MECHANO-SORPTIVE CREEP IN REINFORCED GLULAM

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ABSTRACT: An investigation was carried out to examine the effect of reinforcement on the creep behaviour of FRP reinforced timber elements in a controlled variable climate. Creep is accelerated by moisture variations due to a variable climate. This is termed the mechano-sorptive effect. In this paper, both unreinforced and reinforced beams are subjected to long-term creep tests loaded to a common maximum compressive stress of 8 MPa. The relative humidity of the variable climate was cycled between $65 \pm 5\%$ and $90 \pm 5\%$ every four weeks while the temperature remained constant at $20 \pm 2°C$. After 75 weeks, the total deflection and creep deflection of the reinforced beams was reduced by 16.46% and 8.37%, respectively, compared to the unreinforced beams. The results have shown that the creep behaviour of the unreinforced and reinforced beams is heavily influenced by the variable climate and it was found that the reduction in total deflection and creep deflection is statistically significant after just the first relative humidity cycle.

KEYWORDS: FRP, Mechano-sorptive creep, Reinforced timber, Sitka spruce, Viscoelastic creep

1 INTRODUCTION

In recent times, FRP (Fibre reinforced Polymer) materials have been increasingly used to strengthen and stiffen structural timber products. Across Europe, this technology has been used, not only in new structures but in the upgrading and repair of existing structures. Additional capacity can be successfully achieved in a timely and cost-effective manner through the use of FRP reinforcement [1–4].

When timber is stressed under long-term load, it is susceptible to creep deformations which may lead to unsatisfactory serviceability limit state performance of the element. Additionally, creep behaviour is accelerated when timber is stressed and simultaneously subject to changes in moisture content as a result of fluctuations in the relative humidity of the surrounding environment. Creep behaviour is accounted for in the design of unreinforced timber structures in Eurocode 5 [5] through the use of modification factors (k_{def}), based on the Service Class conditions. However, the influence of reinforcement on these effects has not been quantified or accounted for in current design codes. This study aims to examine the influence of FRP reinforcement on the long-term behaviour of timber elements by simultaneously loading unreinforced and reinforced beams to a common bending stress level in a controlled variable climate.

2 LITERATURE REVIEW

When stressed, timber elements display instantaneous elastic behaviour followed by viscoelastic behaviour with time. Due to the hygroscopic nature of timber, additional effects must be considered when the relative humidity of the surrounding environment fluctuates. In a variable climate condition, mechano-sorptive creep and swelling/shrinkage behaviour must also be considered.

Mechano-sorptive creep behaviour in flexural timber elements manifests itself as an increase in deflection. Mechano-sorptive creep behaviour has been observed in solid and engineered wood products loaded under various stress levels and subjected to various relative humidity cycles [6–12]. Due to the complex nature of timber, and the variability in properties, quantifying creep, both viscoelastic and mechano-sorptive, can be difficult. Bengtsson [13] monitored the influence of many material parameters on mechano-sorptive creep in Norway spruce beams. These parameters included annual ring width, slope of grain, knot area, percentage compression wood, density, and modulus of elasticity. The results by Bengtsson [13] have shown that the relationship between relative creep and elastic modulus was strongly correlated while comparisons with the other properties demonstrated weaker correlations.

It has also been shown by Armstrong [6], that the greater the moisture differential in each relative humidity cycle, the greater the amount of mechano-sorptive creep. EN 1156 [14] describes procedures for determining the creep modification factors (k_{def}), of wood-based panels. It recommends the moisture cycle implemented must be designed to coincide with one of the three service classes as defined in Eurocode 5 [5]. Service Class 1 is described as 'dry conditions', which is characterised by a material moisture content corresponding to a temperature of 20°C and a relative humidity only exceeding 65% for a few weeks per year. Service Class 2 is described as 'humid conditions', which is characterised by a material moisture content corresponding to a temperature of 20°C and a relative humidity only exceeding 85% for a few weeks per

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year. Service Class 3 is described as 'exterior conditions', which is characterised by a material moisture content corresponding to climatic conditions leading to higher moisture contents than that occurring in Service Class 2 conditions.

