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The mechano-sorptive creep behaviour of basalt FRP reinforced timber elements in a variable climate

Conan O'Ceallaigh[a,*], Karol Sikora[b], Daniel McPolin[c], Annette M. Harte[a]

[a] College of Science and Engineering, National University of Ireland Galway, University Rd., Galway, Ireland
[b] Faculty of Engineering and Information Sciences, University of Wollongong in Dubai, United Arab Emirates
[c] School of Planning, Architecture and Civil Engineering, Queen's University Belfast, University Road, Belfast BT7 1NN, UK

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ABSTRACT

The use of Fibre Reinforced Polymer (FRP) reinforcement has been shown to improve the short-term flexural behaviour of timber elements. This is particularly important when reinforced elements are subjected to a variable climate condition, which is known to accelerate long-term or creep behaviour. In this paper, both unreinforced and Basalt FRP reinforced beams are subjected to creep tests at a common maximum compressive stress of 8 MPa over a 75-week period. Results demonstrated a significant reduction in total creep deflection due to the FRP reinforcement. Using matched groups, experimentally measured total strain behaviour is decomposed into the elastic, viscoelastic, mechano-sorptive and swelling/shrinkage strain components. Analysis has shown that the mechano-sorptive component is similar in unreinforced and reinforced beams. The reduction in creep behaviour of the reinforced members was primarily due to the restrained swelling/shrinkage response of the reinforced beams and was independent of the mechano-sorptive effect. This finding demonstrates the positive influence of FRP reinforcement on the long-term behaviour of timber elements and indicates a potential to describe the long-term deflection performance of FRP reinforced elements from short-term swelling/shrinkage tests.

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 [1,2]. When retrofitting these structures, changes in use of the building or, indeed, changes in building regulations often require a higher load capacity than that of the existing members. The additional capacity requirements can be successfully achieved in a timely and cost-effective manner through the use of FRP reinforcement [1–15]. More widespread use of this technology has been hampered by the lack of a harmonised standard governing their design. Currently, design rules for FRP reinforcement are not included in Eurocode 5 [16]. This is partly due to a lack of knowledge, particularly related to the long-term behaviour.

In timber structures, when stressed under load, the initial elastic response is followed by viscoelastic behaviour with time. Viscoelastic creep is the deformation with time at constant stress under constant environmental conditions. Due to the hygroscopic nature of timber, additional effects must be considered when the relative humidity of the surrounding environment fluctuates, namely, mechano-sorptive and swelling/shrinkage behaviour. Minimisation of the long-term deformation is key to efficient design as this is often the controlling factor in the design of timber structures, particularly in variable climatic conditions.

The total strain (ε_T), experienced by a timber element in a variable climate may be written as

$$\varepsilon_T = \varepsilon_e + \varepsilon_{ve} + \varepsilon_{ms} + \varepsilon_s \tag{1}$$

where ε_e = elastic strain, ε_{ve} = viscoelastic strain, ε_{ms} = mechano-sorptive strain, ε_s = swelling/shrinkage strain.

Due to the complex nature of timber, quantifying creep, both viscoelastic and mechano-sorptive, can be difficult. Several investigators have shown that viscoelastic creep rates increase with increasing stress [17,18], temperature [19] and moisture content [20]. The use of FRP reinforcement has been shown to be effective in enhancing the viscoelastic behaviour of timber elements under the same load level [21–24]. O'Ceallaigh et al. [24] showed that this reduction in

* Corresponding author.
E-mail addresses: conan.oceallaigh@nuigalway.ie (C. O'Ceallaigh), karolsikora@uowdubai.ac.ae (K. Sikora), d.mcpolin@qub.ac.uk (D. McPolin), annette.harte@nuigalway.ie (A.M. Harte).

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viscoelastic creep can be attributed to the enhanced flexural stiffness of the reinforced beams.

Mechano-sorptive creep in solid and engineered wood products loaded at different stress levels and subjected to different relative humidity cycles has been investigated by several authors [25–36]. Researchers have also examined the effect of a range of variables on mechano-sorptive creep. Bengtsson [37] monitored the influence of several material parameters on mechano-sorptive creep in Norway spruce beams and found that relative creep was most strongly related with the elastic modulus. Armstrong [25] has shown that the greater the moisture differential in each relative humidity cycle, the greater the magnitude of creep. Abdul-Wahab et al. [38] performed long-term creep tests on 65 unreinforced glued laminated and solid timber beam specimens under three sets of environmental conditions over an eight-year period. These conditions happened to coincide with Service Classes 1, 2 and 3 as defined in Eurocode 5 [16]. They found that beams where the relative humidity (RH) was cycled between 30% and 100% displayed a 285% increase in creep compared to beams tested at a constant RH of 60%. When cycling between 30% and 70%, the corresponding increase was 165%.

While the mechano-sorptive creep of timber has been the subject of many studies, this behaviour in reinforced timber members has received less attention. Some of the more relevant studies were performed by Gilfillan et al. [39] and Kliger et al. [40]. In an external but sheltered climate, Gilfillan et al. [39] performed creep tests on an equal proportion of unreinforced control beams and beams reinforced with carbon fibre reinforced polymer (CFRP). As only three beams of each type were tested, it was not possible to draw any significant conclusions; however, a reduced total creep deflection was recorded in the reinforced beams. In Kliger et al. [40], a total of 24 beams measuring $45 \times 70 \times 1100\ mm^3$ were manufactured. Four groups, equal in terms of elastic modulus were created, and three of these groups were reinforced with a different reinforcing material in the tension zone. The three reinforcement schemes involved the adhering of either CFRP or steel plates in grooves routed the entire length of the beams. Each beam was loaded in four-point bending to a common maximum compressive bending stress in the timber of 8 MPa. The 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 indicate that the addition of approximately 2% area reinforcement of CFRP reinforcement not only improves the short-term flexural performance of the beam but also reduces the long-term mechano-sorptive creep deflection so that it is possible to increase the span length by as much as 20% compared to unreinforced beams. It must be noted that in this study, the total creep was measured without distinguishing between the viscoelastic (ε_{ve}), mechano-sorptive (ε_{ms}) and swelling/shrinkage (ε_s) behaviour so the influence of the reinforcement on the mechano-sorptive component of the response cannot be quantified.

1.1. Objectives of the current study

The objective of the current study is to investigate the influence of near surface mounted (NSM) flexural FRP reinforcement on the long-term behaviour of structural timber beams in a variable climate. To develop models to predict long-term responses requires that the influence of reinforcement on each component of the response is characterised. This requires the decomposition of the total strain into the elastic, viscoelastic, mechano-sorptive and swelling/shrinkage components. The elastic strain (ε_e) and viscoelastic strain (ε_{ve}) have been previously characterised by O'Ceallaigh et al. [24] by testing matched groups in a constant climate. Their results have shown that there is a statistically insignificant difference in the creep deflection behaviour of unreinforced and reinforced beams in a constant climate condition. The current study focuses on characterising the total strain (ε_T) behaviour and swelling/shrinkage strain (ε_s) behaviour in a variable climate. From this, the mechano-sorptive (ε_{ms}) component of the unreinforced and reinforced beams is determined using Eq. (2).

$$\varepsilon_{ms} = \varepsilon_T - (\varepsilon_e + \varepsilon_{ve} + \varepsilon_s) \quad (2)$$

The experimental programme has been specifically designed to minimise the influence of timber variability and stress level on the response so that the influence of the FRP reinforcement can be isolated. The knowledge gathered in this study will contribute to the future development of design guidelines for reinforced timber elements.

2. Experimental programme

2.1. Introduction

The test programme is designed to enable the elastic, viscoelastic, mechano-sorptive and swelling/shrinkage components of unreinforced and reinforced beams to be individually characterised so that the influence of the FRP reinforcement can be determined.

