

NUMERICAL STUDY OF FRP REINFORCED TIMBER MEMBERS SUBJECTED TO VARIABLE CLIMATES

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Abstract

The use of FRP reinforcement, even in small percentages, has been shown to improve the short-term flexural behaviour of timber members. This technology has been successfully used in new construction and in the repair and renovation of existing buildings across Europe. However, the enhancement of the long-term behaviour due to FRP reinforcement is often disregarded in design.

In this study, a coupled finite element numerical model was developed to examine the influence of a variable climate on the long-term deflection of FRP reinforced members. The time-dependent coupled hygro-mechanical model utilises a thermo-hygro analogy to define the movement of moisture through the member depending on the relative humidity of the surrounding environment. The model considers the elastic and viscoelastic behaviour of timber, in addition to the moisture dependent, mechano-sorptive creep and swelling/shrinkage behaviour. The model has been validated against experimental results from long-term variable climate tests on unreinforced and reinforced timber beams under four-point bending.

A parametric study was carried out to examine the influence of reinforcement material on the long-term behaviour of reinforced timber members over a ten-year period under a sinusoidal relative humidity cycle. The materials considered were glass fibre reinforced polymer (GFRP), basalt fibre reinforced polymer (BFRP), aramid fibre reinforced polymer (AFRP) and carbon fibre reinforced polymer (CFRP). Results have shown that unreinforced members experience the largest deflection over the ten-year period, as expected. The deflection behaviour of the FRP reinforced beams was found to be dependent on the stiffness of the FRP material with the least stiff GFRP reinforcement experiencing a greater deflection than the stiffer BFRP, AFRP and CFRP materials. By considering the relative creep deflection results, it has been shown that a single creep design factor k_{def} may be used to predict the long-term performance of reinforced beams regardless of FRP type.

1 INTRODUCTION

Fibre reinforced polymer (FRP) materials have been successfully used to reinforced timber elements, increasing the bending stiffness and the ultimate moment capacity of such elements, when positioned strategically [1–8]. This technology has been largely implemented in the repair and restoration of existing structures. FRP reinforcement has been used to repair damaged elements often restoring such elements to their original load carrying capacity. Also, during the restoration or redevelopment of existing structures, there is often a change of use or a change in building regulations, which requires elements to have a greater capacity than that of the original element. While the short-term bending stiffness and moment carrying capacity have been shown to benefit significantly from FRP reinforcement, the influence of FRP reinforcement on the long-term or creep behaviour is rarely considered in design.

A number of studies have attempted to examine the influence of FRP materials on the long-term behaviour of FRP reinforced elements by comparing the creep deflection of unreinforced and reinforced elements [9–13]. Under constant climate conditions, timber behaves as a visco-elastic material and its total deformation is time dependent. Under variable climates conditions, additional effects such as mechano-sorptive creep, swelling/shrinkage strains and changes in material properties due to changes in moisture content must be considered. As all of these creep effects occur simultaneously, it is often difficult to decompose the total deflection into its component parts and to evaluate the influence of the FRP reinforcement. In a carefully designed experimental programme, O’Ceallaigh et al. [14] subjected unreinforced and reinforced beams to creep testing in both constant and variable climates. The use of matched groups provided a basis from which the individual creep components for unreinforced and reinforced beams were characterised, allowing the influence of the FRP to be determined. Their results showed that the overall deflection of the reinforced beams was reduced due to the addition of FRP reinforcement, however, unlike other studies, which attribute this reduced deflection to reduced mechano-sorptive behaviour, O’Ceallaigh et al. [14] found that the reduction in creep was as a result of reduced swelling/shrinkage effect due to the restraining behaviour of the FRP reinforcement.

Examining long-term effects on the timber response, as the name suggests, requires long durations of experimental testing to observe the desired behaviour. In many cases, the longer the test, the more reliable the result; however, such tests are expensive not only in terms of time but also cost and resource use. A validated numerical model can be used as an effective way to examine various parameters without any substantial time and economic constraints.

