Mechano-sorptive Creep of FRP Reinforced Laminated Timber Beams

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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 well understood. The long-term or creep behaviour has received less attention. Due to the hygroscopic nature of timber, creep is accelerated by moisture variations, resulting in the so-called mechano-sorptive effect. In reinforced timber beams, the influence of the reinforcement and adhesive on the long-term response must be taken into account.

The objectives of the present work are to determine the durability of reinforced timber beams with respect to load duration (viscoelastic creep) and variable climate (mechano-sorptive creep), and to develop appropriate modification factors for design purposes. 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 was reinforced with basalt-fibre reinforced polymer (BFRP) rods. The test programme has been designed to determine the flexural behaviour of the beams with respect to load duration and variable climate. One sub-sample of the beams is to be tested at constant temperature and relative humidity and a second sub-sample in a climate with varying temperature and relative humidity. This paper contains a description of the test set-up and presents the short-term modulus of elasticity (MOE) results for reinforced and unreinforced beams and details the experimental procedure for creep measurements.

KEY WORDS: BFRP, Glued Laminated Timber, Irish Grown Sitka Spruce, Mechano-sorptive 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 30 – 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 additional 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].

Long term effects in these timber beams are of crucial importance to structural engineers when designing timber structures. Duration of load and creep effects must be understood as excessive deflection will result in failure. These effects result when the beam is stressed under load for a long period of time. The duration of load effect is a loss of strength with time under a sustained load. Similarly with creep, there is a reduction in stiffness in time. This effect manifests itself as an increase in deflection with time under constant stress. Mechano-sorptive creep occurs due to an interaction between stress and moisture content change. Depending on environmental conditions, this effect can greatly increase the creep deflection of a beam and ultimately lead to failure. To the authors knowledge, only one study addresses these effects on unreinforced and reinforced glulam beams made from Irish grown Sitka spruce [2].

2 LITERATURE REVIEW

Mechanical degradation is commonly seen in timber when stressed under load for long periods of time. The most common effects of mechanical degradation are known as duration of load effect and creep effect. For solid timber the strength reduction under a sustained load for ten years can be as high as 40% [5, 6]. The creep effect is the increase in deflection with time for a given constant load. Creep can be divided into two categories, namely viscoelastic creep and mechano-sorptive creep. Timber is a viscoelastic material so its deformation response is a combination of both elastic and viscous components. Since viscoelastic creep is time dependent, at any instant in time under load its performance will be a function of its past history. Viscoelastic creep is defined as a deformation with time at constant stress and at constant environmental conditions. Mechano-sorptive behaviour is a deformation due to an interaction between stress and moisture content change [7, 8]. It is independent of time and it does not occur in constant temperature and relative humidity conditions [9]. It is directly related to the change in moisture content and mechanical stress.

These phenomena have been the subject of particular interest for the timber engineering research community.

Viscoelastic and mechano-sorptive creep within timber is difficult to separate and monitor as each effect operates simultaneously. Apart from these two effects a third, pseudo-creep and recovery that has been ascribed to differential swelling and shrinkage must also be monitored. Creep is quantified by a number of time dependent parameters. The most common are creep compliance and relative creep. Creep compliance may be described by the following formula:

$$C_C(t) = \frac{\Delta\varepsilon(t)}{\sigma_0} \tag{1}$$

where:
C_C = Creep compliance,
$\Delta\varepsilon = \varepsilon_t - \varepsilon_0$ = Change in strain with time,
σ_0 = Applied constant stress.

Relative creep (C_R) is defined as the increase in deflection at time t, expressed in terms of the initial elastic deflection, as follows:

$$C_R(t) = \frac{\Delta\varepsilon(t)}{\varepsilon_0} = \frac{\varepsilon_t - \varepsilon_0}{\varepsilon_0} \tag{2}$$

where:
C_R = Relative creep,
ε_0 = Initial strain.

