VISCOELASTIC CREEP IN REINFORCED GLULAM

Conan O’Ceallaigh¹, Karol Sikora², Daniel McPolin³, Annette M. Harte⁴

ABSTRACT: The reinforcement of timber elements using fibre reinforced polymer (FRP) rods or plates is widely accepted as an effective method of increasing the strength and stiffness of members. 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 long-term performance 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. The creep component is defined as a deformation with time at constant stress and under constant environmental conditions. Sitka spruce is the most widely grown species 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 on the compression face of an equal proportion of unreinforced and reinforced beams. 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.

KEYWORDS: BFRP, Glulam, Irish Grown Sitka Spruce, Reinforced, 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. 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 [1]. In Ireland, this species has an average rotation length of 35 – 40 years [2]. 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 elements 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 elements 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. The viscoelastic creep component is defined as the deformation with time at constant stress and under 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.

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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 and focuses on the viscoelastic creep mechanisms in unreinforced and reinforced beams under constant load and 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 [5–7]. In a study by Hering and Niemz [8], 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 examined. 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][8]

Another study designed to examine if the rate of creep eventually decreases towards a creep limit was performed by Hunt [9]. Experimental creep data on unreinforced timber was examined in a carefully controlled test environment over a 13 week period. Creep functions were matched to these experimental test results and to creep test results performed by Gressel (1984) over a much longer period of time (8 years [10]). The curves were 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. 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 and are not accounted for in design standards. The short-term behaviour of these reinforced elements demonstrate significant improvements in stiffness and ultimate moment carrying capacity [3–4, 11]. 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.

In a study by Yahyaei-Moayyed and Taheri [12], the creep performance of southern yellow pine (SYP) and Douglas fir (DF) timber beams reinforced with aramid fibre reinforced polymer (AFRP) was examined. These creep tests were carried out in an uncontrolled climate over a period of 800 hours and it is noted that the applied loads were not the same for the unreinforced and reinforced beams. In the results (Figure 2a), a comparison between one SYP unreinforced (S5-PIV) and one SYP reinforced beam (S5-PI) can be seen and although there appears to be a reduction in creep deflection, it is not clear if this reduction is due to varying loads within the timber or the AFRP reinforcement. The reduced load on the reinforced beam will lead to a lower stress level within the timber. Interestingly in Figure 2b where one unreinforced DF beam (S10-PI) and one reinforced DF beam (S10-PIV) are compared; there is a slightly higher load on the reinforced beam and a similar creep deflection is observed. It is unclear if the stress is comparable within both beams. There is also an influence of the variable relative humidity and possible swelling/shrinkage or mechano-sorptive creep deformations as a result of the fluctuating moisture content.

![Figure 2: Creep deflection comparison results][12]
Davids et al. [13] performed long-term creep tests on unreinforced and reinforced Douglas fir and western hemlock glulam beams in a sheltered environment with controlled temperature and uncontrolled relative humidity. A proportion of the beams were reinforced with glass fibre reinforced polymer (GFRP) plate to two area reinforcement ratios, namely, 1.1% and 3.3%. While the laboratory tests demonstrate the effectiveness of the GFRP reinforcement in reducing the total deformation between the unreinforced beams and the reinforced beams, a difference between the relative creep deformation of the unreinforced glulam beams and the GFRP-reinforced glulam beams is only seen at the higher reinforcement level (Figure 3). It is noted by the authors that the effectiveness of FRP-reinforcement on reducing creep cannot be inferred from the test data due to the different load levels and the uncontrolled relative humidity during the test.

Figure 3: Relative creep values of Douglas fir specimens [13]

Plevris and Triantafilou [14] 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 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. 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. To solely focus on viscoelastic creep, it is important to perform all long-term creep test in a controlled constant environment to avoid any additional deformations as result of a fluctuating moisture content.

3 EXPERIMENTAL PROCEDURE

3.1 INTRODUCTION

This study is performed to examine the long-term performance of reinforced glued laminated beams in a constant climate. The glued laminated beams used in the test programme are manufactured using Irish grown Sitka spruce. The lay-up of each glued laminated beam is designed and manufactured with a proportion of the beams reinforced with basalt fibre reinforced polymer (BFRP) rods in the bottom tensile laminate. These unreinforced and reinforced beams underwent short and long-term flexural testing in a controlled, constant environment.