In this paper, a non-linear coupled hygro-mechanical model developed by O’Ceallaigh [14] is utilised to describe the creep behaviour of structural-sized unreinforced and reinforced beams under long-term loading in a variable climate. The 3-dimensional hygro-mechanical model was developed using Abaqus finite element analysis software [15] and has been validated using experimental tests presented by O’Ceallaigh et al. [14,16–19]. The validated model is used in a parametric study to examine the effect of reinforcement type on the long-term behaviour of reinforced timber beams in a variable climate. The materials considered were glass fibre reinforced polymer (GFRP), basalt fibre reinforced polymer (BFRP), aramid fibre reinforced polymer (AFRP) and carbon fibre reinforced polymer (CFRP). This paper examines the influence of the reinforcement type on the creep behaviour in a variable climate over a ten-year period.

2 NUMERICAL MODEL

2.1 Introduction

Numerical modelling can be an important tool when modelling structures, particularly, structures utilising complex materials. Timber is often considered a complex material in terms of

modelling due to its anisotropic behaviour and inherent variability. Abaqus finite element analysis software has been used to develop a numerical model capable of examining the long-term behaviour of timber elements subjected to load in a variable climate. This versatile software can be adapted to predict moisture movement within timber with the use of a thermo-hygro analogy. This analogy allows the moisture diffusion within timber to be described using a standard heat-transfer or coupled temperature-displacement analysis available in Abaqus [17]. This is possible as both heat and moisture transfer are driven by diffusion. Numerical tools have also been shown to adequately model various reinforcement materials in various configurations. The following presents a summary of the constitutive equations implemented in a user subroutine to describe the creep behaviour of FRP reinforced timber elements in variable climates and its implementation in Abaqus. For more information related to the formulation of the model, material properties, creep coefficients, see O’Ceallaigh et al. [14].

2.2 Numerical Model Formulation

As mechano-sorptive creep modelling capability is not currently available in Abaqus, a user-defined UMAT subroutine is implemented to define the mechano-sorptive behaviour in addition to other strain components during loading and simultaneous moisture movement within timber. The simulated total strain ε_T , given in Equation (1) can be subdivided into five separate strain components.

$$\varepsilon_T = \varepsilon_e + \sum_{i=1}^k \varepsilon_{ve} + \varepsilon_{ms} + \varepsilon_{ms,irr} + \varepsilon_s \quad (1)$$

where ε_e = Elastic strain component, ε_{ve} = Viscoelastic strain component, ε_{ms} = Mechano-sorptive strain component, $\varepsilon_{ms,irr}$ = Irrecoverable mechano-sorptive strain component and ε_s = Swelling/shrinkage strain component. The k term denotes the number of viscoelastic Kelvin elements used in the formulation of the viscoelastic creep component.

The elastic component (ε_e) follows a generalized Hooke’s law, which in its 3-dimensional form, defines the orthotropic elastic stress-strain behaviour of timber in the radial, tangential and longitudinal directions. The elastic properties of the timber are not constant and equations provided by Santaoja et al. [20] and Mirianon et al. [21] are implemented to adjust the properties when the environmental conditions are different from the prescribed, reference conditions (12% moisture content). The viscoelastic component (ε_{ve}) is an extension of the 1-dimensional model presented by Toratti [22] and the viscoelastic creep contribution is described by four Kelvin type elements with different characteristic times validated by experimental tests [14]. The total mechano-sorptive creep strain comprises a recoverable mechano-sorptive creep component (ε_{ms}) associated with repeating cycles of relative humidity and an irrecoverable mechano-sorptive creep component ($\varepsilon_{ms,irr}$), which is dependent on moisture content changes to levels not previously attained during previous moisture cycles. The irrecoverable component follows the approach implemented by Mirianon et al. [21] and Fortino et al. [23]; however, a significant alteration was made to the irrecoverable mechano-sorptive creep matrix to include irrecoverable deformations in the longitudinal direction based on the experimentally observed longitudinal strain results [14]. The swelling/shrinkage strain component (ε_s) occurs within timber under changing moisture content. This change in strain depends on the material direction and magnitude of the change in moisture content. The values of the swelling/shrinkage coefficients in the radial, tangential and longitudinal direction were determined from experimental tests [14,17].