Hunt [15] examined the influence of humidity changes and suggested that the rate of moisture content change might be important in mechano-sorptive creep development. This means that the full extent of the mechano-sorptive effect will require the timber to adjust to the equilibrium moisture content of its new environmental conditions. For this reason, short relative humidity changes or moisture cycles on full scale tests will provide inaccurate results. As there is no harmonised standard for examining the mechano-sorptive effect in engineered wood products, the duration of creep tests and relative humidity cycles have varied considerably in the test programmes reported in the literature.

Abdul-Wahab et al. [16] performed long-term creep tests on 65 unreinforced glued laminated and solid timber beam specimens under different environmental conditions over an eight-year period. The beams were subject to four-point bending in three sets of environmental conditions. These conditions happened to coincide with Service Classes 1, 2 and 3 as defined in Eurocode 5 [5]. Environmental condition 1 was set at a constant temperature of 20°C and a constant relative humidity of 60 ± 10%. Environmental condition 2 was a controlled variable climate condition with a constant temperature of 20°C and a relative humidity ranging between 30% and 70%. Environmental condition 3 was an external climate in a covered enclosure with a variable relative humidity ranging between 30% and 100%. Abdul-Wahab et al. [16] found that Service Class 3 beams experienced the greatest creep averaging a 285% increase in creep when compared to Service Class 1 beams at constant temperature and relative humidity. Service Class 2 beams in the controlled variable climate experienced an increase in creep of 165% when compared to the beams tested in Service Class 1. The deformations of beams loaded in variable climate conditions are significantly greater than that experienced in the constant environmental condition and motivate the need for greater understanding of these effects. While the mechano-sorptive behaviour of timber has been the subject of many studies, this behaviour in reinforced timber beam has received less attention.

Some of the most relevant studies were performed by Gilfillan et al. [17] and Kliger et al. [18]. In an external but sheltered climate, Gilfillan et al. [17] performed creep tests on an equal proportion of unreinforced control beams and beams reinforced with carbon fibre reinforced polymer (CFRP). It was not possible to draw any significant conclusions as only 6 beams were tested; however, a reduced creep deflection was recorded in the reinforced beams.

In Kliger et al. [18], a total of 24 beams measuring 45 x 70 x 1100 mm³ were manufactured. Four groups, equal in terms of elastic modulus were created, and three of these groups were reinforced, each with a different reinforcing material in the tension zone. The three reinforcement schemes involved the adhering of a reinforcing material in grooves routed the entire length of the beams. They loaded each beam in four-point bending to a common maximum compressive bending stress in the timber of 8 MPa. The controlled variable climate was cycled between 30% and 90% relative humidity in a 28 day cycle while the temperature remained constant at 23°C for the duration of the test. The results demonstrated that the addition of approximately 2% CFRP reinforcement not only improves the short-term flexural performance of the beam but also reduces the long-term creep deflection when compared to unreinforced beams.

3 EXPERIMENTAL PROCEDURE

3.1 INTRODUCTION

This study was performed to examine the long-term mechano-sorptive creep performance of FRP reinforced glued laminated beams in a controlled variable climate and to quantify the influence of the FRP reinforcement. The experimental procedure implemented in this study follows that presented in O'Ceallaigh et al. [19] which examined the influence of FRP reinforcement on the viscoelastic creep response on beams loaded in a constant climate. The beams used in this test programme are manufactured using Irish-grown Sitka spruce. A proportion of the beams were reinforced with basalt fibre reinforced polymer (BFRP) rods. The unreinforced and reinforced beams underwent short- and long-term testing. The mid-span vertical deflection was measured with time. The total deflection measured encompasses the elastic deflection and viscoelastic creep deflection, together with mechano-sorptive creep deflection and deformations due to swelling and shrinkage.

3.2 GLULAM BEAM MANUFACTURE

The timber used in this study was grade C16 Sitka spruce. Each laminate was strength graded using a mechanical grading machine. Glued laminated beams, comprising four laminations and measuring approximately 98 mm x 125 mm x 2300 mm, were designed and manufactured. The adhesive applied was a 1:1 phenol resorcinol formaldehyde adhesive and the beams were clamped in a rig to a minimum pressure of 0.6 MPa in accordance with EN 14080 [20]. The beams remained clamped in the rig for 24 hours to allow the adhesive to cure prior to being placed into a conditioning chamber for 5 weeks to condition at a relative humidity of 65 ± 5% and at a temperature of 20 ± 2°C.