Relative creep has also been expressed as the change in creep compliance ($Cc(t)$) at time t divided by the initial creep compliance (Cc_0). As was mentioned above, viscoelastic creep is described as deflection with time at constant moisture content and environmental conditions, however, the magnitude of viscoelastic creep is dependent on the stress level and moisture content. A higher stress level will result in greater creep. Similarly, a higher initial equilibrium moisture content will result in higher viscoelastic creep. When moisture content and environmental conditions change, mechano-sorptive creep is induced.

Changes in the moisture content of timber result not only in mechano-sorptive creep effects but also in dimensional changes of timber. These dimensional changes (shrinkage and swelling (ε_S)) result in increased deflection and must be monitored.

The total measured strain ε_m, may be written as

$$\varepsilon_m = \varepsilon_e + \varepsilon_{vc} + \varepsilon_{ms} + \varepsilon_s \tag{3}$$

where:

ε_{VC} = Viscoelastic strain,

ε_{ms} = Mechano-sorptive strain,

ε_S = Swelling/shrinkage strain of a matched zero-load control specimen.

The mechano-sorptive component may then be calculated as

$$\varepsilon_{ms} = \varepsilon_m - \left(\varepsilon_e + \varepsilon_{vc} + \varepsilon_s\right) \tag{4}$$

Mechano-sorptive behaviour has been the focus of many studies, due to its ability to increase deflection and cause premature failure of timber beams. There is no defined method for examining the creep factors of timber beam elements. As a result, many methods and test rigs have been designed and used to examine creep deflection. The majority of authors implement a four-point bending test setup in accordance with EN 408, however, in some cases a three-point bending test set up [10] or an evenly distributed load across the whole length of the member have been used [11].

Due to the complex nature of timber, and the numerous variables involved, quantifying creep, both viscoelastic and mechano-sorptive, can be difficult. Many researchers have attempted to examine the many variables and their effect on creep behaviour. Bengtsson [12] monitored the influence of many material parameters on mechano-sorptive creep in Norway spruce. These parameters included annual ring width, slope of grain, knots, compression wood, density and modulus of elasticity. It was seen that the relationship between relative creep and elastic modulus was strongly correlated, however, other comparisons demonstrated weaker correlations.

Changes in moisture content of timber arise due to variations in relative humidity. The greater the moisture differential in each relative humidity cycle, the higher the amount of creep [7]. The differential in each moisture cycle is important for design purposes. EN 1156 [13] describes procedures for determining the creep factors of wood based panels. It recommends the moisture cycle implemented must be designed to coincide with a Service Class as defined in Eurocode 5 [14]. There are 3 service classes. Service Class 1 would be described as dry conditions which is characterised by a material moisture content corresponding to a temperature of 20°C and a relative humidity only exceeding 65% for a few weeks per year. Service class 2 would be described as humid conditions which is characterised by a material moisture content corresponding to a temperature of 20°C and a relative humidity only exceeding 85% for a few weeks per year. Service Class 3 would be described as exterior conditions which is characterised by a material moisture content corresponding to climatic conditions leading to higher moisture contents than in Service Class 2.

Hunt [15] questioned the importance of humidity changes and suggested the speed of moisture change might be important in mechano-sorptive creep. The speed of moisture change indicates a size effect that has previously been predicted by van der Put [16]. It is easy to see that the full extent of the mechano-sorptive effect will require the timber to adjust to the equilibrium moisture content of its new environmental conditions. For this reason short moisture cycles on full scale tests on in-grade timber specimens will provide inaccurate results. Duration of creep tests and moisture cycles vary considerably in the literature.