A DFLUX subroutine is utilised to define the exchange of moisture between the exposed surface of the timber and the surrounding environment. The relative humidity of the

surrounding environment, which corresponds to a specific moisture content in the timber, is applied to the exposed surfaces of the model. The rate of moisture flow (q_n) from the surrounding environment to the exposed surface of the timber is governed by Equation (2) [17,21,22,24].

$$q_n = S_u(\phi_{eq} - \phi_{surf}) \quad (2)$$

where S_u = Surface emission coefficient, ϕ_{surf} = Moisture concentration of the wood surface and ϕ_{eq} = Equilibrium moisture concentration of timber corresponding to the relative humidity of the surrounding environment. The surface emission coefficient, S_u , defines the rate of moisture content exchange across the boundary. The selection of appropriate material direction dependent diffusion coefficients for timber is fundamental when examining moisture flow within timber elements. In this study, the differences between the diffusion coefficients in the radial and tangential directions are assumed negligible and no distinction is made; however, the longitudinal diffusion coefficient is significantly larger [14,17].

3 PARAMETRIC STUDY

The model described above has been validated using experimental tests presented by O’Ceallaigh et al. [14,16–19]. The validated model is used in a parametric study to examine the influence of FRP type on the creep behaviour of reinforced beams in a variable climate.

3.1 Model Geometry

In this study the geometry of an unreinforced and an FRP reinforced beam are modelled in Abaqus finite element software. As seen in Figure 1, the unreinforced and reinforced beam sections measuring 98 x 125 mm² comprise four laminations. The reinforced beam model is created similar to that of the unreinforced beam; however, in the bottom tensile lamination, two routed grooves are created to accommodate two 12 mm diameter FRP rods and the 2 mm structural epoxy adhesive.

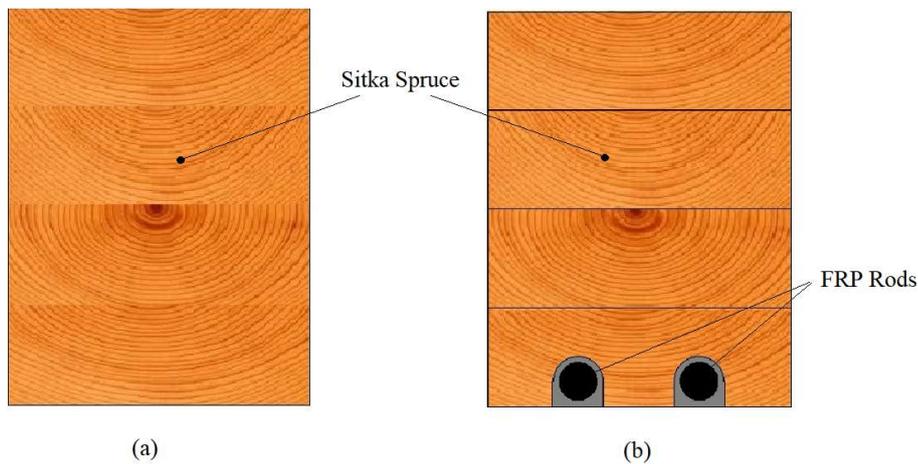


Figure 1: Beam cross-section: (a) Unreinforced beam, (b) Reinforced beam.

The glued laminated beam in the creep test set-up is loaded in four-point bending as seen in Figure 2a. Half symmetry is utilised allowing half of the 2300 mm long beam to be modelled in order to reduce the computational time as seen in Figure 2b. The glue-line has been omitted in this mechanical model. Each of the four laminations is assigned material properties in a local cylindrically orientated coordinate system. Each model uses 8-noded coupled thermal-

displacement C3D8T elements. The respective mesh sizes for the unreinforced and reinforced beam models were determined from mesh sensitivity studies to provide accurate results in a reasonable time frame. The beam is simply supported on 80 mm x 100 mm plates which are free to rotate about their central axis.