2.2. Materials and methods

The timber used in this study was grade C16 Sitka spruce [41]. Forty glulam beams, comprising four laminations and measuring approximately 98 mm × 125 mm × 2300 mm, were designed and manufactured. Short-term flexural testing in accordance with EN 408 [42] was performed on all beams and statistical methods were utilised to create five matched groups equal in terms of mean flexural stiffness. Using matched groups helps to minimise the differences in responses arising from the natural variability in timber properties. The statistical tests involved Shapiro-Wilk test and Levene's test to assess normality of the samples and homogeneity of the group variances, respectively. Depending on the results of the Shapiro-Wilk tests and Levene's test, either a Student's *t*-test or modified Student's *t*-test (Welch's *t*-test) was carried out to compare the means of each group to one another. The results showed no statistical evidence to suggest that the mean of any group is not equal to any other group in their unreinforced state. Subsequently, twenty of the beams were reinforced with two, 12 mm diameter basalt fibre reinforced polymer (BFRP) rods inserted into routed grooves along the bottom tensile lamination as seen in Fig. 1(a). This corresponds to a mean reinforcement area of 1.85% of the beam cross-sectional area. The grooves were centred 30 mm from each side of the beam and sized to include the BFRP rods plus a 2 mm epoxy glue-line. The adhesive used was a two-part thixotropic structural epoxy specially formulated for bonding of FRP to timber. To ensure the correct glue-line thickness was achieved, 2 mm rubber rings were placed at 300 mm centres along the length of the BFRP rod. Once reinforced, the ends and the bottom face of each beam in the test programme were coated with a waterproof varnish to ensure both unreinforced and reinforced specimens are subjected to common exposure conditions in the variable climate.

The BFRP rods used were reported by the manufacturers to have a modulus of elasticity of 45,000 + N/mm^2 and a tensile strength of 1000 + N/mm^2 [43]. Experimental tests in accordance with ISO 10406-1 [44] gave a mean modulus of elasticity of 50,700 N/mm^2 and a mean tensile strength of 905 N/mm^2 for the batch used in this study [45]. Creep tests on the BFRP rods were carried out at stress levels of 3.85%, 8% and 15% of the ultimate tensile strength using the same standard [42]. The theoretical stress level in the BFRP rods in the loaded experimental beams in this study is 3.85%. The results showed that the creep of the BFRP rods was negligible at all stress levels tested with a maximum creep strain of only 25 με occurring at a stress level of 15%.

To characterise the influence of the reinforcement on the total creep response of timber elements, two matched groups (one unreinforced and one reinforced), comprising nine beams each, were subjected to long-term creep testing in a variable climate condition. These are referred to as "Group UV" (UV = Unreinforced Variable Climate) and

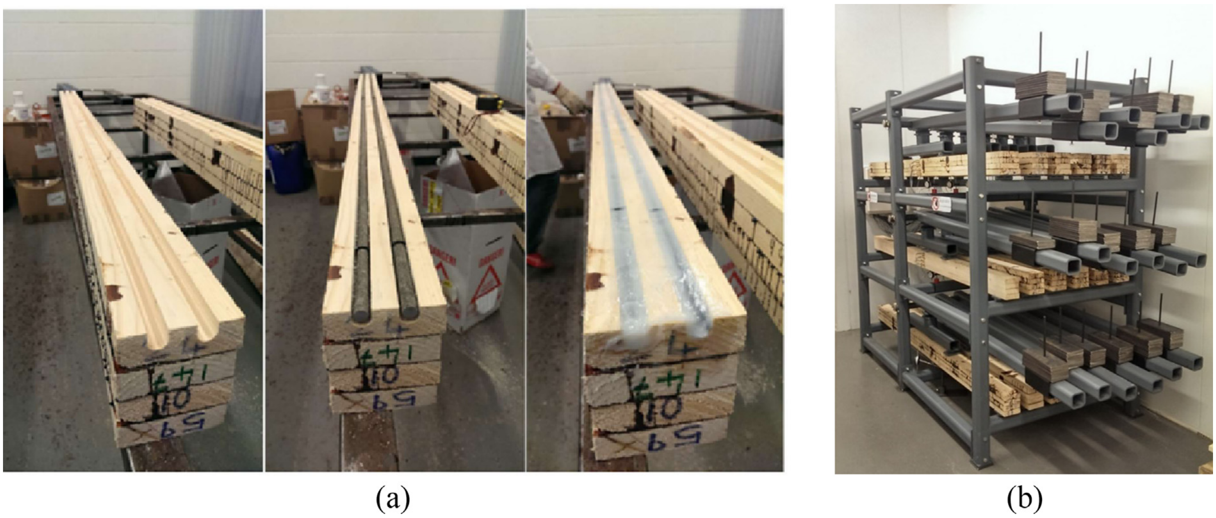

Fig. 1. Reinforced beams: (a) Manufacture of reinforced members, (b) 18 beams loaded in the creep test frame.

"Group RV" (RV = Reinforced Variable Climate). The beams were initially conditioned in a constant climate at a relative humidity of 65 ± 5% and at a temperature of 20 ± 2 °C prior to testing. Each beam was loaded under four-point bending in the creep test frame to a common maximum compression bending stress of 8 MPa. The magnitude of the bending stress is greater than that typically experienced by an in-service timber element [46] but was chosen to produce measurable creep deformations in a reasonable period without causing failure of the member. This common compressive bending stress produces a similar stress distribution in both unreinforced and reinforced beams but also means that different loads must be applied to the unreinforced and reinforced members. Mean vertical loads of approximately 6241 N and 5748 N were applied via a lever arm mechanism to the reinforced and unreinforced beams, respectively [24]. The mid-span vertical deflection was monitored throughout using Mitutoyo displacement dial gauges with an accuracy of 0.01 mm. The initial elastic deflection of both unreinforced and reinforced beams was shown to be in good agreement with the predicted deflection based on a linear elastic model. The long-term vertical deflection test results are monitored relative to the supports and 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 seen in Eq. (3) [29].

$$C_R(t) = \frac{w(t)}{w_0} \tag{3}$$

where C_R = relative creep, w_0 = initial deflection defined as the deflection 60 s after the load was applied and $w(t)$ = deflection at time t.

The mid-span longitudinal strain is measured using electrical resistance strain (ERS) gauges (TML type PLW-60-11) on the compression and tension faces as seen in Fig. 2. The initial elastic strain agreed with predicted elastic strain behaviour of beams subjected to a maximum compressive stress of 8 MPa. The ERS strain gauges, specifically designed for long-term measurements on low modulus materials such as wood, measure a change in the electrical resistance of the gauge which is correlated to strain. The ERS gauge length of 60 mm was chosen to overcome some of the inherent variability of timber. Natural defects can potentially result in poor strain measurement when using smaller strain gauges. A gauge length of 60 mm is less influenced by small defects and provides a better representation of the strain on the timber surface.

In the same variable climate, the hygro-expansion or swelling/shrinkage (ε_s) strain components are measured on non-loaded beams. These beams known as "Group MC" (MC = Moisture Content), are used to measure the swelling/shrinkage behaviour of the timber in a non-loaded state. This group is one of the five groups which was matched based on the flexural stiffness. This group comprised four specimens measuring 98 × 125 × 1000 mm^3. Each beam is monitored with ERS gauges aligned in the longitudinal direction on the top and bottom faces as seen in Fig. 2a and b. The longitudinal strain measured on the top and bottom face of each beam represent the moisture-induced swelling/shrinkage strain component that would occur on the compression and the tension face of the loaded creep test specimens, respectively [47]. For this reason, the bottom face is referred to as the tension face and the top face is referred to as the compression face. The specimens were supported at 250 mm centres on low-friction polytetrafluorethylene (PTFE) plates to allow free swelling and shrinkage of each specimen and minimise strains due to self-weight [47].