3.2 GLULAM MANUFACTURE

The grade of timber used in this study was C16. Each laminate was strength graded using a mechanical grading machine and ranked in descending order of modulus of elasticity. Forty beams were designed using the machine graded results and manufactured in the Timber Engineering Laboratory at the National University of Ireland, Galway. The beams were laminated by applying a 1:1 phenol resorcinol formaldehyde adhesive and clamping to a pressure of 0.6 N/mm² for 24 hours in accordance with EN 14080 [15]. The beams comprise four laminations with each beam measuring approximately 98 mm x 125 mm x 2300 mm. These beams were specifically designed to exhibit similar flexural stiffness properties in each manufactured beam. Each beam was conditioned in a constant climate condition at a temperature of 20 ± 2 °C and at a relative humidity of 65 ± 5%, prior to reinforcement. Twenty beams are 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, as seen in Figure 4. A two-part structural epoxy adhesive was used to bond the reinforcement to the timber. The BFRP rod manufacturer reported the material properties listed in Table 1.

Table 1: Basalt fibre properties [16]

<table>
<thead>
<tr>
<th>Tensile Strength (N/mm²)</th>
<th>Tensile Modulus of Elasticity (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000+</td>
<td>45+</td>
</tr>
</tbody>
</table>

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 to cure for a period of 3 weeks prior to any testing.
3.3 SHORT-TERM TESTING

Each beam underwent non-destructive flexural testing to evaluate the flexural properties. The short-term bending test set-up is in accordance with EN 408 [17] as seen in Figure 5. The load is 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 test is limited to a maximum of 40% of the ultimate failure load. The deflection at the midspan of the beam was measured using two LVDTs, one for determining the local stiffness and the other for the global stiffness.

This short-term test was performed on all beams in their unreinforced state to determine their initial flexural stiffness. Once reinforced, the flexural test was repeated. The test set up remained constant throughout allowing the percentage increase in stiffness to be calculated.

Figure 5: Bending test set-up [17]

3.4 LONG-TERM TESTING

3.4.1 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 [14] or an evenly distributed load across the whole length of the member have been used [18].

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. 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 6. The lever arm length is adjustable and loads (steel plates) can be added or removed as necessary.

Figure 6: 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, when relatively rapid creep deformations occur. This frequency was slowly reduced with time to its current frequency of 1 hour. The beams are tested in a controlled 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.

3.4.2 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 [11]. The measured mean modulus of elasticity of each beam was used in a transformed section analysis to determine the required load. A total vertical load of approximately 6241 N and 5748 N was applied to the reinforced and unreinforced beams, respectively.

Figure 7: 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 in four-point bending separately through individual lever arms (Figure 7, Figure 8). The initial elastic deformation is noted for
each beam directly after loading and the deflection results are then recorded at regular intervals with time.

Figure 8: Creep test beam loaded in four-point bending

4 RESULTS

4.1 SHORT-TERM TEST RESULTS

The short-term test results for the reinforced beam group are presented in Figure 9 and Table 2. The mean local and global stiffness is presented for beams in their unreinforced and reinforced state together with the associated standard deviations. The percentage increase in stiffness is also presented.

![Figure 9: Short-term flexural stiffness results](image)

Figure 9 displays the effect of reinforcement on the short-term bending stiffness of the twenty reinforced beams.

Table 2: Short-term flexural stiffness

<table>
<thead>
<tr>
<th>Stiffness (Nmm²)</th>
<th>No</th>
<th>Unreinforced</th>
<th>Reinforced</th>
<th>Percentage Increase (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elₗₗ (x10¹¹)</td>
<td>20</td>
<td>1.46 (.120)*</td>
<td>1.69 (.119)</td>
<td>16.30 (3.66)</td>
</tr>
<tr>
<td>Elₙₙ (x10¹¹)</td>
<td>20</td>
<td>1.35 (.123)</td>
<td>1.47 (.113)</td>
<td>8.8 (5.90)</td>
</tr>
</tbody>
</table>

*Mean Values (Std. Deviation)

There is a significant increase in local bending stiffness and an increase to a lesser extent in the global bending stiffness. A mean increase in local bending stiffness of 16.30% for a moderate percentage reinforcement ratio of 1.85% was observed.

There was a mean increase of 8.8% in global bending stiffness. There is a significant standard deviation of 5.9% associated with this global stiffness measurement. This large variation is thought to be as a result of shear deflections. Indentation at load points observed during testing are measured globally leading to the reduced mean values. This low density timber is susceptible to such indentations during testing. The significant improvement in local bending stiffness has demonstrated the beneficial effect of BFRP reinforcement in timber beams and promotes fast-grown Irish Sitka spruce as a suitable donor material to reinforce with FRP materials to improve the short-term flexural performance.