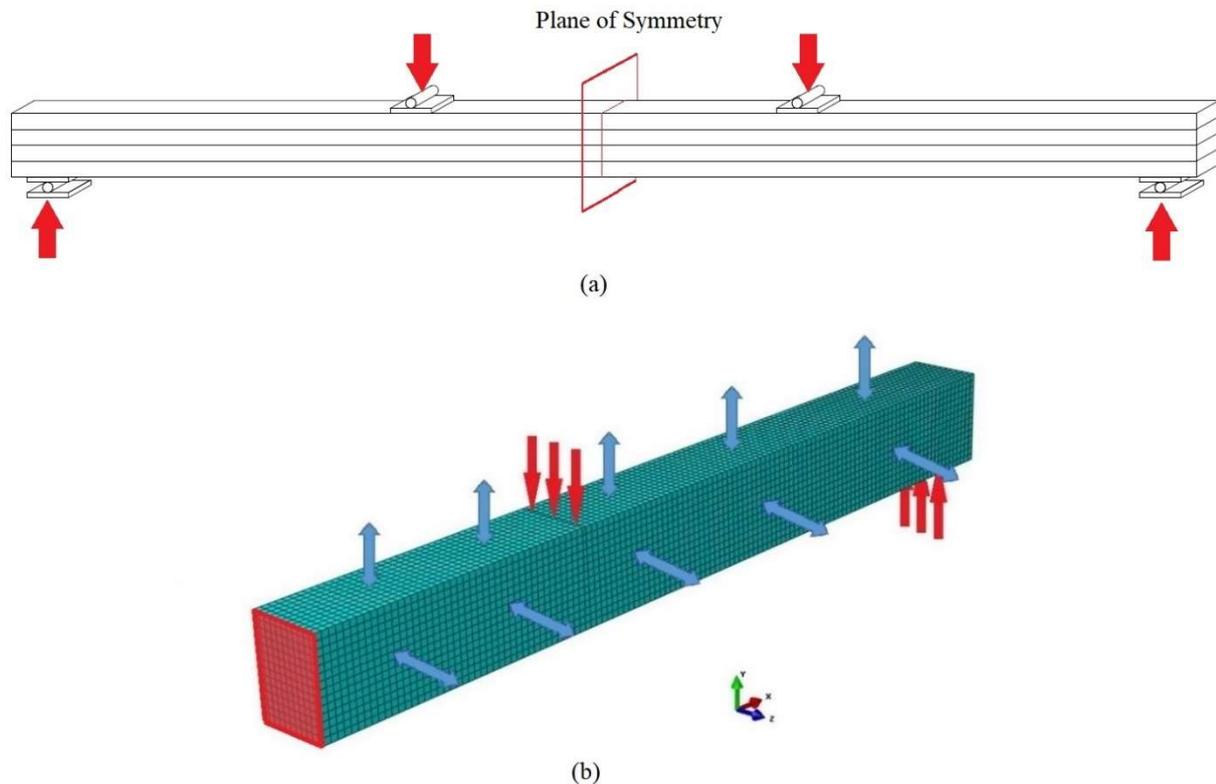


Figure 2: Test Set up: (a) Creep test set-up and plane of symmetry, (b) Finite element coupled hygro-mechanical creep model of the unreinforced glued laminated beam: The red arrows represent the load point and support point on the top and bottom surface, respectively, and the blue arrows represent the relative humidity load shown on the exposed surfaces.

These plates are modelled using 2-dimensional shell S3 elements. Hard contact is defined between the surface of the beam and the steel plate with a tangential friction coefficient of 0.4. Similar plates are used to apply the dead load in tests. These are also modelled using S3 shell elements and the load is applied as a uniform pressure over the plate area. A constant dead load of 6241 N was applied to all unreinforced and reinforced beams under examination. This corresponds to a maximum bending stress of 8 MPa in the compression zone of the BFRP reinforced timber member as was the case for the experimental tests [14] used to validate this numerical model.

3.2 Material properties

The timber used in this study was C16 grade Sitka spruce grown in Ireland. The material properties for the timber in the radial, tangential and longitudinal remained unchanged from those presented by O’Ceallaigh [14]. Further information related to the elastic moduli, shear moduli and Poisson’s ratios used in this study in the three material directions are presented by O’Ceallaigh [14].

The material properties of the FRP rods used in the validated model are adapted to examine the influence of different FRP materials on the hygro-mechanical creep behaviour. The geometry of the rods remained constant. The different materials used are presented in Table 1. The

elastic modulus value for BFRP has been determined from experimental testing by O’Ceallaigh et al. [16] and the remaining elastic modulus values have been previously reported by Harte and Dietsch [25]. Where a range of values is reported, the average value has been used.