Abdul-Wahab et al. [17] performed long-term creep tests on 65 unreinforced glued laminated and solid timber beam specimens under different environmental conditions over an eight year period. The beams were subject to four-point bending as shown in Figure 1. These beams were subjected to three sets of environmental conditions. Although not deliberate, these conditions happened to coincide with Service Classes 1, 2 and 3 as defined in Eurocode 5 [11]. Environmental condition 1 was set at a constant temperature of 20°C and a constant relative humidity of 60 ± 10%. Environmental condition 2 was a variable climate condition with a constant temperature of 20°C and a variable relative humidity ranging between 30% and 70%. Environmental condition 3 was an external climate in a covered enclosure with a variable relative humidity ranging between 30% and 100%. Moisture measurements were taken regularly as well as temperature and relative humidity. It was noted that for a six week wetting/drying period that equilibrium moisture content was not achieved. In order to fully understand the mechano-sorptive effect longer relative humidity cycles are required. The size and shape of the beam is also of great importance. The shape and size of section, expressed in terms of volume/surface area, has a significant effect on creep. The smaller the ratio, the greater is the creep tendency.

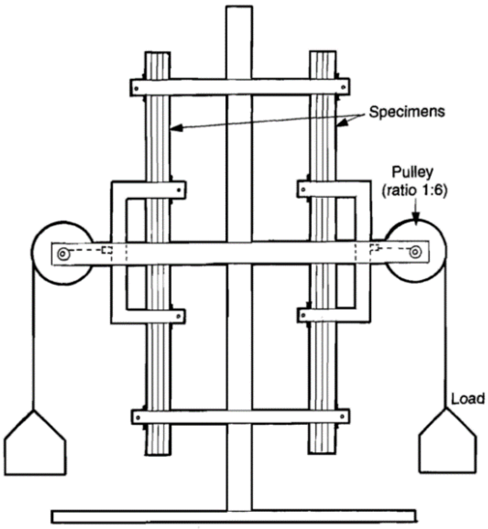

Figure 1. Vertical creep experimental rig [14].

Abdul-Wahab et al. [17] found that Service Class 3 beams experienced the greatest creep averaging a 285% increase in creep when compared to Service Class 1 beams at constant temperature and relative humidity. Service Class 2 in the variable climate experienced an increase in creep of 165% when compared to the beams at Service Class 1 at constant temperature and relative humidity. These deformations are significant and motivate the need for greater understanding of these effects.

3 EXPERIMENTAL PROCEDURE

This project is designed to study the long-term effects on FRP reinforced glued laminated beams manufactured from Irish grown Sitka spruce. Long-term creep tests will be performed under varying environmental condition and appropriate modification factors will be determined for design purposes. This paper details the short-term experiments, which were carried out prior to long-term creep tests. In total, thirty six glulam beams were manufactured in the Timber Engineering Laboratory at the National University of Ireland, Galway. Thirty beams used in the experimental programme will be subject to creep tests and six supplementary beams will be used to monitor shrinkage/swelling and moisture content variations during creep testing. The beams consist of four laminations. Each beam measures 98 mm x 125 mm x 2300 mm. The beams are divided into two matched groups, one group will be tested in a controlled climate at 20 ± 2°C and at a relative humidity of 65 ± 5% and the other group will be placed in a variable climate chamber. Each beam will be subjected to four-point bending for a period of at least two years to examine the duration of load effects and the creep effects in different climate conditions.

3.1 Glulam Manufacture

Each laminate was strength graded using a mechanical grading machine. From these results, each laminate was ranked in descending order of modulus of elasticity (1 being the highest MOE and 150 being the lowest MOE). This ranked table was divided into 4 divisions with the 1st division representing the highest MOE laminates and the 4th division representing the lowest MOE laminates. In each division there is a maximum and minimum value and by balancing between each division, 36 beams of similar properties were created. Division 1 contains the strongest 36 laminates which make up the 36 bottom tensile laminates for each beam. Division 2 is the 2nd strongest group and contains laminates ranked 37-73. These laminates are situated in the top of each beam and applied in ascending order of strength (73-37) to balance each beam and create beams of similar properties. So if a beam has the strongest tensile laminate ranked laminate number 1 in division 1, it received the weakest laminate in division 2 (laminate number 73). Division 3 contains laminates ranked 74-110, and is situated on top of the tensile laminate. Division 4 contains the weakest laminates ranked 111-147 and is located below the top laminate. Similar to division 2, division 4 is applied in ascending order of strength (147-111) to create beams of similar properties. This is illustrated in Figure 2.

