Creep Behaviour of Heterogeneous Timber-UHPFRC Beams Assembled by Bonding: Experimental and Analytical Investigation

K. Kong, E. Ferrier, L. Michel

Abstract—The purpose of this research was to investigate the creep behaviour of the heterogeneous Timber-UHPFRC beams. New developments have been done to further improve the structural performance, such as strengthening of the timber (glulam) beam by bonding composite material combine with an ultra-high performance fibre reinforced concrete (UHPFRC) internally reinforced with or without carbon fibre reinforced polymer (CFRP) bars. However, in the design of wooden structures, in addition to the criteria of strengthening and stiffness, deformability due to the creep of wood, especially in horizontal elements, is also a design criterion. Glulam, UHPFRC and CFRP may be an interesting composite mix to respond to the issue of creep behaviour of composite structures made of different materials with different rheological properties. In this paper, we describe an experimental and analytical investigation of the creep performance of the glulam-UHPFRC-CFRP beams assembled by bonding. The experimental investigations creep behaviour was conducted for different environments: in- and outside under constant loading for approximately a year. The measured results are compared with numerical ones obtained by an analytical model. This model was developed to predict the creep response of the glulam-UHPFRC-CFRP beams based on the creep characteristics of the individual components. The results show that heterogeneous glulam-UHPFRC beams provide an improvement in both the strengthening and stiffness, and can also effectively reduce the creep deflection of wooden beams.

Keywords—Carbon fibre-reinforced polymer (CFRP) bars, creep behaviour, glulam, ultra-high performance fibre reinforced concrete (UHPFRC).

I. INTRODUCTION

GLULAM is a type of structural timber that has been and remains a widely used structural material. Timber is more environmentally friendly than many other materials thanks to advantages such as its availability and renewability. However, glulam members, such as any other building materials, have their disadvantages. As a natural material, mechanical properties are not the most reproducible and uniform. In spite of that, glulam is a material with adequate strength both in tension and compression; however, its relatively low stiffness has often been a limiting factor in the designs. As a result, designs are often controlled by deflection limits. Furthermore, glulam beams must be deeply related to satisfy serviceability conditions.

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To fulfil the aim of improving the performance of the timber structural, including stiffness and ultimate bending load, reinforced timber (Timber-UHPFRC) has been developed for several decades. The first idea to ensure better performance in flexing wooden beams is to combine them with other materials, such as composite elements or hybrids, as suggested by many authors [1]-[3]. According to Ferrier [4], it is necessary to develop hybrid systems that focus on the ecology, economy and performance of the final product. This solution allows for reducing the height of wooden beams and can also increase the load capacity and stiffness of such hybrid structures. To improve the mechanical behaviour in flexure for large beam spans or high loading, one of the solutions corresponds to inserting carbon fibre-reinforced polymer (CFRP) on the lower part of the cross section of the glulam beam.

However, in the design of wooden structures, in addition to the criteria of strengthening and stiffness, deformability due to the creep of wood, especially in horizontal elements, is also a design criteria. Several studies on the creep response of mixed wood-concrete beams or wood reinforcements, including [5], [6], showed that the creep of wood was much more important than other reinforcement materials. Glulam, UHPFRC and CFRP may be an interesting composite mix to respond to the issue of creep behaviour of composite structures made of different materials with different rheological properties.

This paper presents the experimental results and iterative, incremental analytical modelling conducted to investigate the creep behaviour of glulam-UHPFRC-CFRP heterogeneous beams under long-term loading. While the short-term behaviour of hybrid beams is evaluated by using a bending static test according to ASTM D198 [7], the creep behaviour is obtained by conducting a bending test under constant long-term loading in different environments: in- and out-house. The analytical model used to investigate the creep behaviour of the timber-UHPFRC composite beams was based on the strain compatibility, and the equilibrium of internal forces in each section, which considers the influence of the rheological properties of component materials, such as shrinkage, the creep coefficient and the environmental changes. The result of the developed analytical model was compared with measured data from an experimental loading test of a period for approximately one year.