Table 1: Parametric study: FRP materials

Notation	Description	Elastic Modulus	Unit	Source
BFRP	Basalt fibre rod reinforcement	50.8	GPa	[16]
GFRP	Glass fibre rod reinforcement	46	GPa	[25]
AFRP	Aramid fibre rod reinforcement	77-135	GPa	[25]
CFRP	Carbon fibre rod reinforcement	120-300	GPa	[25]

3.3 Environmental Conditions

The influence of the environment and particularly a changing environment has a significant effect on the creep behaviour of timber elements. The environmental load or relative humidity load is implemented in Abaqus through a DFLUX subroutine in order to apply a defined relative humidity boundary condition as a function of time. The climate condition implemented varies sinusoidally with a period of one year with an amplitude cycling between 65% and 90% relative humidity as illustrated in Figure 3.

The sinusoidal curve was chosen to be an approximate representation of an annual change in relative humidity with a mean relative humidity of 65% in the middle of summer transitioning slowly to a mean of 90% relative humidity in the middle of winter. The model does not consider daily fluctuations in relative humidity. This relative humidity load is applied to the exposed surfaces of the glued laminated beam for a duration of 10 years.

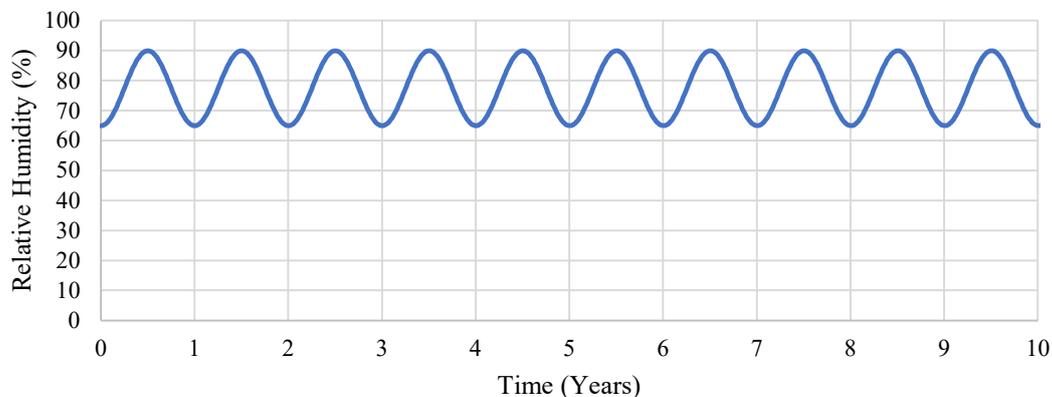


Figure 3: Sinusoidal relative humidity cycle implemented to examine the performance of different types of FRP materials.

4 PARAMETRIC STUDY RESULTS

The numerical model was used to characterise the variation of midpoint deflection of the unreinforced and FRP reinforced beams with time. The total deflection results over a 10-year period for the unreinforced and reinforced beams in the parametric study are presented in Figure 4. Additionally, the peak deflections at a series of relative humidity cycles were chosen and have been presented in Table 2. When examining the results in Figure 4 and Table 2, it is important to remember that the beams are loaded to a common dead load of 6241 N and each beam is subject to the same relative humidity cycle and only the stiffness of the reinforcement has been changed in each reinforced model. As a result, each beam is subjected to a different

bending stress distribution through the cross-section. This influences the initial elastic deflection and as viscoelastic and mechano-sorptive creep are driven by stress in the timber, the difference in bending stress has resulted in different rates of deformation with time.

