2000) 426–441.
- 480 [26] G. Raftery, A. Harte, Material characterisation of fast-grown plantation spruce, *Struct. Build.* 167 (2014) 380–386.
481 doi:10.1680/stbu.12.00052.
- 482 [27] J.R. Gilfillan, S.G. Gilbert, G.R.H. Patrick, The use of FRP composites in enhancing the structural behavior of
483 timber beams, *J. Reinf. Plast. Compos.* 22 (2003) 1373–1388. doi:10.1177/073168403035583.
- 484 [28] CEN, EN 14080. Timber structures - Glued laminated timber and glued solid timber - Requirements, Comité
485 Européen de Normalisation, Brussels, Belgium, 2013.
- 486 [29] R. Parnas, M.T. Shaw, Q. Liu, Basalt fiber reinforced polymer composites, *New Engl. Transp. Consortium. Proj.*
487 *Rep. No. 03-7 NETCR63. (2007).*
- 488 [30] V. Lopresto, C. Leone, I. De Iorio, Mechanical characterisation of basalt fibre reinforced plastic, *Compos. Part B*
489 *Eng.* 42 (2011) 717–723.

- 490 [31] D. Yeboah, S. Taylor, D. McPolin, R. Gilfillan, Pull-out behaviour of axially loaded Basalt Fibre Reinforced
491 Polymer (BFRP) rods bonded perpendicular to the grain of glulam elements, *Constr. Build. Mater.* 38 (2013) 962–
492 969. doi:DOI 10.1016/j.conbuildmat.2012.09.014.
- 493 [32] C. O’Neill, D. McPolin, S.E. Taylor, A.M. Harte, C. O’Ceallaigh, K.S. Sikora, Timber moment connections using
494 glued-in basalt FRP rods, *Constr. Build. Mater.* 145 (2017) 226–235. doi:10.1016/j.conbuildmat.2017.03.241.
- 495 [33] MagmaTech Limited, Rockbar-Corrosion resistant basalt fibre reinforcing bars, Tech. Data Sheet, Accessed,
496 11/10/2014. (2014). www.magmatech.co.uk.
- 497 [34] ISO, 10406-1. Fibre-reinforced polymer (FRP) reinforcement of concrete Test methods Part 1: FRP bars and grids,
498 ISO, Geneva, Switzerland, 2015.
- 499 [35] CEN, EN 408. Timber structures - Structural timber and glued laminated timber - Determination of some physical
500 and mechanical properties, Comité Européen de Normalisation, Brussels, Belgium, 2014.
- 501 [36] R.W. Runyen, D.W. Dinehart, S.P. Gross, W.G. Dunn, Creep behavior of wood I-joists with web openings exposed
502 to normal and low relative humidity conditions., in: *Proc. World Conf. Timber Eng. 2010, WCTE 2010, June 20,*
503 *2010 - June 24, 2010, Trento, Italy, 2010.*
- 504 [37] C. Bengtsson, *Mechanosorptive Creep in Wood - Experimental studies of the influence of material properties,*
505 *Chalmers University of Technology, Goteborg, Sweden, 1999.*

506