Viscoelastic Creep of FRP Reinforced Glulam

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ABSTRACT: The reinforcement of timber using fibre reinforced polymer (FRP) rods or plates is widely accepted as an effective method of increasing the strength and stiffness of members, while at the same time reducing the variability in properties. The short-term behaviour of these reinforced members is relatively well understood, however, the long-term or creep behaviour of such members has received less attention. The objectives of the present work are to determine the durability of reinforced timber beams under sustained loading and constant climate conditions. Timber is a viscoelastic material so its deformation response is a combination of both elastic and viscous components. This viscous creep component is defined as a deformation with time at constant stress and at constant environmental conditions.

Sitka spruce is the most widely grown specie in Ireland and is the focus of this study. Glued Laminated (Glulam) beams were manufactured from Sitka spruce and a selected portion of them were reinforced with basalt-fibre reinforced polymer (BFRP) rods. The short-term flexural testing of these beams in their unreinforced and reinforced state demonstrated a significant increase in stiffness with a modest percentage reinforcement ratio. The long-term flexural testing required the design of a creep test frame to implement a constant stress of 8 MPa in the compression zone of an equal proportion of unreinforced and reinforced. The long-term strain and deflection results for the first 52 weeks of testing are presented. The reinforcement was found to have an insignificant impact on the creep deflection but the maximum tensile creep strain was significantly reduced.

KEY WORDS: BFRP, Irish Grown Sitka Spruce, Reinforced Timber, Viscoelastic Creep

1 INTRODUCTION

The mechanical and physical properties of softwood timber can vary considerably as a result of the age and rate of growth of the tree and other environmental factors which affect the wood cell density and strength [1]. Sitka spruce is characterised as a fast growing, low density timber which when subjected to flexural loading generally fails in tension due to the presence of knots [2]. In Ireland, this species has an average rotation length of 35 – 40 years [3]. This low density timber demonstrates limited capacity to carry substantial loads. However, when combined to create a composite element such as a glued laminated beam, the capacity of this softwood timber may be greatly increased.

The performance of glued laminated beams may also be enhanced with the addition of fibre reinforced polymer (FRP) composite reinforcement. It has been seen that the addition of modest reinforcement ratios can delay tension failure in glued laminated elements. The reinforcement utilises the additional capacity of the timber in the compression zone resulting in much more consistent behaviour as well as a significant increase in flexural stiffness [4, 5].

Long-term effects in these timber beams are of crucial importance to structural engineers when designing timber structures. These long-term effects, or creep effects, are commonly seen in timber elements when stressed under a load for long periods of time. Creep effects in timber can be divided into two primary categories, namely viscoelastic creep and mechano-sorptive creep. Timber is a viscoelastic material so its deformation response is a combination of elastic and viscous components. This viscoelastic creep component is defined as a deformation with time at constant stress and at constant environmental conditions. Mechano-sorptive creep is a deformation due to an interaction between stress and moisture content change [5, 6] in variable environmental conditions. Mechano-sorptive creep is independent of time [8] and is directly related to the change in moisture content and mechanical stress.

These creep effects must be understood as excessive deflection will result in premature failure. The objective of this study is to examine the long-term deformation of FRP reinforced timber beams manufactured from fast grown Irish timber. This study focuses on the viscoelastic creep mechanisms in unreinforced and reinforced beams under constant load in constant environmental conditions.

2 LITERATURE REVIEW

Creep phenomena have been the subject of particular interest for the timber engineering research community. Under serviceability conditions, viscoelastic creep depends on the stress and temperature of the timber and although viscoelastic creep occurs under a constant climate conditions, it is important to note, the magnitude of viscoelastic creep also depends on the moisture content of the timber [8, 9]. In a study by Hering and Niemz [10], the viscoelastic behaviour of European beech timber subjected to four-point bending was investigated and the longitudinal creep compliance at three different moisture contents (8.14%, 15.48% and 23.2 %) was investigated. Each timber specimen was loaded to approximately 25% of the ultimate bending strength. As can be seen in Figure 1, a viscoelastic compliance function which increased linearly with moisture content was successfully fitted to the data. This study was performed over a relatively short period of time (≈200hr).