A subset of the beams was reinforced with two 12 mm BFRP rods positioned in two circular routed grooves in the bottom tensile laminate. The grooves were sized to accommodate the BFRP rod plus a 2 mm glue line. A two-part structural epoxy adhesive was used to bond the reinforcement to the timber. The beams were then placed in the conditioning chamber with a temperature of 20 ± 2 °C and with a relative humidity of 65 ± 5%, where they remained for a period of 3 weeks prior to any testing.

3.3 SHORT-TERM TESTING

Each beam was subjected to non-destructive flexural testing in accordance with EN 408 [21] to establish the bending stiffness. The beams were initially tested in their

unreinforced state. The load was applied through a hydraulic actuator at a rate of 0.15 mm/s (< 0.003 x h limit) to a maximum stroke of 15 mm to ensure that the deflection did not exceed the elastic limit. The deflection at the mid-span of each beam was measured using two linear variable differential transformers (LVDTs), one for determining the local stiffness and the other for the global stiffness.

Statistical student's t-tests were then carried out to create matched groups based on the non-destructive flexural test results. In this study, all statistical tests were carried out to a significance level of 0.95 ($\alpha = 0.5$). Two matched groups, the Unreinforced Group and the Reinforced Group, statistically equal in terms of bending stiffness, were created to minimise the influence of timber variability on the creep response. The Reinforced Group was reinforced as described in Section 3.2 and then subsequently retested to establish the increase in bending stiffness.

3.4 LONG-TERM TESTING

In this study, a long-term creep test frame was designed to implement the same test configuration described in EN 408 [21] for short-term flexural tests. The unreinforced and reinforced groups were subjected to a dead load under four-point bending in a controlled variable climate chamber with a relative humidity ranging from $65 \pm 5\%$ to $90 \pm 5\%$ in a cycle length of 8-weeks (4 weeks at 65% and 4 weeks at 90%). The climate room data collected during the test period can be seen in *Figure 1*.
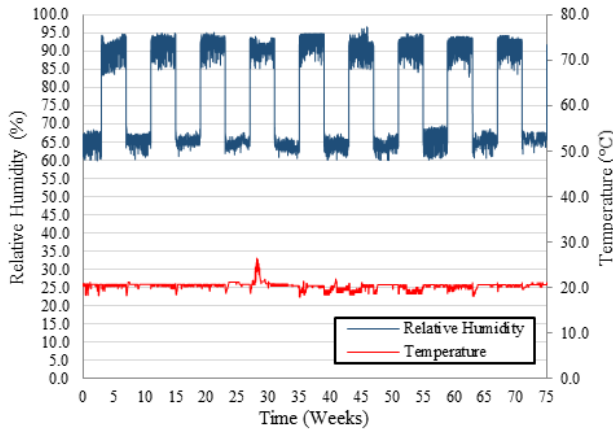

Figure 1: Creep test controlled variable climate conditions

Each beam was loaded to a common maximum compressive stress of 8 MPa. This ensured that each beam was subjected to a similar maximum stress in both the unreinforced and reinforced beams. To achieve this stress level, different loads were required for each beam with greater loads required on the reinforced beams. A total vertical dead load of approximately 5748 N and 6241 N was applied to the unreinforced and reinforced beams, respectively. The constant dead load was applied via a lever arm mechanism rotating about the fulcrum as seen in *Figure 2*. The number of steel plates may be adjusted, and the load hanger may be moved to increase or decrease the lever arm length, to accurately apply the required dead load on each beam.
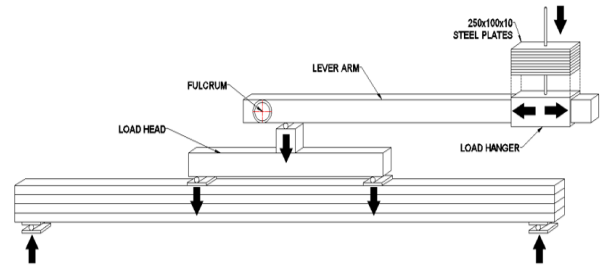

Figure 2: Creep test beam loaded through a lever arm

The mid-span vertical deflection was monitored throughout using displacement dial gauges with an accuracy of 0.01 mm. The long-term deflection is expressed in terms of both total deflection and relative creep (C_R) deflection, which is defined as the deflection at time t, expressed as a proportion of the initial elastic deflection as defined in Equation (1) [22]

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

where C_R = Relative creep, w_0 = Initial deflection and $w(t)$ = deflection at time t.