4.2 LONG-TERM TEST RESULTS

The creep 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 in terms of both total deflection and relative creep (Cₚ) deflection, which is defined as the deflection at time t, expressed as a proportion of the initial elastic deflection as seen in Equation (1) [19]

\[
C_p(t) = \frac{w(t)}{w_0}
\]

Where \( C_p \) = Relative creep, \( w_0 \) = Initial deflection and \( w(t) \) = deflection at time, t.

![Figure 10: Unreinforced deflection results](image)

![Figure 11: Reinforced deflection results](image)
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 maximum compression bending stress of 8 MPa in four-point bending. Seven of these beams are monitored with vertical displacement dial gauges (Figure 10). Beam 27 (8.89 mm) and Beam 34 (6.54 mm) 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 maximum compression bending stress of 8 MPa in four-point bending. Seven of these beams are monitored with vertical displacement dial gauges (Figure 11). Beam 30 (7.88 mm) and Beam 26 (5.97 mm) 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 10 and Figure 11. 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 of each beam group are shown in Figure 12. After 52 weeks, the mean total deflection in the unreinforced beam group (7.92 mm) is 11% greater than the reinforced beams group (7.13 mm).

4.2.2 Long-Term Strain Results

The strain results are measured using electrical resistance strain gauges designed for long-term use on timber. The longitudinal strain has been measured on the tension and compression faces of 7 unreinforced and 7 reinforced beams. The strain gauges on the tension face of the reinforced beams are adhered to the timber surface of the beam situated between two routed grooves which house the BFRP rods (Figure 14). The mean total strain measurement from the tension and compression face of the unreinforced and reinforced beam groups are presented in Figure 15.

![Figure 12: Average group deflection](image)

To focus on the long-term deflection after the initial elastic deflection, the relative creep results are presented. Figure 13 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 13: Mean relative creep deflection](image)

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 BFRP rod reinforcement resulting in the reduced strain within the timber.

![Figure 14: Strain gauge position on reinforced beam](image)
Figure 15: 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 16. Similar mean strains are observed on 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 mean 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.

It is important to note that the controlled climate chamber remained at a constant temperature of 20 ± 2 °C and at a constant relative humidity of 65 ± 5% throughout the duration of the test.

Figure 16: Mean viscoelastic strain measurement results

The standard deviation associated with the viscoelastic strain measurement on the tensile face can be seen in Figure 17. The reinforced beams experience much more consistent viscoelastic behaviour after loading. There is a greater standard deviation observed within unreinforced beams.

Figure 17: Standard deviation of tension strain measurement

Representative results of strains measured through the cross section of the unreinforced (Beam 40) and reinforced (Beam 26) beams are presented in Figure 18 and Figure 19, respectively. It must be noted that these results are observed on single beams and are 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 (Table 3). After 51 weeks the percentage increase in viscoelastic creep within the unreinforced beam (26.9%) is almost twice that measured in the reinforced beam (13.8%). 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.

Table 3: Percentage increase in viscoelastic strain with time

<table>
<thead>
<tr>
<th>Tension Face Strain</th>
<th>Week 0</th>
<th>Week 3</th>
<th>Week 15</th>
<th>Week 35</th>
<th>Week 51</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unreinforced (Beam 40) (με)</td>
<td>827.1</td>
<td>949.5</td>
<td>1003.1</td>
<td>1041.7</td>
<td>1049.3</td>
</tr>
<tr>
<td>Percentage Increase (%)</td>
<td>0.0%</td>
<td>14.8%</td>
<td>21.3%</td>
<td>25.9%</td>
<td>26.9%</td>
</tr>
<tr>
<td>Reinforced (Beam 26) (με)</td>
<td>497.5</td>
<td>533.5</td>
<td>556.2</td>
<td>561.4</td>
<td>566.1</td>
</tr>
<tr>
<td>Percentage Increase (%)</td>
<td>0.0%</td>
<td>7.2%</td>
<td>11.8%</td>
<td>12.9%</td>
<td>13.8%</td>
</tr>
</tbody>
</table>

5 CONCLUSIONS

The long-term viscoelastic creep effects in unreinforced and reinforced timber and the experimental programme designed to measure these effects have been described. The addition of BFRP rod reinforcement in modest quantities can greatly increase the short-term flexural 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 loaded to a common bending stress.

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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