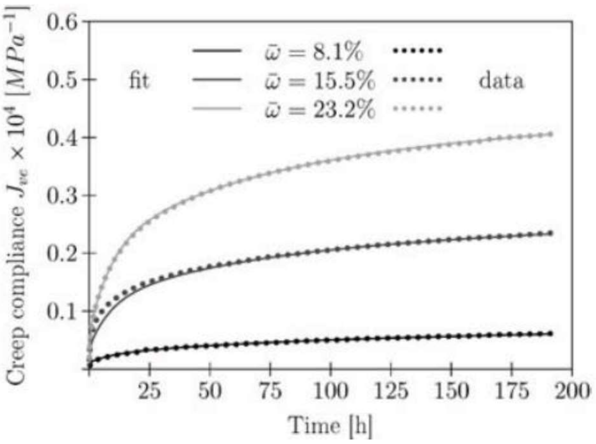

Figure 1. Creep data vs creep compliance function fit [10]

Another study designed to examine if the rate of creep eventually decreases towards a creep limit was performed by Hunt [11]. Experimental creep data on unreinforced timber was examined over a 13 week period. The conclusions from these tests were then applied to creep tests over a much longer period of time (8 years [12]). Creep functions were matched and extrapolated to estimate the long-term creep after 50 years under load. No evidence was found to suggest a viscoelastic creep limit in timber when stressed in a constant climate. There are no long-term creep tests results of a similar duration to disprove their findings. This shows the potential for timber elements to deform throughout their service life and demonstrates the importance of understanding its behaviour.

The long-term creep behaviour of timber elements has been shown to produce significant deformations with time and these are accounted for in design standards for various Service Class conditions. However, the long-term behaviour of timber elements that have been reinforced with the use of a FRP material has received little attention in previous research. The short-term behaviour of these reinforced elements demonstrate significant improvements in stiffness and ultimate moment carrying capacity. The long-term behaviour of reinforced timber elements have also primarily focused on creep effects in a variable climate and only a limited number of studies focus on viscoelastic creep effects within constant climate conditions.

Lu et al. [13] imposed a constant load on unreinforced and reinforced glued laminated beams under constant climate conditions. Ten beams were loaded in four-point bending. The 460 kg load applied corresponded to 30% of the ultimate strength of the glulam beam. The results allowed for the comparison of different reinforcement configurations (6mm rebar in compression zone, 6mm rebar in the tensile zone and 8mm rebar in the tensile zone) against the control (unreinforced) specimens as shown in Figure 2. Although a significant reduction in creep can be seen, the constant dead load on both unreinforced and reinforced beams leads to varying stress levels within each beam, a key contributor to the overall magnitude of viscoelastic creep.

Plevris and Triantafillou [15] performed long-term creep tests on reinforced beams. There was a relatively small sample size of 3 beams, one unreinforced control beam and two reinforced beams with two different percentage area reinforcement ratios of 1.18% and 1.65% respectively. The tests were carried out under constant climate conditions. They determined from the experimental results, that the creep behaviour of the FRP-reinforced wood is primarily dominated by creep within the timber.

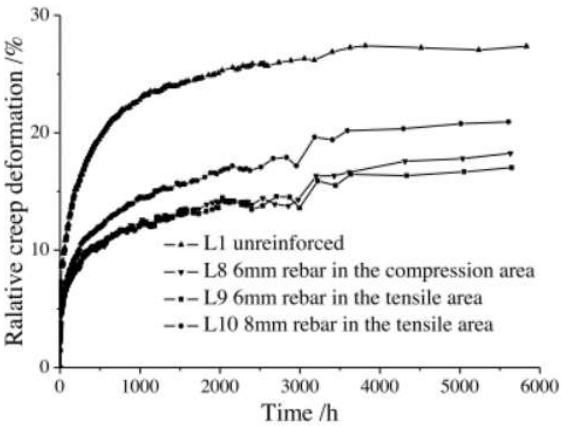

Figure 2. Relative creep results Lu et al. [14]

Therefore, in order to examine the influence of the reinforcement on the performance of reinforced beams, it is important to apply a common stress level in all unreinforced and reinforced timber beams.