This normalised measure of relative creep removes the influence of the initial stiffness of each member and presents the creep behaviour with time. Testing commenced at a relative humidity of $65 \pm 5\%$ and at a temperature of $20 \pm 2°C$. The initial elastic deflection was noted for each beam 60s after loading. The vertical deflection results were then recorded at regular intervals with time.

4 RESULTS

4.1 SHORT-TERM TEST RESULTS

The short-term tests were performed on a total of forty glued laminated beams in accordance with EN 408 [21]. In this paper, only the results for beams subjected to long-term testing in a controlled variable climate are presented. There are eight unreinforced beams in the Unreinforced Group and eight BFRP reinforced beams in the Reinforced Group. For further information on the short-term test results for the additional unreinforced and reinforced beams omitted from this paper, see [19].
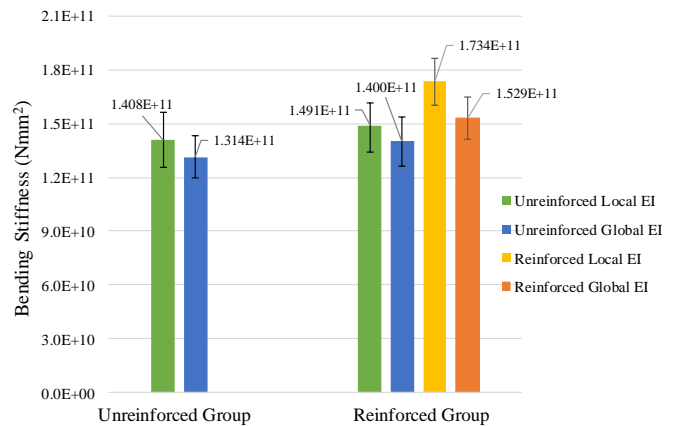

Figure 3: Bending stiffness results of the unreinforced and reinforced beam groups

The local and global bending stiffness of the Unreinforced Group and the Reinforced Group can be seen in *Figure 3*. There is a potential difference of 5.7% and 6.4% between the local and global bending stiffness results, respectively when comparing the Unreinforced Group and Reinforced Group in their unreinforced state. Statistical student's t-tests have demonstrated that there is no evidence to suggest that the mean value of each group is not equal. This is valid when examining both the mean elastic modulus and bending stiffness results and provides a common base for comparative long-term studies in a variable climate.

The local and global bending stiffness of the reinforced beams in the Reinforced Group can also be seen in *Figure 3*. The influence of the FRP reinforcement can be seen to increase both the local and global bending stiffness. This has allowed the percentage increase in bending stiffness to be determined. A mean increase in local bending stiffness of 15.09% for a moderate percentage reinforcement ratio of 1.85% was observed. There was a mean increase of 8.8% in global bending stiffness.

4.2 LONG-TERM TEST RESULTS

The creep test results over a period of 75 weeks are presented. Sixteen beams (8 unreinforced and 8 reinforced) are tested under constant load in the variable climate. The mid-span deflection of unreinforced and reinforced beams loaded to a maximum compression bending stress of 8 MPa in four-point bending can be seen in *Figure 4* and *Figure 5*, respectively. In *Figure 4*, the total deflection (initial elastic deflection, viscoelastic deflection, mechano-sorptive creep deflection and swelling/shrinkage deformation) of the unreinforced beams range from 10.18 mm (Beam 21) to 15.49 mm (Beam 15) after 75 weeks. In *Figure 5*, the total deflection of the reinforced beams ranges from 9.34 mm (Beam 14) to 11.39 mm (Beam 19) after 75 weeks. The overall deflection of the beams is generally lower in the Reinforced Group. This is expected due to the increased stiffness as a result of the BFRP reinforcement, but it is worth noting that there are additional loads on the reinforced beams to induce a common bending stress of 8 MPa in all beams. During the first three weeks of the test, each beam experienced instantaneous elastic deflection and viscoelastic creep only as the relative humidity remained constant at 65% ± 5% throughout this time (*Figure 1*). Following this period, there is a dramatic increase in the mid-span deflection of each beam as the first moisture content cycle commences, and the relative humidity increases from 65% ± 5% to 90% ± 5% for a period of 4 weeks between week 3 and week 7. A large