Further tests were performed on the BFRP rods to examine their swelling/shrinkage behaviour. Swelling and shrinkage tests demonstrated that the BFRP rod reinforcement was dimensionally stable when subjected to the same variable climate as the beams [45]. There was no appreciable lateral or longitudinal expansion or increase in moisture content observed. It is believed that the epoxy resin used during the manufacture to bind BFRP fibres impedes the flow of moisture and provides a stable material under cyclic relative humidity conditions.

2.3. Variable climate conditions

The variable climate condition induces mechano-sorptive creep in the loaded beams together with swelling/shrinkage strains due to hygro-expansion. This occurs due to the change in the relative humidity and subsequent change in the moisture content of the beams. A relative humidity cycle length of eight weeks (four weeks at 90% RH and four weeks at 65% RH) was implemented over a 75-week test period. This relative humidity cycle differential and length were chosen to implement a significant moisture content change throughout the cross-section of each beam in each relative humidity cycle [2]. Testing commenced at a relative humidity of 65 ± 5% and at a temperature of 20 ± 2 °C for a period of three weeks, after which, the relative humidity in the variable climate chamber was changed to 90% ± 5%. The high relative humidity was maintained for a period of four-weeks when it was reduced to 65 ± 5% for another four weeks. It was considered beneficial to delay cycling the relative humidity for the first three weeks to observe the relatively rapid viscoelastic movement in the earlier stages of the creep test. The recorded relative humidity and temperature data can be seen in Fig. 3. The small abnormality within the temperature data at 28 weeks can be attributed to a thermostat failure in the conditioning chamber resulting in variations from the set

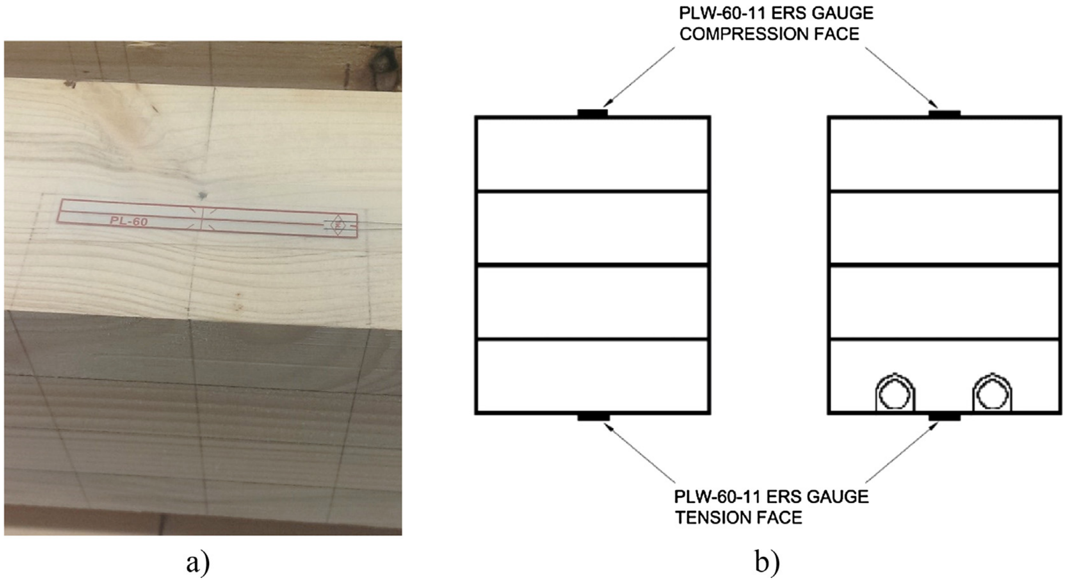

Fig. 2. PLW-60-11 ERS gauge, (a) PLW-60-11 ERS gauge alignment, (b) PLW-60-11 ERS gauge positions on the tension and compression face of the unreinforced and reinforced beams.

constant temperature of 20 °C ± 2 °C.

3. Experimental test results

The creep deflection and longitudinal strain results for the unreinforced (Group UV) and reinforced (Group RV) beams subjected to a variable relative humidity are presented together with the longitudinal swelling/shrinkage strain measurements for the unloaded Group MC. The mean mechano-sorptive strain component of the two groups are compared to examine the influence of the FRP reinforcement.

3.1. Long-term deflection results

The beam group, Group UV, consists of unreinforced beams loaded to a maximum compression bending stress of 8 MPa in four-point bending. Eight of these beams are monitored with vertical displacement dial gauges. The deflection results for these beams over the 75-week test period can be seen in Fig. 4. A large increase in the total deformation due to the variable relative humidity is found. The mid-span deflection of the similarly stressed beams in Group RV can be seen in Fig. 5. When compared to the deflection results of Group UV, the total deflection of the Group RV is significantly lower and is more consistent with reduced variation over the 75-week test period. The reduced variation in the deflection of Group RV is to be expected as defects or abnormalities, which naturally occur in timber, are reinforced and are less influential on the overall deflection resulting in more consistent deflection behaviour. There is a trend of slowly increasing deflection with each moisture cycle in both groups. Typically, there is an increase in the deflection during each drying phase and a decrease in deflection during the wetting phase. The exception to this occurs during the first cycle

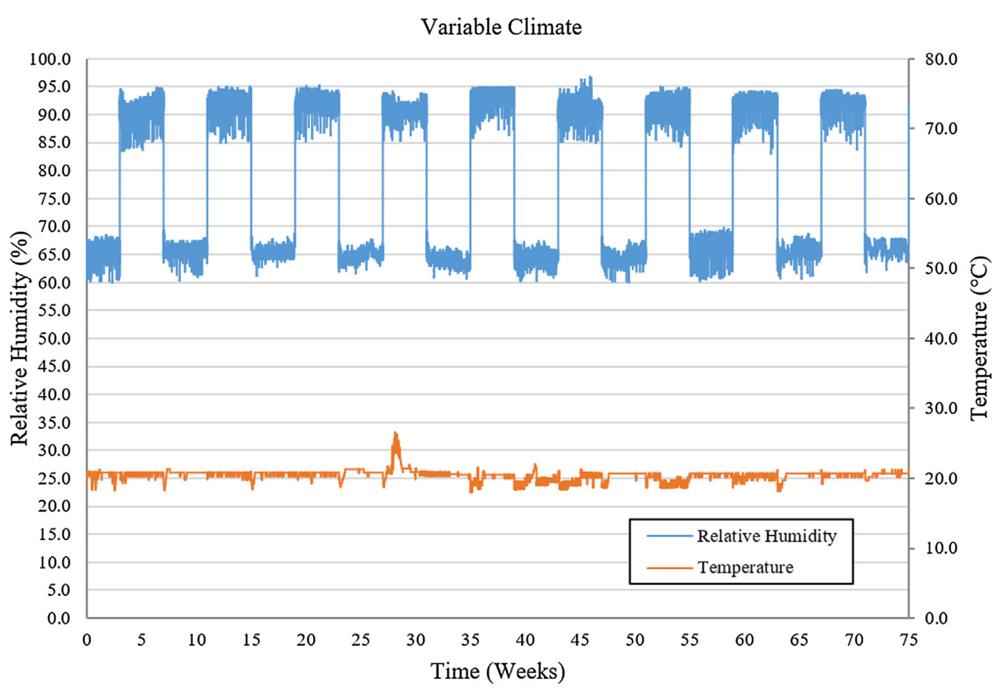

Fig. 3. Relative humidity and temperature data recorded in the variable climate chamber.