3 EXPERIMENTAL PROGRAMME

3.1 Introduction

To examine the effect of rod reinforcement on the long-term performance of glued laminated beams in constant environment, the following experimental programme has been designed.

Irish grown Sitka spruce boards were conditioned to approximately 12% moisture content and strength graded using a mechanical grading machine. From the grading results, 40 glued laminated beams were designed and manufactured in the Timber Engineering Laboratory at the National University of Ireland, Galway. The beams comprise of four laminations, with each beam measuring 98 mm x 125 mm x 2300 mm. These beams were specifically designed to exhibit similar stiffness properties in each manufactured beam. This was successfully demonstrated in short-term flexural testing of each beam in its unreinforced state. Twenty of these beams were subsequently reinforced with two, 12 mm basalt fibre reinforced polymer (BFRP) rods adhered within two circular routed grooves in the bottom tensile laminate (Figure 3). This accumulated to a modest percentage reinforcement of 1.85%. Once reinforced, short-term flexural testing was repeated to examine the increase in bending stiffness as a result of the reinforcement. An equal proportion of the unreinforced and reinforced beams where then subjected to a constant dead load in a controlled climate chamber. The controlled climate chamber was set to a constant relative humidity of 65% ± 5% and a constant temperature of 20°C ± 2°C throughout the test.

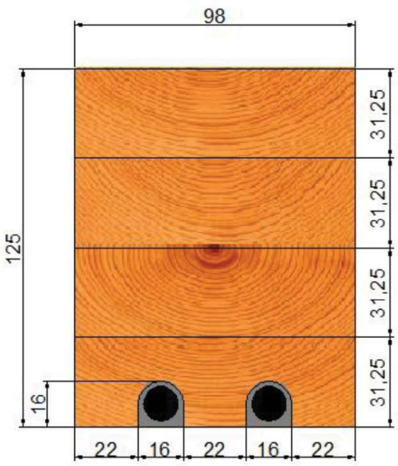

Figure 3. BFRP Reinforced Glulam

3.1.1 Test Frame Design and Instrumentation

There is no standard method for examining the creep behaviour of timber beam elements. As a result, different methods and test rigs have been designed and used to examine creep deflection. The majority of authors implement a four-point bending test setup, however, in some cases a three-point bending test set up [15] or an evenly distributed load across the whole length of the member have been used [16].

In this study the long-term creep test frame was designed to implement the same test configuration described in EN 408 [17] for short-term flexural tests (Figure 5). The test frame was designed to accommodate 18 beams simultaneously loaded to a constant bending stress to induce viscoelastic creep with time. The sustained load is applied through a lever arm as illustrated in Figure 4. The lever arm length is adjustable and loads (steel plates) can be added or removed as necessary. A total vertical load of approximately 6241 N and 5748 N was applied to the reinforced and unreinforced beams, respectively.

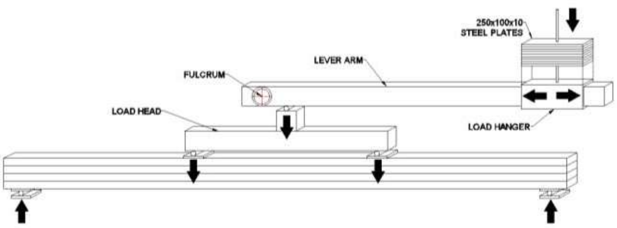

Figure 4. Creep test beam loaded using lever arm

The beam mid-span deflection is measured using a dial gauge and the longitudinal strain is measured using electrical resistance strain gauges on the tension and compression faces. A proportion of the beams are monitored with additional strain gauges on the side of the beams to observe the strain profile through the cross section. These long-term strain results are monitored using a Campbell Scientific data acquisition system, which initially recorded strains every 5 minutes during the early stages of the test, which is associated with relatively rapid creep deformations. This frequency was slowly reduced with time to its current frequency of 1 hour. The beams are tested in a climate chamber at a temperature of 20 ± 2 °C and at a relative humidity of 65 ± 5 % throughout, which coincides with Service Class 1 as defined in Eurocode 5.