increase in deflection has been previously observed in creep tests on timber products in variable climates where the moisture content increases to a level not previously attained. This large increase is often referred to as the irrecoverable mechano-sorptive component of creep [23–25] which occurs in addition to mechano-sorptive creep and deflection attributed to swelling/shrinkage.
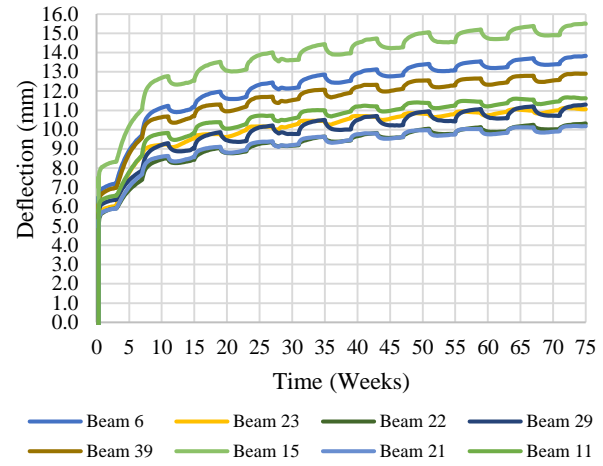

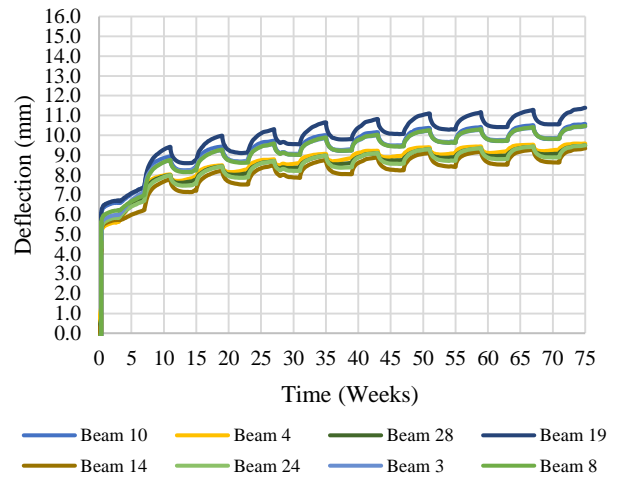*Figure 4: Unreinforced Group mid-span deflection*

Figure 5: Reinforced Group mid-span deflection

Generally, a wetting phase or increase in moisture content is associated with a decrease in deflection. This general behaviour can be seen in subsequent cycles in *Figure 4* and *Figure 5* along with a corresponding increase in deflection during the drying phase of the relative humidity cycle.

The mean creep deflection of the Unreinforced Group and the Reinforced Group in a variable climate condition are presented in *Figure 6* and *Table 1*.

Table 1: *Mid-span deflection comparison at a series of time points throughout the test*

