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# Mechano-sorptive Creep in Reinforced Sitka Spruce

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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, the 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 strength modification factors for design purposes. Sitka spruce is the most widely grown species in Ireland and is the timber used in this study. Glued Laminated (Glulam) beams are constructed from Sitka spruce and a proportion of the Glulam beams are reinforced with basalt-fibre reinforced polymer (BFRP) rods. Short-term flexural tests are performed on all unreinforced beams. Six matched groups are created and four of these groups are reinforced and retested. The creep test beams are loaded in bending and the effects of load duration and varying climate are being monitored. One sub-sample of the beams is being 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 bending stiffness increase results for reinforced beam groups.

***Keywords*:** Mechano-sorptive Creep, Glued Laminated Timber, Irish Grown Sitka Spruce, BFRP

## Introduction

Sitka spruce is the most abundant tree species grown in Ireland. This species has an average rotation length of 30 – 40 years (Moloney and Bourke 2004) leading to low density, low grade material. 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.

Further increases in glulam capacity can be achieved with the addition of FRP reinforcement material. By deploying the reinforcement on the tensile side, the additional capacity of the timber in the compression zone is utilised and results in much more consistent behaviour as well as significantly increasing the flexural stiffness (Raftery and Harte 2011). Basalt fibre reinforced polymer (BFRP) is a novel FRP material, which has shown great potential as a reinforcement material for timber elements.

The long-term behaviour of such reinforced glulam beams is of critical importance to structural engineers when designing timber structures. Creep effects must be understood as excessive deflection will result in untimely failure. The creep effect manifests itself as an increase in deflection with time under a sustained load. This time dependent creep is known as viscoelastic creep. Mechano-sorptive creep occurs due to an interaction between stress and moisture content change. Although it occurs simultaneously with viscoelastic creep, it is independent of time. Depending on environmental conditions, this effect can greatly increase the creep deflection of a beam and accelerate the time to failure. To the authors knowledge, only one study addresses these effects on unreinforced and reinforced glulam beams made from Irish grown Sitka spruce (Gilfillan et al. 2003).

## Literature Review

The creep effect is the increase in deflection with time for a given constant stress. Creep within timber structures 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. 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 change in moisture content due to variations in relative humidity (Armstrong and Kingston 1960; Armstrong and Christensen 1961). It is independent of time and it does not occur in constant temperature and relative humidity conditions (Armstrong 1972). Due to the complex nature of timber, and the numerous variables involved, quantifying creep, both viscoelastic and mechano-sorptive, can be difficult.

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:

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

Equation (1)

where:
$C_C$ = Creep compliance,
$\Delta\varepsilon = \varepsilon_t - \varepsilon_0$ = Change in strain with time,
$\sigma_0$ = 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:

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

Equation (2)

where:
$C_R$ = Relative creep,
$\varepsilon_0$ = 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 ($Cc_0$). Changes in the moisture content of timber result not only in mechano-sorptive creep effects but also in dimensional changes in timber. These dimensional changes (shrinkage and swelling ($\varepsilon_s$)) result in increased deflection and must be monitored.
The total measured strain $\varepsilon_m$, may be written as

$$\varepsilon_m = \varepsilon_{vc} + \varepsilon_{ms} + \varepsilon_s$$

Equation (3)

where:
$\varepsilon_{vc}$ = Viscoelastic strain,
$\varepsilon_{ms}$ = Mechano-sorptive strain,
$\varepsilon_s$ = Swelling/shrinkage strain of a matched zero-load control specimen.

The mechano-sorptive component may then be calculated as

$$\varepsilon_{ms} = \varepsilon_m - (\varepsilon_{vc} + \varepsilon_s)$$

Equation (4)

Mechano-sorptive behaviour has been the focus of many studies due to its ability to increase deflection and cause premature failure of timber elements. There is no defined method for examining creep factors in timber beam elements. This has resulted in many different test methods and test rigs being designed and used to examine creep deflection. Duration of creep tests and moisture cycles also vary considerably in the literature. EN 1156 (NSAI 2013a) 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 (NSAI 2005+NA:2010+A1:2013). Abdul-Wahab et al. (1998) 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. 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 (NSAI 2005+NA:2010+A1:2013). Abdul-Wahab et al. (1998) 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. The addition of reinforcement, regardless of material type, has been shown to reduce the creep effect within timber elements when compared to unreinforced members (Davids et al. 2000; Kliger et al. 2008; Lu et al. 2013). BFRP is a novel reinforcement material that has demonstrated 35-42% higher elastic modulus when compared to GFRP (Lopresto et al. 2011). The long-term effects on timber elements reinforced with BFRP require attention.

## Experimental Procedure

This project is designed to study the long-term creep effects of BFRP reinforced glued laminated beams manufactured from C16 Irish grown Sitka spruce. Long-term creep tests will be performed under constant and variable environmental conditions 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 2 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.

**Glulam Manufacture**. Each laminate was initially strength graded using a mechanical grading machine. Each laminate was ranked accordingly. It was desirable to manufacture thirty six beams of equal properties to create matched groups for comparative studies of long-term effects at a later stage. The beam lay-up was designed by arranging each laminate based on the strength graded data. 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 (NSAI 2013b). A 1:1 phenol resorcinol formaldehyde adhesive was used to bond each laminate. Adhesive was applied to the surfaces to be bonded ensuring an even spread of a minimum of 350 g/m$^2$. To ensure complete wetting of the bonding surfaces, 200 g/m$^2$ was applied to each surface using a rubber roller. The beams were clamped in a steel rig applying a minimum pressure of 0.6 N/mm$^2$ in accordance with EN 14080 (NSAI 2013b). The beams remained in the rig for 24 hours to cure 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.