3.1.2 Loading Regime

The applied load chosen corresponds to approximately 25-30% of the ultimate load of the unreinforced glued laminated beam which will produce measurable deflections in a reasonable time scale without causing failure in the specimen. Each beam is loaded to achieve a stress of 8 MPa on the compression face. To achieve this stress level, different loads were required for each beam with greater loads required on the reinforced beams. Short term flexural test results provided stiffness values of each beam [18]. The measured mean modulus of elasticity of each beam was used in a transformed section analysis to determine the required load.

Figure 5. Loaded Creep Frame in Constant Climate

This method is implemented to examine the long-term effect of reinforcement when the timber is loaded to similar stress levels.

Each beam is loaded separately through individual lever arms. The initial elastic deformation is noted for each beam directly after loading and the deflection results are then recorded at regular intervals with time.

4 RESULTS

4.1 Short-term Test Results

The short-term test results for the twenty reinforced beams are presented in Table 1. The mean bending stiffness is presented for these beams in their unreinforced and reinforced states (Table 1). There is a significant increase in bending stiffness with an average increase of 16.30 % for a moderate percentage reinforcement of 1.85 %. This promotes fast-grown Irish Sitka spruce as a suitable donor material to reinforce with FRP material, due to the significant improvement in the short-term flexural performance. The percentage increase in stiffness is also presented.

Table 1: Short-term flexural stiffness

Stiffness (N/mm^2)	Unreinforced	Reinforced	Percentage Increase (%)
EI_{Local} ($x10^{11}$)	1.46 (.120)*	1.69 (.119)	16.30 (3.66)

*Mean Values (Std. Deviation)

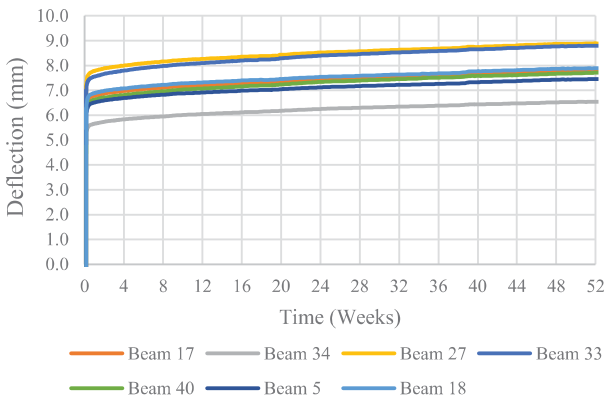

Figure 6. Unreinforced Deflection Results

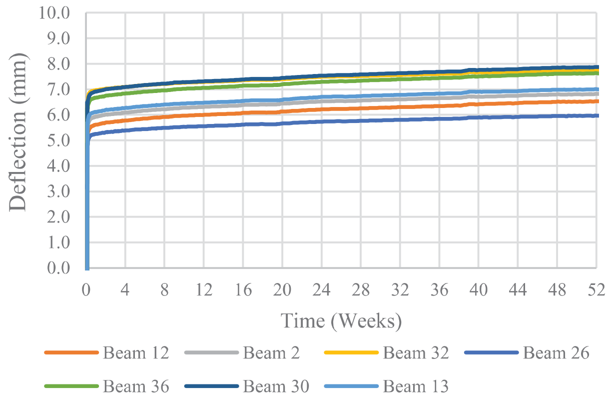

Figure 7. Reinforced Deflection Results

4.2 Long-term Test Results

The test results for the first 52 weeks are presented. Eighteen beams (9 reinforced and 9 unreinforced) are tested under constant load in the constant climate. The long-term deflection test results are expressed as total deflection and relative creep (C_R) deflection, which is defined as the deflection at time t, expressed in terms of the initial elastic deflection as seen in Equation (1) [19].