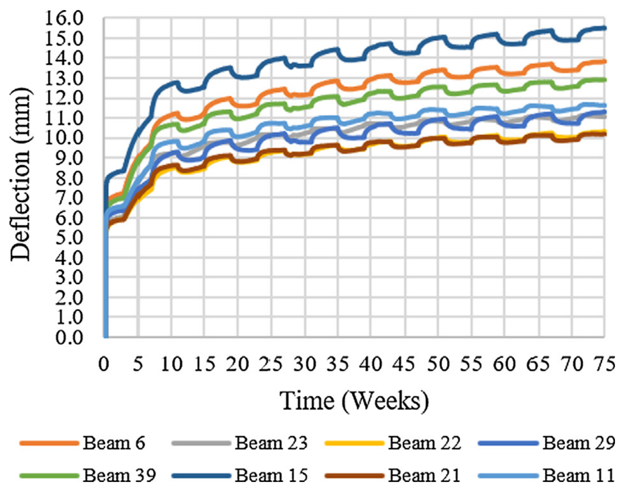

Fig. 4. Group UV mid-span deflection (mm) results.

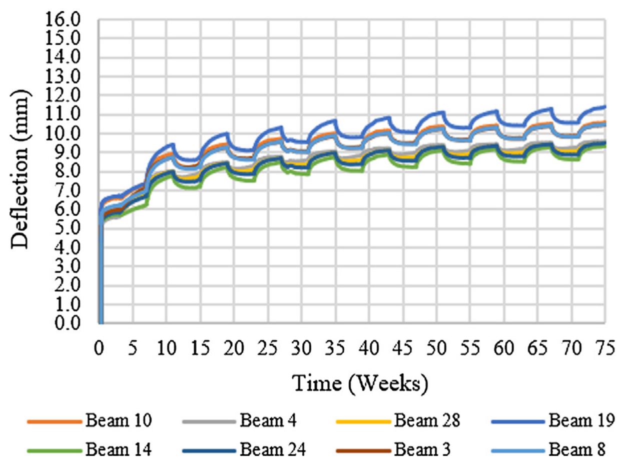

Fig. 5. Group RV mid-span deflection (mm) results.

where the moisture content increases to a level not previously attained (Week 3–Week 7), and a significant increase in deflection was recorded during a wetting phase. This behaviour has been previously observed in creep testing of timber products in variable climates [33]. The magnitude of the increase is more pronounced in the unreinforced beams than in the reinforced beams.

To compare the effect of the reinforcement on the long-term deflection, the mean total deflection of Group UV and Group RV are plotted together in Fig. 6. There is a significant difference between the initial elastic deflection (8.9%) of both groups due to the increased stiffness of the Group RV, as expected. This difference between the two groups increases during the first relative humidity cycle change (Week 3–Week 7) where the humidity changes from 65% ± 5% to 90% ± 5%. With additional cycles, the percentage difference continues to increase up to a maximum of 17.9% after 75 weeks with a maximum mean deflection of 12.09 mm and 10.10 mm in Group UV and the Group RV, respectively.

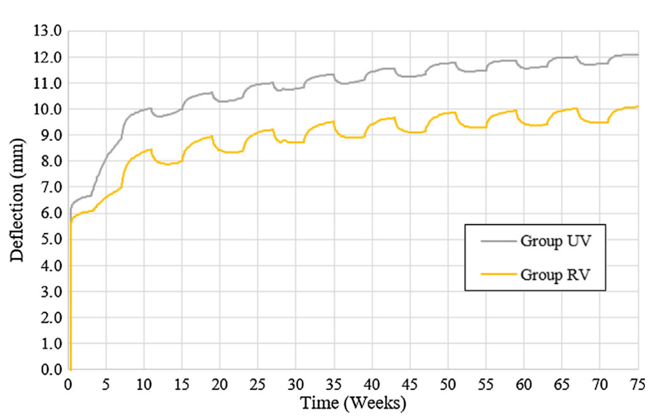

Fig. 6. Comparison between the unreinforced and reinforced group mean deflection results (mm) over a 75-week test period.

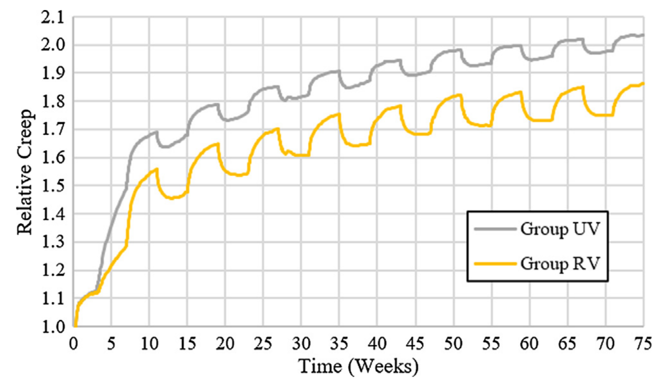

Fig. 7. Comparison between the unreinforced and reinforced group mean relative creep results over a 75-week test period.

Fig. 7 presents the average relative creep deflection results of the unreinforced and reinforced beam groups. When comparing the mean results for both groups, the unreinforced beams are found to be affected by moisture cycling to a greater extent than the reinforced beams. As seen when examining the total deflection results of these groups, the first change in relative humidity has a significant effect on the behaviour of both groups. Interestingly, the reinforced beams experience greater mean creep fluctuations with each relative humidity cycle. This was also observed by Kliger et al. [40]. This is perhaps due to an increased ability to recover creep deflection due to the addition of the reinforcement or an effect of the differential swelling/shrinkage on the tension face of reinforced beams.

To further assess the differences in responses, statistical Student's *t*-tests were performed at a series of time points shown in Table 1. In this study, all statistical tests are carried out to a significance level of 0.95 (α = 0.05). The results show that there is no statically significant difference between Group UV and Group RV up until week 3. However, after the first complete relative humidity cycle at week 11, a statically significant difference of 8.2% exists between the relative creep deflection of Group UV and Group RV. The difference remains statistically significant throughout the remainder of the test period demonstrating the beneficial influence of the reinforcement in reducing the creep deflections. The percentage difference between the two groups increased with time to a maximum of 8.8% after 75 weeks.

3.2. Long-term strain results

The longitudinal strains were measured on the tension and compression faces of seven unreinforced and seven reinforced beams using ERS gauges designed for long-term use on timber. The mean longitudinal strain results are presented in Fig. 8. Similar mean elastic strain was observed in both groups on both faces after the initial loading as seen at time t = 0 in Fig. 8. On the tension face, mean elastic strain values of 614.6 με and 577.3 με were observed for Group UV and Group RV, respectively. This difference was found to be statistically insignificant. The difference in the mean elastic strain on the compression face (−708.0 με and 642.6 με for Group UV and Group RV, respectively) was also found to be statistically insignificant. During the first three weeks of the creep test, the climate remained constant at 65% ± 5% relative humidity and there was a slight increase in longitudinal strain due to viscoelastic creep. After this period, the relative humidity was

Table 1
Comparison between the mean (standard deviation) relative creep deflection of Group UV and Group RV at a series of time points throughout the test.