|		Week 0	Week 3	Week 11	Week 19	Week 35	Week 51	Week 75
Unreinforced Group	Mean	5.95	6.67	9.99	10.62	11.32	11.77	12.09
	Std. Dev.	0.79	0.83	1.45	1.55	1.68	1.77	1.85
Reinforced Group	Mean	5.44	6.08	8.40	8.93	9.52	9.88	10.10
	Std. Dev.	0.40	0.40	0.58	0.63	0.67	0.70	0.73
	Percentage Difference	8.91%	9.28%	17.26%	17.25%	17.30%	17.47%	17.93%
	Student's t-test	Not Sig.	Not Sig.	Sig.	Sig.	Sig.	Sig.	Sig.
	p-Value	0.1266	0.0909	0.0182	0.0185	0.0200	0.0203	0.0195
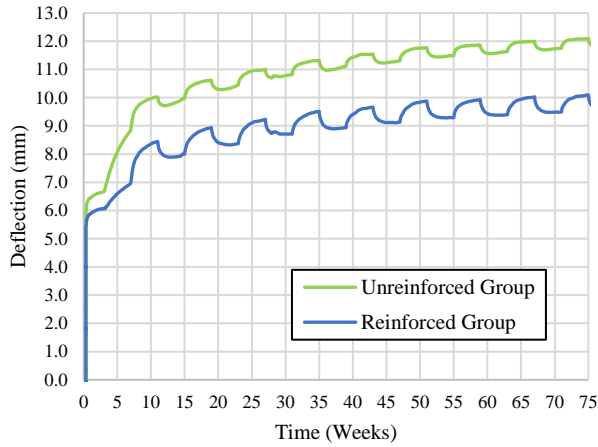
Figure 6: Mean deflection results of each group

There is a clear difference in deflection response between the unreinforced and reinforced beam groups over the 75-week test period. Directly after loading (Week 0), there is an initial percentage difference of 8.91% in the mean elastic deflection of both groups as seen in *Table 1*. This difference is as expected due to the increased stiffness of the Reinforced Group, but statistical student's t-tests have shown that this difference is not statistically significant. The percentage difference at week 3 of 9.28% signifies the difference in elastic and viscoelastic deflection. At week 3 the difference is not statistically significant.

A large difference between the two groups develops during the first 8-week cycle change (Week 3-Week 7-Week 11), where the humidity changes from 65% ± 5% to 90% ± 5% and back to 65% ± 5%. The unreinforced and reinforced beam groups are significantly affected by this first change in relative humidity. At week 11 the percentage difference is statistically significant at 17.26%. With additional cycles, the percentage difference in mid-span deflection continues to increase up to a maximum of 17.93% after 75 weeks with a maximum mean deflection of 12.09 mm and 10.10 mm in the Unreinforced Group and the Reinforced Group, respectively. This indicates that there is a beneficial reduction in the total deflection of reinforced beams and demonstrates the positive influence of the BFRP reinforcement when stressed to a common maximum compressive stress. This positive influence of the BFRP affects the elastic behaviour and the long-term creep behaviour.

To focus on the long-term creep deflection behaviour after the initial elastic deflection, the relative creep results are presented. This normalised measure of relative creep (Equation (1)) allows for comparisons to be made between the long-term creep deflection behaviour of the Unreinforced Group and the Reinforced Group. *Figure 7* presents the mean relative creep deflection results of the unreinforced and reinforced beam groups. The viscoelastic behaviour of the unreinforced and reinforced beam groups during the first 3 weeks is very similar and there is no statistically significant difference as seen in *Table 2*. However, after the first relative humidity cycle at week 11, the mean relative creep values of 1.68 and 1.55 can be observed for the unreinforced and the reinforced beam groups, respectively. There is a statistically significant difference of 8.21% between the relative creep deflection of the Unreinforced Group and Reinforced Group. In subsequent weeks, the deflection increases due to changes in the relative humidity. The percentage difference between the relative creep of the Unreinforced Group and Reinforced Group increases to a maximum of 8.83% after 75 weeks. This corresponds to a relative creep value of 2.03 for Unreinforced Group and 1.86 for the Reinforced Group (*Table 2*). The results demonstrate that the long-term deflection of the Unreinforced Group is affected by changes in relative humidity to a greater extent than that of the Reinforced Group when stressed to a common maximum stress level.
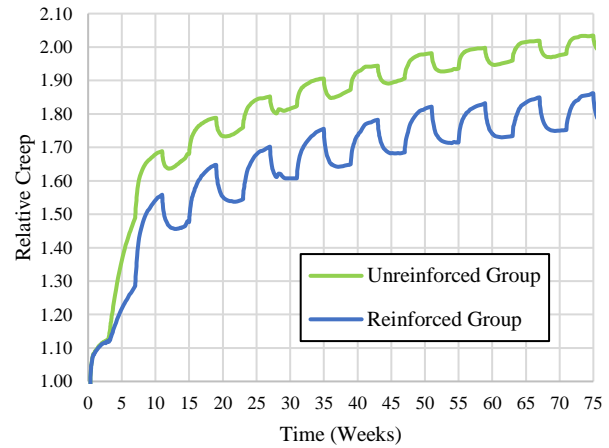