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

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

4.2.1 Long-Term Deflection Results

The long-term deflection of each beam under load in a constant climate condition is presented. The unreinforced beam group consists of nine unreinforced beams loaded to a bending stress of 8 MPa in four-point bending. Seven of these beams are monitored with vertical displacement dial gauges (Figure 6). Beam 27 (8.89mm) and Beam 34 (6.54mm) have the highest and lowest total deformation (initial elastic deformation and long term creep deflection) after 52 weeks, respectively. This is as expected as they have the lowest and highest bending stiffness, respectively, when measured during short-term flexural tests. The reinforced beam group consists of nine reinforced beams similarly loaded to a bending stress of 8 MPa in four-point bending. Seven of these beams are monitored with vertical displacement dial gauges (Figure 7). Beam 30 (7.88mm) and Beam 26 (5.97mm) have the highest and lowest total deflection after 52 weeks, respectively. The variability within timber can be seen in the total deflection results in Figure 6 and Figure 7. In order to compare the deflection results between the unreinforced group and reinforced group and observe the effect of reinforcement on long-term deflection, the average deflections are of each beam group are shown in Figure 8. After 52 weeks, the mean total deflection in the unreinforced beam group (7.92mm) is 11% greater than the reinforced beams group (7.13mm).

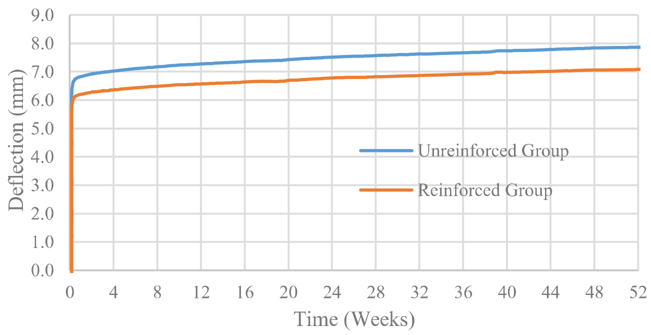

Figure 8. Average Group Deflection

To focus on the long-term deflection after the initial elastic deflection, the relative creep results are presented. Figure 9 presents the mean relative creep deflection results with time for the unreinforced beam group and the reinforced beam group beams in a constant climate. Although there is a reduction in the overall deflection in the reinforced beam group due to the FRP reinforcement, there is less than 1.5% difference between the measured relative creep deflections of both groups. A statistical analysis of the group means has shown no statistically significant reduction in viscoelastic creep due to the FRP reinforcement in a constant climate.

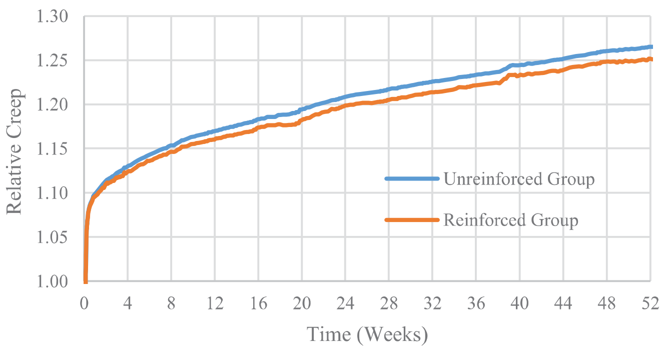

Figure 9. Mean relative creep deflection

4.2.2 Long-Term Strain Results

As previously mentioned, the strain results are measured using electrical resistance strain gauges designed for long-term use on timber. The strain gauge is adhered to the timber surface of the beam situated between two routed grooves which house the BFRP rods (Figure 10). The longitudinal strain has been measured on the tension and compression face of 7 unreinforced and 7 reinforced beams. The mean total strain measurement from the tension and compression face of the unreinforced and reinforced beam groups are presented in Figure 11.