Relative Creep	Week 0	Week 3	Week 11	Week 19	Week 35	Week 51	Week 75
Group UV	1.004 (0.017)	1.126 (0.010)	1.682 (0.053)	1.788 (0.059)	1.906 (0.070)	1.981 (0.075)	2.034 (0.082)
Group RV	1.004 (0.012)	1.122 (0.010)	1.549 (0.035)	1.647 (0.039)	1.756 (0.044)	1.822 (0.046)	1.862 (0.048)
Percentage Diff.	0.0%	0.4%	8.2%	8.2%	8.2%	8.4%	8.8%
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

increased and significant changes in longitudinal strain on the tension and compression face were observed. In Fig. 8, the mean total longitudinal strain (ε_T) on the tension face of the unreinforced group is seen to be larger than that of the reinforced group over the 75-week test period, with the largest changes seen during the first moisture content change. On the compression face, the unreinforced group experienced greater mean longitudinal strain over the entire test duration when compared to the reinforced group.

To solely examine the creep strain (ε_{creep}) component, the elastic strain component has been subtracted from the individual total strain (ε_T) results for each beam and the mean of these total creep strain results are presented in Fig. 9. During the first three weeks, similar total creep behaviour is seen on the tension and compression faces of both beam groups. Once the relative humidity is increased, significant increases in strain are observed immediately as mechano-sorptive creep effects and swelling/shrinkage strains occur. During weeks 3–7, there was a significant increase in strain as a result of the combined mechano-sorptive creep component and the swelling component as the moisture content increases. During weeks 7–11, there was a reduction in the strain measured in each case as the relative humidity reverted to 65% ± 5% and the moisture content decreased. As the relative humidity cycling continued, it can be seen that on both the tension and compression face, the Group UV experience greater mean total creep strain.

In Fig. 10, the mean total creep strains and corresponding standard deviations on the tension side of both Group UV and Group RV can be seen at a series of time points. The standard deviation is plotted to compare the significance of the observed differences.

A proportion of these time points are chosen and presented in Table 2. All of the points after week 3 are chosen to correspond with peak strains associated with the end of a wetting period. It can be seen that, at week 3, a statistically insignificant difference of 3.7% exists between the mean total creep strain of the two groups. While there is a large increase in the percentage difference (28.0%) after week 7 due to the first wetting cycle, the difference is not statistically significant. The total creep strain slowly increases with each subsequent cycle and the percentage difference between Group UV and Group RV continuously increases up to a maximum of 35.2% at week 71. Statistical Student's t-tests have shown that after week 31 the difference becomes statistically significant and there is a beneficial reduction in total creep strain on the tension face due to the reinforcement.

In Fig. 11, the mean total creep strains and the corresponding standard deviations on the compression faces of both the unreinforced and the reinforced groups can be seen at a series of time points. It can be seen that Group UV experiences greater total creep compression strains on average. To investigate this further, significance testing is carried out at a series of time points and results are presented in Table 3. After week 3, these points were chosen to correspond to the peak total creep compressive strains associated with the end of a drying period.

The percentage difference increases from 25.4% at week 3 to 41.9% at week 11 after the first relative humidity cycle. The percentage difference continues to increase with each cycle; however, the difference has been shown to be not statically significant.

3.3. Viscoelastic strain component

To characterise the viscoelastic strain behaviour (ε_{ve}) of

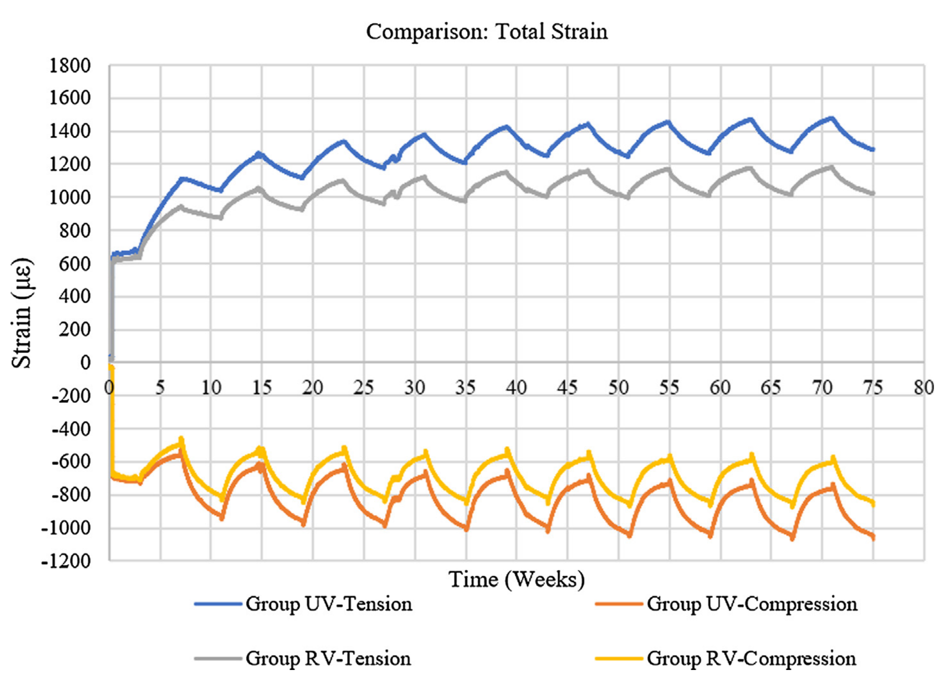

Fig. 8. Mean total longitudinal strain on the tension and compression faces of Group UV and Group RV ($\varepsilon_T = \varepsilon_e + \varepsilon_{ve} + \varepsilon_{ms} + \varepsilon_s$).

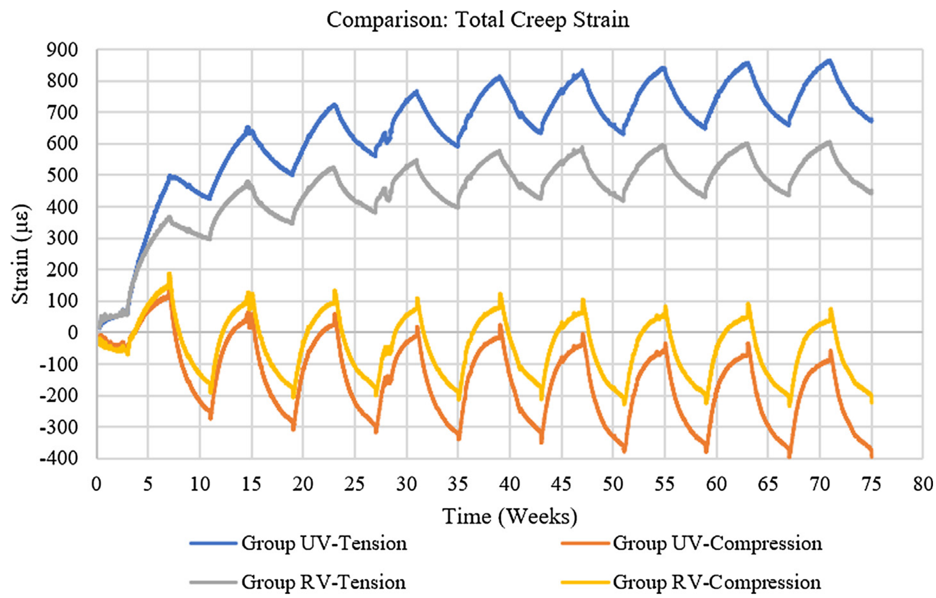

Fig. 9. Mean longitudinal creep strain on the tension and compression faces of Group UV and Group RV ($\varepsilon_{creep} = \varepsilon_{ve} + \varepsilon_{ms} + \varepsilon_{s}$).

unreinforced and reinforced beams, O'Ceallaigh et al. [24] subjected matched groups of beams to creep testing in a constant climate condition. These groups are referred to as "Group UC" (UC = Unreinforced Constant Climate) and "Group RC" (RC = Reinforced Constant Climate). The mean viscoelastic creep strain on the tension and compression face of the unreinforced Group UC and the reinforced Group RC are presented graphically in Fig. 12 and further information may be found in the article [24]. The mean viscoelastic creep strain on the compression face of Group UC and Group RC can be seen to be in good agreement. In contrast, on the tension face, a beneficial reduction in viscoelastic creep strain can be observed in the reinforced Group RC, demonstrating the positive influence of FRP reinforcement on the creep behaviour of reinforced members. It should be noted that although there was a beneficial reduction in viscoelastic creep strain on the tension face, there was no statically significant reduction in creep deflection over the 75-week test period.