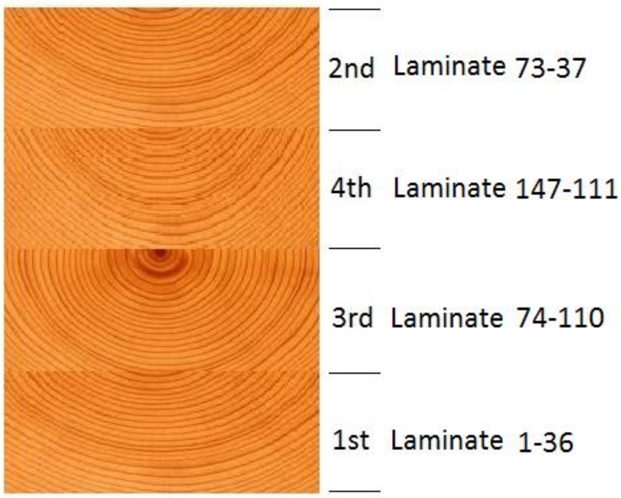

Figure 2. Glulam beam lay up.

To create a secure bond at the timber interface, each laminate was knife planed in order to create a smooth surface with which to adhere, free from irregularities and torn grain in accordance with EN 14080 [18].

It should also be free from impurities such as oils, dirt and other debris as these will affect both the mechanical and chemical bonding process at the timber interface. After planing, the thickness of each laminate was 31.25 mm on average. In order to achieve the best bond, the adhesive was applied within 2 hours after planing so that the wood pores opened by the planing process could absorb the glue applied [19]. The glue applied is a 1:1 phenol resorcinol formaldehyde adhesive which is fully weatherproof as well as being suitable for structural applications such as wooden laminated beams. Adhesive was applied to all interfaces to be bonded ensuring an even spread

Figure 3. Clamping Rig.

of a minimum of 350 g/m². In order to ensure complete coverage and an even distribution, 200 g/m² was applied to each face using a rubber roller.

The beams were clamped in a rig applying a minimum pressure of 0.6 N/mm² in accordance with EN 14080 [18] as seen in Figure 3. The beams remained in the clamping rig for 24 hours after which they were placed into a conditioning chamber to cure for 5 weeks at 20 ± 2 °C and at a relative humidity of 65 ± 5% prior to short term testing.

3.2 *Reinforcing glued laminated beams*

From the 36 beams created, 20 of the beams were reinforced with basalt fibre reinforced polymer (BFRP). Two 12 mm BFRP rods were inserted into two circular grooves routed the full length of bottom tensile laminate and centered 30 mm from each edge as shown in Figure 4. The grooves were measured to account for the BFRP rod diameter plus a 2 mm glue line. These two BFRP rods accumulate to a percentage reinforcement ratio of 1.85%.

To guarantee a solid bond, each groove was cleaned using compressed air to ensure it is free from dust and other impurities. A two part thixotropic structural epoxy adhesive was chosen to bond the reinforcement to the timber as it is specially formulated for the bonding of FRP to timber [20]. The two parts were mixed together from their pre-packaged containers. The paste was mixed thoroughly and placed into a cartridge for application using an injection gun. The groove was initially filled to approximately two-thirds of the routed depth. The BFRP rod was then inserted into the groove forcing excess adhesive around the sides of the rout up to the top of the rod. Additional adhesive was then applied to complete the 2 mm glue line. The beams were then placed in the conditioning chamber with a temperature of 20 ± 2 ºC and with a relative humidity of 65 ± 5%, where they remained to cure for a period of 3 weeks.