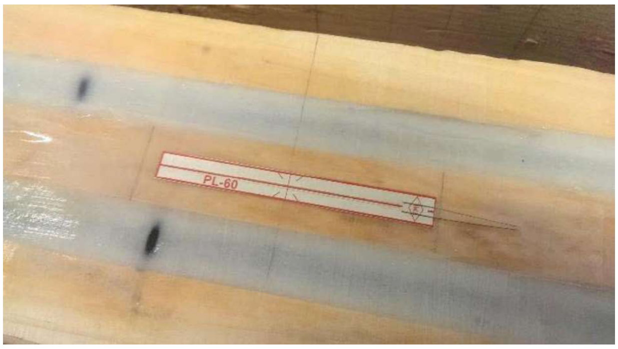

Figure 10. Strain Gauge Position on Reinforced Beam

The strain gauge measurements on the compression face are similar when both beam groups are compared with the reinforced beam group experiencing 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 52 weeks. This difference is as a result of the rod reinforcement and its position within the tensile laminate of each reinforced beam. The strains which would normally appear within the timber have been shared with the superior BFRP rod reinforcement resulting in the reduced strain within the timber.

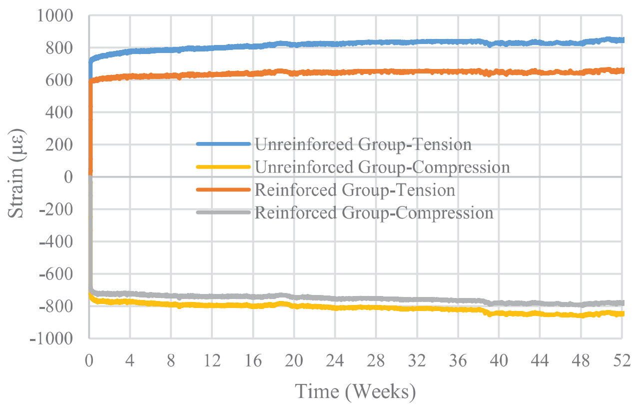

Figure 11. Mean Total Strain Measurement Results

To solely examine the viscoelastic strain, the mean strain results have been presented without the elastic strain component in Figure 12. Similar mean strains are observed in the compression face of both the unreinforced and reinforced beams groups indicating a similar stress and creep rate within both beam groups. In comparison, the mean strains on the tension face show larger strains within the unreinforced beam group. This is again as a result of the reinforcement within the reinforced beam group and its position within the tensile laminate.

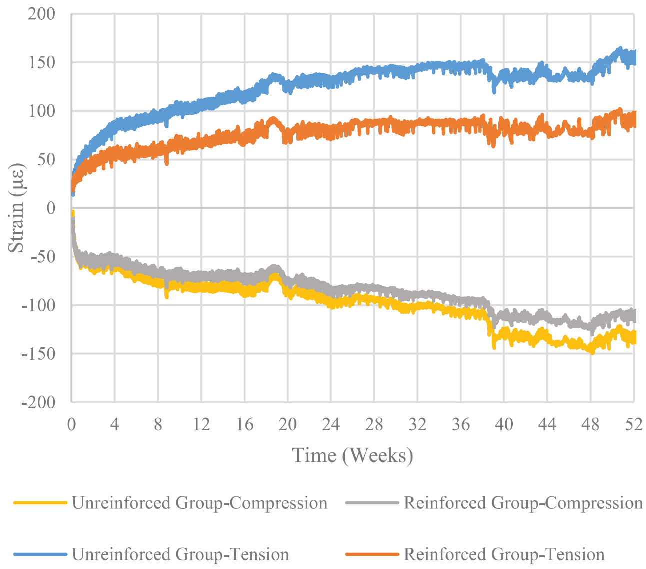

Figure 12. Mean Viscoelastic Strain Measurement Results

Representative results of strains measured through the cross section of the unreinforced (Beam 40) and reinforced (Beam 26) beams are presented in Figure 13 and Figure 14, respectively. It must be noted that these results are observed on singular beams and not an average value, hence the variability within timber must considered when examining these beams. It can be seen that the unreinforced beam experiences greater strain in the tension zone than the reinforced beam. The rate of creep is seen to be higher in the unreinforced specimen. The measured strains in the compression zone are similar when comparing the unreinforced and reinforced beams and any difference is thought to be associated with the inherent variability within timber.