3.4. Swelling/shrinkage strain component

To investigate the swelling/shrinkage behaviour of the unreinforced and reinforced beams, four specimens were placed in the variable climate condition to monitor strains development due to changing moisture content. These beams, collectively known as Group MC, comprise two reinforced beams (Beam 20 and Beam 25) and two unreinforced beams (Beam 37 and Beam 38). Prior to reinforcement, this beam group had been matched in terms of bending stiffness to Group UV and Group RV using statistical methods to ensure common timber material properties for each group. The beams were initially conditioned to approximately 12% moisture content and placed in the variable climate presented previously in Fig. 3.

The strain in the longitudinal direction on the top (compression face) of the beams is shown in Fig. 13. The top lamination is exposed to the surrounding environment on the top surface and both sides of the lamination. The measured swelling/shrinkage strain in the longitudinal direction remains at approximately 0 με for the first 3 weeks of the test as the relative humidity remained constant at 65% ± 5%. After this period, the relative humidity is cycled between 65% ± 5% and 90% ± 5%.

The increase in relative humidity causes a rapid increase in strain due to the increasing moisture content of the beams. The opposite is seen as the relative humidity is reduced with a rapid decrease in the swelling/shrinkage strain during the desorption phase of the cycle. There was negligible difference between strain measured on the compression face of the unreinforced and reinforced beams as each ERS gauge is aligned along the top lamination, which is negligibly affected by the reinforcement in the bottom lamination

The measured longitudinal strain on the bottom (tension face) of the beams can be seen in Fig. 14. The unreinforced specimens, shown in

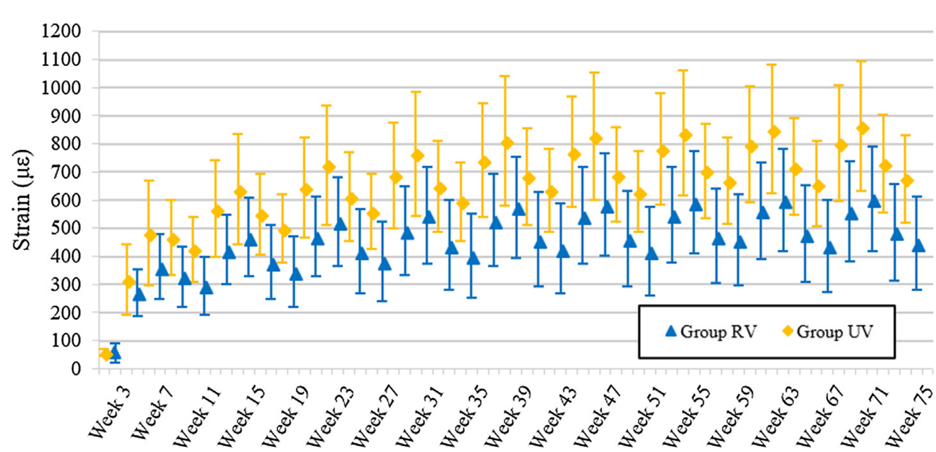

Fig. 10. Mean and standard deviation of total longitudinal creep strain on the tension face ($\varepsilon_{creep} = \varepsilon_{ve} + \varepsilon_{ms} + \varepsilon_{s}$).

Table 2
Comparison of mean (standard deviation) total longitudinal creep strains on the tension faces of Groups UV and RV.

Strain (με)	Week 3	Week 7	Week 15	Week 31	Week 47	Week 55	Week 71
Group UV	58.38 (13.10)	481.81 (186.50)	638.39 (195.62)	765.69 (220.12)	826.40 (226.81)	838.86 (221.02)	863.38 (229.49)
Group RV	56.26 (34.05)	363.64 (115.30)	467.53 (139.84)	546.21 (171.40)	583.22 (182.78)	591.72 (183.12)	605.18 (187.43)
Percentage Diff.	3.7%	28.0%	30.9%	33.5%	34.5%	34.6%	35.2%
Student's *t*-test	Not Sig.	Not Sig.	Not Sig.	Not Sig.	Sig.	Sig.	Sig.
p-Value	0.880	0.179	0.085	0.059	0.047	0.042	0.040

blue, experience greater swelling/shrinkage strains in the longitudinal direction, when compared to the reinforced specimens, shown in orange. As both unreinforced and reinforced beam specimens are sealed on the bottom face with a waterproof varnish, moisture flow through this tensile laminate is through the sides. The position of the BFRP rod reinforcement in the tension zone of the reinforced members not only provides a restraining force but also impedes moisture flow and results in a reduction in the measured swelling/shrinkage strains or hygro-mechanical response of the reinforced members.

To compare the swelling/shrinkage strain on the tension face of unreinforced and reinforced beams, the mean strain results are compared at a series of time points. These time points correspond to each maximum peak swelling/shrinkage strains and are tabulated in Table 4. There is a 24.8% difference between the strains measured on unreinforced and reinforced beams after 0 weeks; however, after the first moisture increase (Week 7), a large 85.5% difference can be seen between the swelling/shrinkage strains measured on the tension face. The percentage difference remains relatively consistent with subsequent cycles achieving percentage differences greater than 100% with a maximum of 106.0% observed at week 71. This difference is likely to be significant but due to the low sample size, statistical tests were not carried out.

This indicates a significant reduction in strain due to the influence of the NSM reinforcement in the tension zone of the reinforced beams. This restraining behaviour is due to the greater stiffness of the BFRP rods and also their dimensional stability under moisture cycling.

3.5. Mechano-sorptive creep strain component

The total creep strain may be separated into its component parts as described previously using Eq. (1). Using matched groups, the mean elastic and viscoelastic strain components reported in [24] and the swelling/shrinkage strain component presented here are subtracted from the mean total strain measurements to determine the mechano-sorptive creep strain. In Fig. 15, the mean mechano-sorptive strain components on the tension face of the unreinforced and reinforced groups at a series of time points are presented. To calculate the standard deviation associated with the mechano-sorptive strain component, the combined variance of the measured strain components is considered in the analysis at each time point. To compare the difference in the mean value of both groups, a series of statistical Student's t-tests were performed, and the results are presented in Table 5.

It can be seen that the percentage difference in mechano-sorptive creep is largest at the beginning of the test with 9.5% at week 11 compared to 2.4% at week 75. The Student's t-tests show no statistically significant differences between the means of both groups on the tension face.

In Fig. 16, the mean mechano-sorptive strain and associated standard deviations on the compression face of the unreinforced and reinforced beams are plotted at a series of time points. There appears to be slightly greater mechano-sorptive creep strain on the Group UV when compared to Group RV. To examine this further, statistical Student's t-tests were performed and a series of these are presented in Table 6.

At week 7, there is a 9.0% difference when comparing the mechano-sorptive creep strain on the compression face of Group UV and Group RV. The percentage difference increases throughout the test period to a maximum of 24.4% after 71 weeks. Although there is a large percentage difference between the mean results of the unreinforced and reinforced beam groups, the difference is not statistically significant at any time during the test.

This shows that despite FRP reinforcement, there is similar mechano-sorptive creep behaviour in the unreinforced and reinforced beams loaded to a common bending stress and subjected to the same changes in moisture content. This finding demonstrates that for the test geometry studied and the FRP reinforcement utilised, the stress level in the timber is the main driver of the mechano-sorptive creep behaviour. This influence of different FRP types and percentage area reinforcement should be investigated to see if this finding applies more generally.