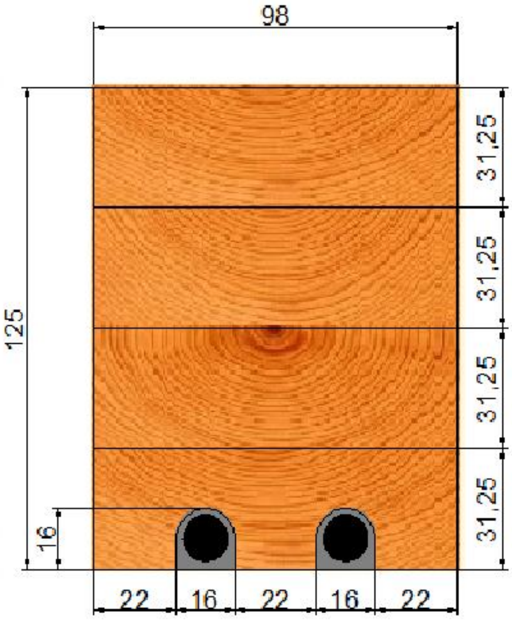

Figure 4. Reinforcement detail.

3.3 *Short Term Testing*

The bending test set up is in accordance with EN 408 [21]. The beams were loaded at a constant cross head 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 of the beam and that the maximum load was less than 40% of the estimated ultimate failure load. The deflection of the midspan of the beam was measured using two LVDTs, one for determining the local stiffness and the other for the global stiffness. In order to determine the local bending stiffness, the deflection was measured over a gauge length of 625 mm = 5h, where h is the height of the beam, using a hanger suspended to the neutral axis, as seen in Figure 5. The LVDT for global stiffness measurement was fixed centrally on the top surface to the beam. Plates were used under at each support and load head to avoid indentation and inaccurate deflection measurement.

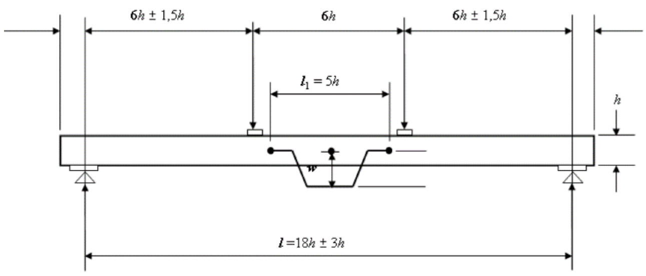

Figure 5. Beam bending set-up [18].

As a precaution each beam was supported laterally using polytetraflourethylene strips and packing to counteract lateral torsional bucking during bending. These strips are free to slide over one another so as not to fully restrain the beam at this location [22]. Subsequent to these 4-point bending tests, the recorded local and global deflection data was plotted against the applied load to obtain the stiffness values. The resulting increment in displacement (w_2 - w_1) corresponding to the load increment (F_2 - F_1) was substituted into Equations (5) and (6) to obtain the values for local and global stiffnesses, respectively:

$$(EI)_{m,l} = \frac{a l_1^2 (F_2 - F_1)}{16(w_2 - w_1)} \tag{5}$$

$$(EI)_{m,g} = \frac{l^3 (F_2 - F_1)}{12(w_2 - w_1)} \left[\left(\frac{3a}{4l} \right) - \left(\frac{a}{l} \right)^3 \right] \tag{6}$$

In these equations $\boldsymbol{a}$ is the distance between the load head and the nearest support, $\boldsymbol{l_1}$ is equal to the gauge length (5 x h) for local modulus measurement, $\boldsymbol{l}$ is equal to the span and $\boldsymbol{F_1}$ and $\boldsymbol{F_2}$ are the loads corresponding to 0.1 and 0.4 F_{max}, respectively. Similarly $\boldsymbol{w_1}$ and $\boldsymbol{w_2}$ are the deflections corresponding to 0.1 and 0.4 F_{max}, respectively. These tests were performed on the unreinforced beams and subsequently on twenty of the reinforced beams. The test set up remained constant throughout allowing the percentage increase in stiffness to be calculated.