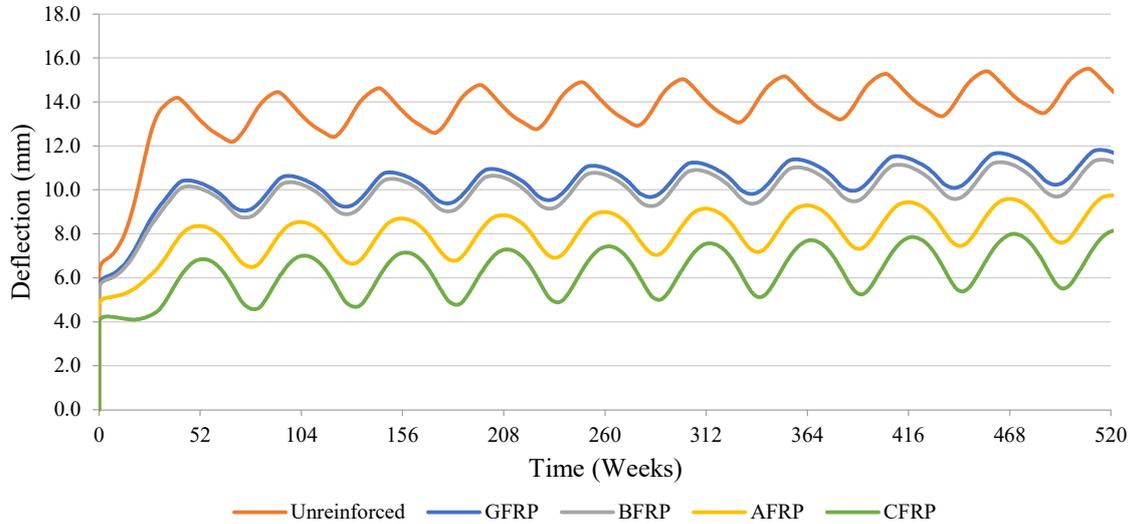


Figure 4: Parametric study: Creep deflection results of unreinforced and FRP reinforced beams over a 10-year period under a constant dead load

Table 2: Parametric study: Peak deflection (mm) during the chosen relative humidity cycles

	Loading	Peak 1	Peak 2	Peak 4	Peak 6	Peak 8	Peak 10
Unreinforced	6.37	14.20	14.46	14.78	15.04	15.29	15.52
GFRP	5.70	10.44	10.64	10.96	11.25	11.54	11.82
BFRP	5.58	10.17	10.36	10.65	10.91	11.15	11.38
AFRP	4.85	8.37	8.54	8.85	9.15	9.45	9.75
CFRP	4.06	6.85	7.01	7.30	7.58	7.86	8.15

In Figure 4 and Table 2, it can be seen that initially, there is a large difference due to the elastic behaviour of the various beams. It can be seen that over a 10-year period the unreinforced beam has experienced the greatest creep deflection as expected. The magnitude of the creep deflection behaviour of FRP reinforced beams can be seen to be influenced by the stiffness of the FRP material with the least stiff GFRP experiencing a greater creep deflection than the stiffer BFRP, AFRP and CFRP reinforcing materials. The GFRP and BFRP reinforced beams have demonstrated similar creep behaviour as a result of their similar stiffness values of 46 GPa and 50.8 GPa, respectively. The creep behaviour of the AFRP reinforced beam results in a large decrease in creep deflection due to the stiffness of the FRP material, however the general behaviour is similar to that of the less stiff FRP materials. When examining the creep behaviour of the CFRP reinforced beam, it can be seen that the creep behaviour is different to that seen for other FRP reinforced beams previously as there is an initial decrease in deflection during the first increase in relative humidity. A similar result was observed by Kliger et al. [9] when experimentally comparing the creep behaviour of CFRP reinforced beams to the creep behaviour of unreinforced beams. Kliger et al. [9] found that higher stiffness materials demonstrated such behaviour. This is believed to be a result of the longitudinal swelling of the timber on the compression face while the stiffer CFRP reinforcement restrains swelling on the tension face.

There also appears to be a phase lag in the response of each beam to the sinusoidal relative humidity cycle in both the unreinforced and reinforced beams. In the first cycle, in which the relative humidity peaked at 90% after 26 weeks and returned to 65% after 52 weeks, the unreinforced beam reached its peak deflection after 40 weeks. The peak deflection of the FRP reinforced beams are further delayed with the GFRP reaching its first peak deflection after 45 weeks, the BFRP after 46 weeks, the AFRP after 51 weeks and the CFRP after 53 weeks. For this reason, it was decided to compare the results of each modelled beam at the peak deflection of each relative humidity cycle.