4. Summary and conclusion

Matched groups of unreinforced glued laminated beams and glued laminated beams reinforced with NSM Basalt FRP reinforcement have been subjected to long-term creep tests in a controlled variable climate. The creep tests confirm that reinforcing timber with an FRP material of

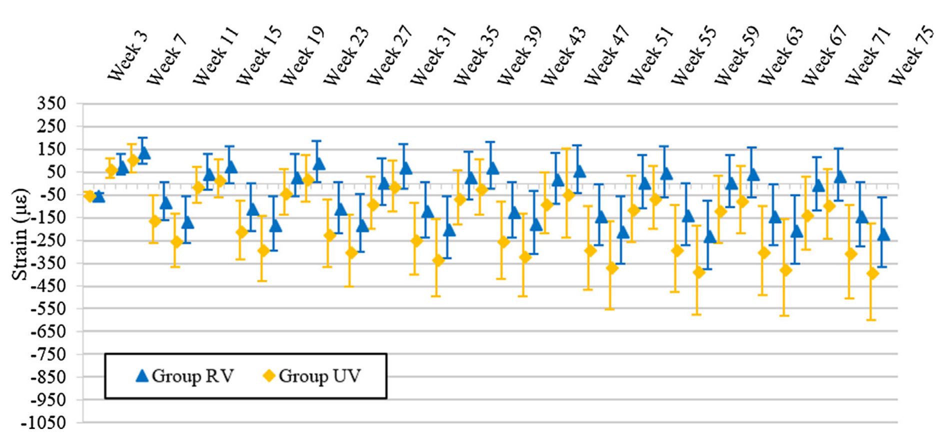

Fig. 11. Mean and standard deviation of total longitudinal creep strain on the compression face.

Table 3
Comparison of mean (standard deviation) total longitudinal creep strains on the compression faces of Groups UV and RV.

Strain (με)	Week 3	Week 11	Week 19	Week 35	Week 51	Week 67	Week 75
Group UV	−46.19 (10.54)	−254.75 (114.54)	−285.76 (143.65)	−327.00 (169.07)	−359.75 (194.95)	−369.28 (211.52)	−386.80 (213.01)
Group RV	−59.62 (18.53)	−166.59 (101.85)	−177.53 (119.45)	−194.14 (136.35)	−204.84 (148.09)	−200.51 (150.81)	−213.78 (151.46)
Percentage Diff.	25.4%	41.9%	46.7%	51.0%	54.9%	59.2%	57.6%
Student's *t*-test	Not Sig.	Not Sig.	Not Sig.	Not Sig.	Not Sig.	Not Sig.	Not Sig.
p-Value	0.124	0.156	0.154	0.134	0.122	0.114	0.108

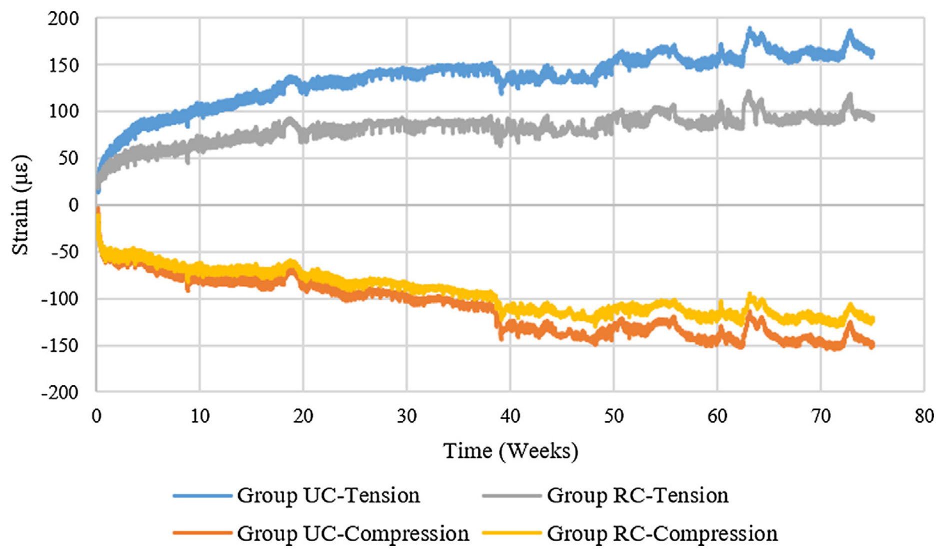

Fig. 12. Mean longitudinal viscoelastic creep strain (ε_{ve}) on the tension and compression faces of Group UC and Group RC.

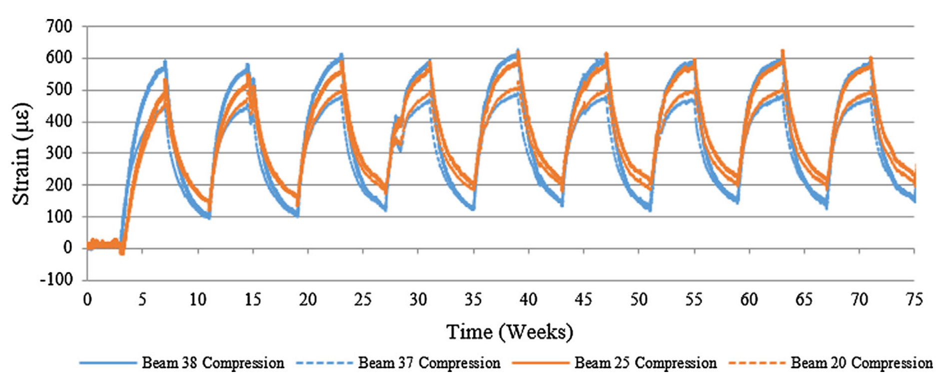

Fig. 13. Swelling/shrinkage strain results (ε_s) on the compression face of unreinforced and reinforced beams.

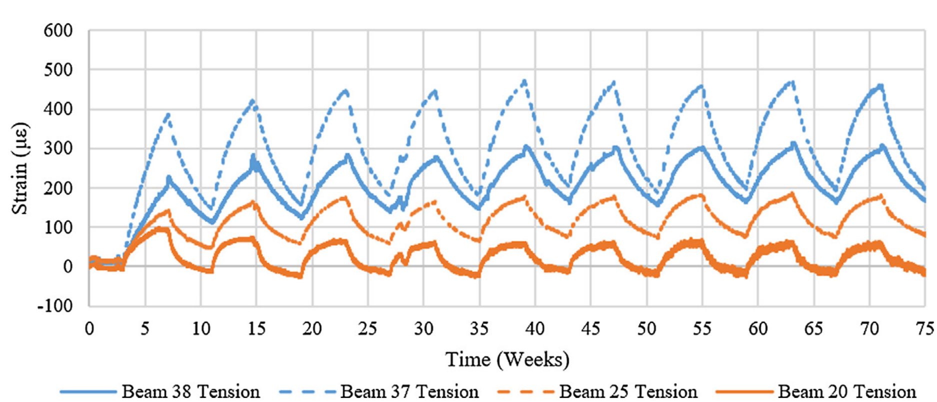

Fig. 14. Swelling/shrinkage strain results (ε_s) on the tension face of unreinforced and reinforced beams.

Table 4
Percentage difference between mean tensile swelling/shrinkage strains (ε_s) observed in the unreinforced and reinforced beams in Group MC (με).