**Reinforced Glulam Manufacture**. From the 36 beams created, 20 of the beams were reinforced with 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 1. The grooves accommodate the BFRP rod plus a 2 mm glue line. The 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 was 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 (Rotafix, 2014). 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 prior to short-term testing.

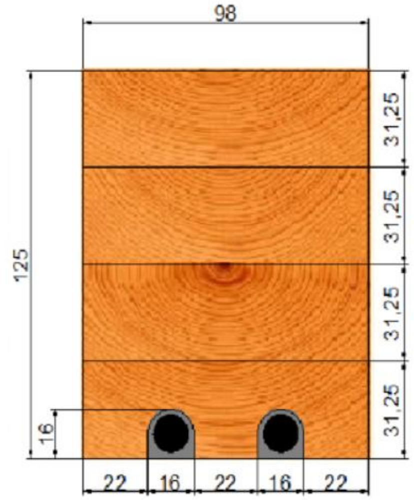
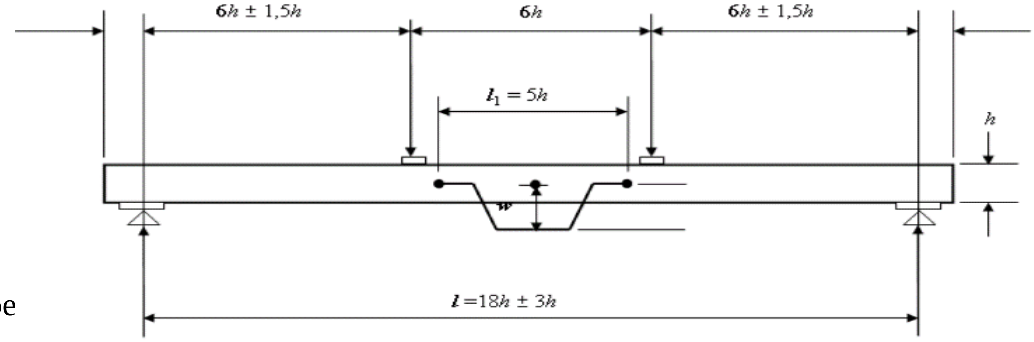



*Figure 1. Reinforcement*

**Short-term Testing**. The bending test set up is in accordance with EN 408 (NSAI 2010+A1-2012). The beams were loaded at a constant cross head rate of 0.15 mm/s 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 was measure locally and globally at the midspan using two linear variable differential transformers (LVDTs). The local deflection was measured over a gauge length of 625 mm using a hanger suspended to the neutral axis as seen in Figure 2.



The recorded local and global deflection data was used to obtain the stiffness values. The 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:

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

*Figure 2. Beam bending set-up (NSAI 2010+A1-2012)*

Equation (5)

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

Equation (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 for local modulus measurement, $\boldsymbol{l}$ is equal to the span and $\boldsymbol{F_1}$ and $\boldsymbol{F_2}$ are the loads corresponding to 10% and 40% $F_{max}$, respectively. Similarly $\boldsymbol{w_1}$ and $\boldsymbol{w_2}$ are the deflections corresponding to 10% and 40% $F_{max}$, 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.

**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 (NSAI 2005+NA:2010+A1:2013)). 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 2. Each beam will be subjected to four-point bending for a period of at least 2 years. Swelling and shrinkage strains will be measured on zero load control beams. Moisture content will be monitored continuously using moisture probes embedded at various depths within the timber to monitor the varying moisture penetration due to the chosen environmental condition. Tensile creep testing of the BFRP rod will be carried out in both controlled and variable environments.

## 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 the experimental procedure. The average increase in bending stiffness of each reinforced group is calculated relative to the stiffness in its unreinforced state. The results can be seen in Table 1 and Figure 3.

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%. Once reinforced the effective local elastic modulus had a mean value of 10727 N/mm$^2$ and the effective global elastic modulus had a mean value of 9307 N/mm$^2$.

| 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% |

*Table 1: Group Beam Results*

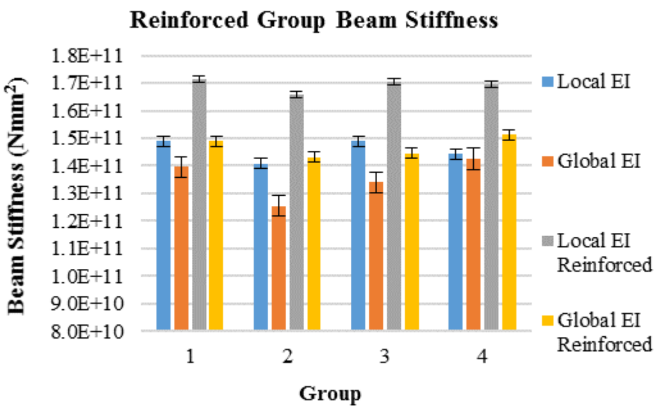



*Figure. 3: Group Beam Results*

## Conclusion

The long-term effects with regards creep effects in timber and the experimental programme have been described. Short-term tests have provided a reliable basis for comparable studies in future work. Flexural tests have 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%.

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