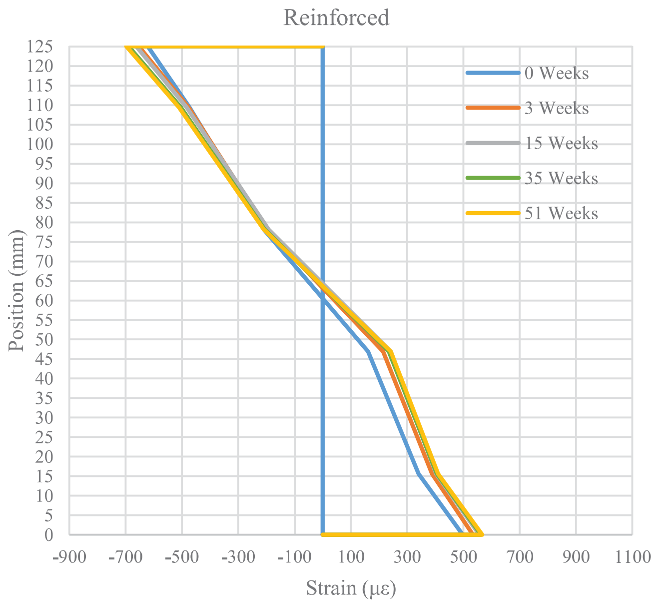

Figure 13. Cross section strain-Reinforced (Beam 26)

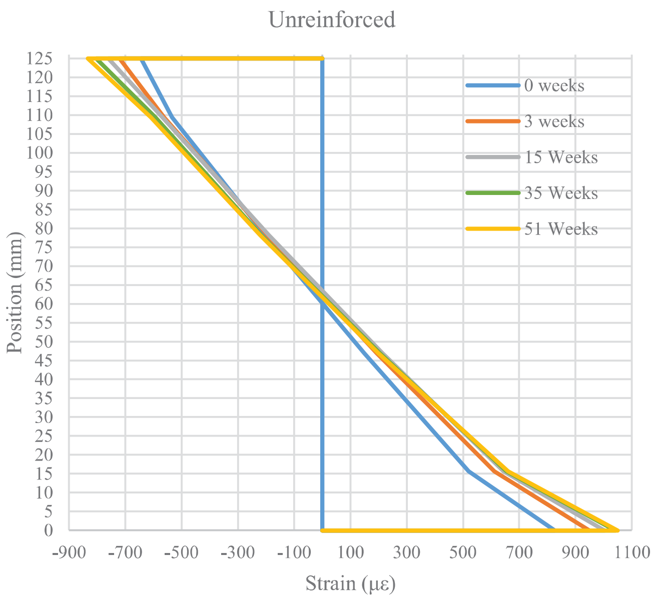

Figure 14. Cross section Strain-Unreinforced (Beam 40)

5 CONCLUSION

The long-term viscoelastic creep effects in unreinforced and reinforced timber and the experimental programme have been described. The short-term four-point bending tests demonstrated that the addition of BFRP rod reinforcement in modest quantities can greatly increase the short-term stiffness of glued laminated beams. An average increase in local bending stiffness of 16.3% was observed for a moderate percentage reinforcement of 1.85%.

The long-term deflection results have shown a beneficial overall decrease in the total deformation (initial elastic deformation and viscoelastic deformation) due to the reinforcement. The analysis of the relative creep results have shown no statistically significant reduction in viscoelastic creep deflection when comparing the mean relative creep results of both beam groups.

The measured strain results in the longitudinal direction and through the cross section of the beams with time have been presented. The long-term viscoelastic strain on the compression face has been shown to be quite similar in both beam groups indicating a similar bending stress has been subjected to each beam in the test programme. The results have also shown a significant reduction in strain on the tension face of the reinforced beam group as a result of the reinforcement. Examining the measured strains through the cross section of both the unreinforced and reinforced beams has also highlighted this reduced strain within the timber in the tension zone of the reinforced beam. Higher levels of creep strain were observed within the unreinforced beams. The reduced magnitude of the creep tensile strain observed within the reinforced beams is thought to be a result of the restraining effect of the FRP rod reinforcement.

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