Strain (με)	Week 0	Week 7	Week 15	Week 31	Week 47	Week 63	Week 71
Unreinforced	10.64 (2.31)	297.20 (124.33)	327.78 (109.71)	361.29 (120.69)	384.30 (120.69)	389.32 (117.90)	384.66 (115.50)
Reinforced	8.29 (10.97)	119.26 (34.15)	107.38 (68.70)	112.97 (75.51)	119.50 (85.43)	120.10 (91.40)	118.15 (88.54)
Percentage Diff.	24.8%	85.5%	101.3%	104.7%	105.1%	105.7%	106.0%

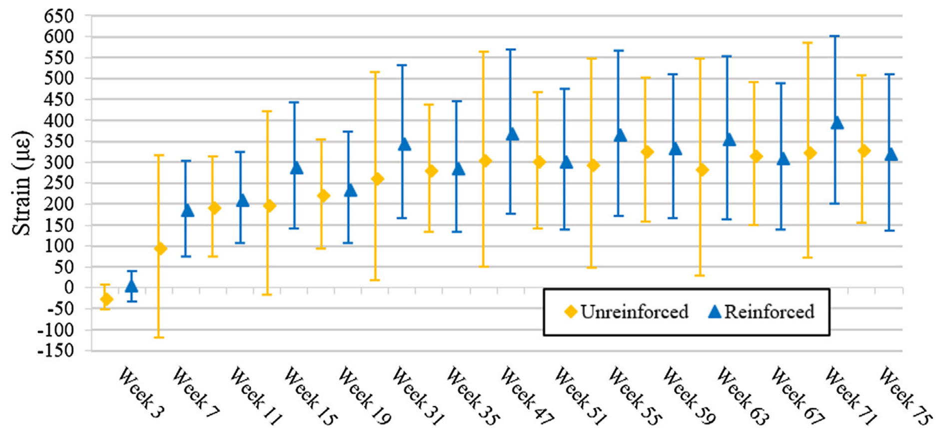

Fig. 15. Mean mechano-sorptive strain (ε_{ms}) and associated standard deviations on the tension face of unreinforced and reinforced beams.

Table 5
Comparison between the mean (standard deviation) mechano-sorptive strain (ε_{ms}) on the tension side of unreinforced and reinforced beams (με).

Strain (με)	Week 11	Week 19	Week 35	Week 51	Week 67	Week 75
Unreinforced	200.17 (119.42)	224.12 (129.94)	285.54 (150.96)	304.65 (161.80)	319.95 (170.87)	331.73 (176.26)
Reinforced	220.07 (108.20)	239.88 (132.46)	290.17 (156.39)	307.23 (169.00)	312.93 (174.92)	323.95 (187.34)
Percentage Diff.	9.5%	6.8%	1.6%	0.8%	2.2%	2.4%
Student's *t*-test	Not Sig.	Not Sig.	Not Sig.	Not Sig.	Not Sig.	Not Sig.
p-Value	0.749	0.826	0.956	0.977	0.941	0.937

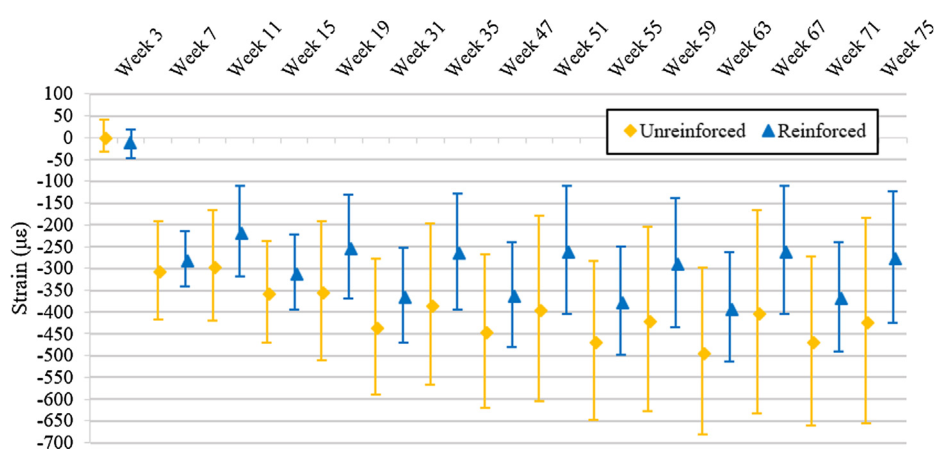

Fig. 16. Mean mechano-sorptive strain (ε_{ms}) and associated standard deviations on the compression face of unreinforced and reinforced beams.

Table 6
Comparison between the mean (standard deviation) mechano-sorptive strain (ε_{ms}) on the compression side of unreinforced and reinforced beams (με).

Strain (με)	Week 7	Week 15	Week 31	Week 47	Week 55	Week 71
Unreinforced	−303.96 (113.25)	−354.10 (117.36)	−433.09 (155.21)	−443.52 (176.59)	−465.90 (182.87)	−466.21 (194.28)
Reinforced	−277.85 (62.27)	−307.26 (86.28)	−361.13 (108.88)	−359.75 (120.87)	−373.92 (123.32)	−364.97 (124.45)
Percentage Diff.	9.0%	14.2%	18.1%	20.9%	21.9%	24.4%
Student's *t*-test	Not Sig.	Not Sig.	Not Sig.	Not Sig.	Not Sig.	Not Sig.
p-Value	0.603	0.411	0.335	0.321	0.291	0.268

superior properties has a positive effect on the creep behaviour of timber in a variable climate. The following conclusions can be formulated based on the investigation presented:

- Due to the BFRP reinforcement, the mean deflection of the reinforced beams were found to be significantly less than that of the unreinforced beams when subjected to a common maximum compressive stress and variable climate. Mean relative creep results demonstrated that the difference is statistically significant after just the first relative humidity cycle. The BFRP reinforcement also resulted in more consistent deflection behaviour in FRP reinforced beams thereby increasing the reliability of such elements when predicting long-term deflections.
- A statistically significant reduction in the total creep strain was measured on the tension face of reinforced beams due to the BFRP reinforcement. As expected, for the total creep strains measured on the compression face, there was found to be a statistically insignificant difference.
- Swelling and shrinkage tests have shown that the superior stiffness of the BFRP rod reinforcement restrains the timber in the tensile zone under changing relative humidity conditions, resulting in reduced hygro-mechanical response or swelling/shrinkage strain in the reinforced beams.
- Utilising matched groups, the mechano-sorptive strain component has been characterised for unreinforced and reinforced beams. The results have shown that the BFRP reinforcement has a statistically insignificant impact on the mechano-sorptive strain on the compression and tension faces.
- A reduced hygro-mechanical response on the tension face of the reinforced beams was observed. The BFRP rod reinforcement restricts the tensile lamination from swelling or shrinking and results in a reduced swelling/shrinkage strain.

The reduced creep deflection of the reinforced beam group, observed in this as well as other studies reported in the literature, cannot be attributed to a reduced mechano-sorptive creep response but is in fact due to a reduction in the swelling/shrinkage response due to the addition of FRP material of greater stiffness. These findings present the potential to describe the long-term deflection of FRP reinforced timber elements through short-term tests on the swelling/shrinkage behaviour of the reinforced section. While these observations are valid for the current test set-up, additional tests are required to confirm its validity as the influence of timber species, FRP type, reinforcement percentage and the applied stress level also influence the creep behaviour and must be examined. The creep results presented in this study, and those from tests performed in a constant climate [24], can be used to validate a hygro-mechanical numerical model to predict the creep behaviour of unreinforced and reinforced timber elements. A validated numerical model will allow various FRP types, reinforcement percentages to be examined in addition to examining the influence of stress level on the creep behaviour.

Declaration of Competing Interest

The authors declared that there is no conflict of interest.

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