Figure 7: Mean relative creep deflection results

Similar to the total deflection results of both groups, the first change in relative humidity has a significant effect on the deflection behaviour. The first relative humidity cycle, often associated with the irrecoverable mechano-sorptive component of creep [23–25], is greater for the unreinforced beams when examining the mean relative creep results. This demonstrates that when glued laminated timber beams are subjected to a common maximum compressive bending stress, the BFRP

Table 2: Relative creep comparison at a series of time points throughout the test

		Week 0	Week 3	Week 11	Week 19	Week 35	Week 51	Week 75
Unreinforced Group	Mean	1.00	1.13	1.68	1.79	1.91	1.98	2.03
	Std. Dev.	0.02	0.01	0.05	0.06	0.07	0.08	0.08
Reinforced Group	Mean	1.00	1.12	1.55	1.65	1.76	1.82	1.86
	Std. Dev.	0.01	0.01	0.04	0.04	0.04	0.05	0.05
	Percentage Difference	0.01%	0.40%	8.21%	8.20%	8.23%	8.38%	8.83%
	Student's t-test	Not Sig.	Not Sig.	Sig.	Sig.	Sig.	Sig.	Sig.
	p-Value	0.9881	0.3786	0.0000	0.0001	0.0001	0.0002	0.0002

reinforcement has a beneficial influence on the creep behaviour of the reinforced beams during this first relative humidity cycle. The percentage difference between both beam groups is increasing with time. Interestingly, the reinforced beams can be seen to experience greater fluctuations in creep defection with subsequent relative humidity cycles (*Figure 7*). This increased fluctuation of deflection with each cycle is thought to be a result of the increased ability to recover creep deflection due to the addition of the FRP reinforcement or an effect of the restrained hygro-mechanical behaviour or differential swelling and shrinkage on the tension face of reinforced beams.

5 CONCLUSIONS

The long-term creep effects in unreinforced and reinforced glued laminated beams have been investigated in a controlled variable climate condition. The beams have been subjected to a common maximum compressive bending stress of 8 MPa to ensure the timber in unreinforced and reinforced beams is subject to a similar stress distribution through the cross-section [19]. This has allowed the influence of the FRP reinforcement to be observed.

The creep test results have shown that reinforcing timber with a material of superior properties has a positive effect on the total deflection of FRP reinforced timber beams. The percentage difference between the mean total deflection results of the unreinforced and reinforced beam groups increases up to a maximum of 17.93% after 75 weeks with a maximum mean deflection of 12.09 mm and 10.10 mm in the Unreinforced Group and the Reinforced Group, respectively. The mean total deflection of the reinforced beams is less than the unreinforced beams, even when additional load is applied to the reinforced beams to induce a common maximum bending stress in the compression zone of the timber. The range of deflection results was also greatly reduced in the case of the reinforced beam group where more consistent total deflection behaviour was observed. This is significant given that a statistical analysis demonstrated that there was no statistically significant difference between the mean bending stiffness of both groups prior to reinforcement and the standard deviation of both means was similar in their unreinforced state (*Figure 3*).

Focusing on the long-term creep behaviour, the normalised measure of relative creep was utilised to compare the unreinforced and reinforced beam groups. The results have shown that there is a statistically significant reduction in relative creep deflection in the reinforced beams when compared to the unreinforced beam group stressed to a common compressive bending stress. Interestingly, the difference was statistically significant after just the first relative humidity cycle. There is a statistically significant percentage difference of 8.21% between the relative creep deflection of the unreinforced and reinforced beam groups. This is believed to be largely due to the reduced irrecoverable mechano-sorptive creep deflection component in the reinforced beams. The difference remains statistically significant throughout the test period demonstrating the beneficial effect of the reinforcement in reducing the mechano-sorptive creep deformations of the FRP reinforced beams in a variable climate.

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