The creep deflection results (Table 2) shows the effect of FRP reinforcement type on the total creep behaviour of such beams. Using a normalised relative creep measure, which is the ratio of total deflection to elastic deflection, the long-term behaviour may be compared. The relative creep results are presented in Table 3. It can be seen that regardless of FRP material, the relative creep values increase with time. The unreinforced beam has the largest relative creep result throughout with a final value of 2.435 after 10 years. Interestingly, although the FRP materials demonstrate different magnitudes of total creep deflection over time, when examining the relative creep results after 10 relative humidity cycles, the relative creep behaviour of all reinforced beams, regardless of FRP type, have shown a similar relative creep result with the GFRP resulting in a value of 2.073, BFRP with 2.038, AFRP with 2.010 and CFRP with 2.006.

Table 3: Parametric study: Peak relative creep result during the chosen relative humidity cycles

	Loading	Peak 1	Peak 2	Peak 4	Peak 6	Peak 8	Peak 10
Unreinforced	1.000	2.228	2.268	2.319	2.360	2.398	2.435
GFRP	1.000	1.831	1.866	1.922	1.973	2.023	2.073
BFRP	1.000	1.821	1.855	1.908	1.954	1.997	2.038
AFRP	1.000	1.725	1.762	1.825	1.887	1.948	2.010
CFRP	1.000	1.687	1.726	1.796	1.865	1.935	2.006

These simulated relative creep results have shown that it may be possible to apply a single factor (k_{def} factor) to predict the long-term performance of reinforced beams regardless of FRP type. It is noted that these results only apply for beams with a similar percentage area reinforcement ratio and under a common dead load. Future examination of the effect of stress level and different percentage area reinforcement ratios is required prior to the provision of reliable modification factors to predict creep behaviour of FRP reinforced beams.

5 SUMMARY AND CONCLUSIONS

Numerical models have played a key role in understanding of the behaviour of timber structures and have contributed to the safe design of large and tall timber buildings under more demanding loading conditions. In this study a hygro-mechanical creep model, which has been developed in a user-defined UMAT subroutine, has been used to predict long-term viscoelastic and mechano-sorptive creep in structural FRP reinforced timber elements subjected to dead load and variable relative humidity conditions. The formulation of the UMAT subroutine by O’Ceallaigh [14] follows the approach implemented by Santaoja et al. [20], Mårtensson [26], Mirianon et al. [21] and Fortino et al. [23]; however, a significant alteration was made to the irrecoverable mechano-sorptive creep matrix to include irrecoverable deformations in the longitudinal direction when stressed under loaded conditions and subject to moisture contents not previously attained.

Following validation of the model against experimental measurements, a parametric study was carried out to examine the effect of different types of FRP on the long-term behaviour of reinforced timber. Glass, basalt, aramid and carbon FRP materials were chosen and implemented into the reinforced beam model and subject to a common dead load under an annual sinusoidal relative humidity cycle ranging between 65% and 90% corresponding to summer and winter conditions, respectively. The results were compared to an unreinforced beam loaded under the same conditions. The use of stiffer FRP materials resulted in reduced creep deflection behaviour over the simulated 10-year period. As a result of the difference in stiffness of the FRP materials, there were large differences in the elastic deflection, and so a normalised relative creep measure was used to compare the long-term performance of each beam. It was found that the FRP reinforced beams performed better than the unreinforced beam throughout. When focusing on the FRP reinforced beams, it was found that after 10 years, there was very little difference between the relative creep results of all the FRP reinforced beams regardless of FRP type. This indicates that a single modification factor (k_{def}) may be suitable to describe the long-term relative creep behaviour of FRP reinforced beams regardless of FRP type. It is noted that the simulated beams are loaded under a common dead load and the timber is subjected to a different maximum bending stress dependent of the elastic modulus of the FRP type used. In future studies, the influence of bending stress must be examined in addition to examining different percentage areas of reinforcement prior to the provision of reliable modification factors for design purposes. This validated model is a useful tool that can be used to investigate such influences on the long-term behaviour of FRP reinforced beams, resulting in significant economic and time savings normally associated with experimental tests.

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