3.4 *Proposed Creep Testing*

As discussed in the introduction one sub group consisting of 15 beams will be subject to creep testing for at least 2 years in a constant environment and one sub group also consisting of 15 beams will be subject to creep testing in a variable climate. The constant climate condition will be at 20 ± 2°C and at a relative humidity of 65 ± 5% (This will coincide with Service Class 1 as defined in Eurocode 5 [14]). The constant climate conditions will provide data for the analyses of viscoelastic creep. The variable climate condition will encompass viscoelastic creep together with mechano-sorptive creep and strains due to swelling and shrinkage.

The test set up will be similar to that in Figure 5. Each beam will be subjected to four-point bending for a period of at least 2 years. A series of strategically placed strain gauges will be used to monitor the deformation of each beam. Swelling and shrinkage strains will be monitored on zero load control beams. Moisture content will be monitored constantly. Moisture probes will be placed at various depths within the timber to monitor the varying moisture penetration due to the environmental conditions.

4 RESULTS

Once the beams had been tested in their unreinforced state, six matched groups were created. Four of these groups were subsequently reinforced as described in section 3.2. The average increase in bending stiffness of each reinforced group is calculated relative to the stiffness in its unreinforced state. These results can be seen in Table 1 and Figure 6.

The average increase in the local bending stiffness is 16.30% with a standard deviation of 1.65% and the average increase in global bending stiffness is 8.80% with a standard deviation of 3.65%. The elastic modulus (E) is measured both globally and locally. Once reinforced the local elastic modulus (E_L) had a mean value of 10727 N/mm^2 and the global elastic modulus (E_G) had a mean value of 9307 N/mm^2.

Table 1. Percentage increase in stiffness.

GROUP	Average Local EI Increase (%)	Average Global EI Increase (%)
1	15.30%	6.54%
2	17.86%	14.14%
3	14.51%	8.15%
4	17.54%	6.36%
Average	16.30%	8.80%
Standard Dev.	1.65%	3.65%
Median	16.42%	7.34%

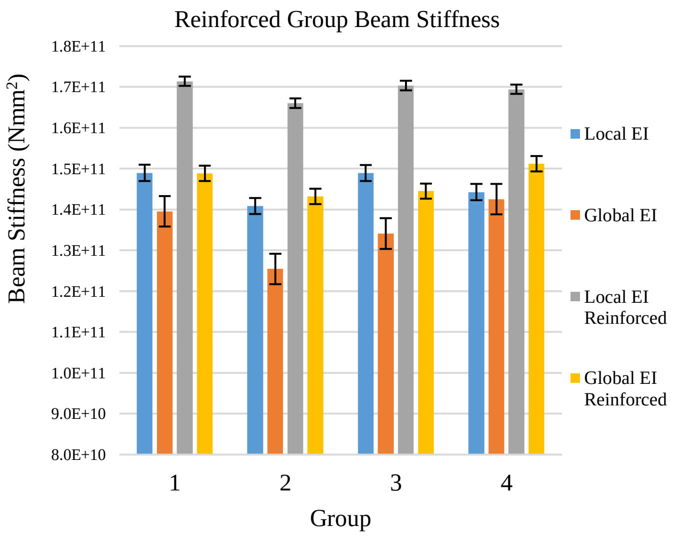

Figure 6. Reinforced group beam stiffness.

The increase in the global bending stiffness of group 2 in Table 1 is significantly higher than that realised in other groups. This may be due to the lower initial global stiffness of group 2 in its unreinforced state. The lower the initial stiffness, the greater is the effect of FRP reinforcement.

The addition of reinforcement has resulted in reduced variability within each group as seen in Figure 6.

5 CONCLUSION

The long-term effects with regards to the duration of load and creep effects in timber and the experimental programme have been described. The short-term testing has been completed and provide a reliable basis for comparable studies in future work.

The 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 proposed creep study will examine the long-term effects of these Sitka spruce glued laminated beams in both constant and varying climate. The addition of reinforcement and its influence on the long-term effects will also be examined.

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