II. EXPERIMENTAL PROGRAM

The four-point bending tests, according to ASTM D198 [7],

were conducted by using sensors from the LGCIE Site Bohr laboratory to evaluate the creep behaviour of hybrid beams in different environments, both in- and out-side. The properties of the materials used for internal strengthening were discussed to understand the behaviour of the glulam-UHPFRC beams. The concept of composite materials and timber beams reinforcement techniques are presented. The detailed description of the geometry and fabrication of the specimen tested is also addressed.

A. Materials and Methods

The materials used in the manufacture of hybrid beams are glulam, ultra-high performance fibre reinforced concrete (UHPFRC) Ductal®-FM Gray type, carbon fibre-reinforced polymer rebar (CFRP) and an epoxy adhesive Sikadur®-31 DW type. The glulam beam used in this study was of the GL24 h flexural strength class of the Spruce group, which is resinous and widely used in construction in France. This type of beam is 97 % solid wood and was delivered by the supplier MARGUERON. The ultra-high performance fibre reinforced concrete (UHPFRC) Ductal®-FM Gray type is produced by adding straight metal fibres (14 mm in length and 0.185 mm in diameter) to a dense matrix; the total percentage of fibre is 2 %. The matrix is 4.5 % fluidizing, 3 % accelerator and the ratio of water/cement is 0.2. The CFRP rebars were distributed by Pultrall.inc under the trademark V-Rod. The mechanical properties of the timber, UHPFRC and CFRP rebars are shown in Table I.

TABLE I
PARAMETERS OF MECHANICAL BEHAVIOUR LAW

Material	Symbol	Quantity	Units	Value
Ultra-high performance concrete (Ductal®)	f_{ctj}	tensile elastic strength	MPa	9
	ε_ε	elastic strain	%	0.02
	f_{ct}	tensile limit strength	MPa	17
	$\varepsilon_{0.3\%}$	tensile strain at 0.3 %	%	0.3
	$\varepsilon_{1\%}$	tensile strain at 1 %	%	1
	$\varepsilon_{\lambda\iota\mu}$	limit strain	%	10
	$\varepsilon_{\beta\chi}$	compressive limit strain	%	0.3
	f_{cc}	compressive strength	MPa	150
	E_c	young's modulus	MPa	50000
Timber (GL24 h)	f_{glt}	tensile strength	MPa	35
	E_{glt}	tensile Young's modulus	MPa	11600
	f_{glc}	compressive strength	MPa	24
	E_{glc}	compressive young's modulus	MPa	13400
	f_{sh}	shear strength	MPa	3.5
CFRP Rebars (Φ10)	$f_{FRP\ r}$	tensile strength	MPa	1900
	$\varepsilon_{\rho\varepsilon}$	tensile limit strain	%	1.35
	E_r	young's modulus	PMa	140000

Timber, UHPFRC and CFRP are assembled by an epoxy seal thin (about two millimetres). Fabrication took place in three distinct stages. The first was devoted to preparing the CFRP rebars, which included bonding the strain gauges on the rebars before positioning them into the grooves on the intrados of the glulam beams, which is called the Near-Surface-Mounted (NSM) method [8], or into the concrete planks. The

second step was to prepare the UHPFRC planks by moulding, casting and curing them. The preparation of the surfaces of the concrete planks by sandblasting was needed before bonding. The final step involved gluing the UHPFRC planks on the top and bottom faces of the glulam beams. The bonding allows a perfect adhesion between each layer to be obtained and a continuous strain distribution between layers to be assumed, as shown by [9].

The selected configuration for the beams has a constant section over the whole length (L) of the beam equal to 5,500 mm and the values of width x height of the section as 315 mm x 90 mm. Hybrid beams were manufactured in two configurations. The first configuration beam is constituted by an upper layer of 45 mm of the UHPFRC, a glulam beam which has been strengthened by two CFRP bars. It was called BLC-P45-C. The second configuration is composed of an upper layer of 20 mm of UHPFRC, a glulam beam and a lower layer of 25 mm of UHPFRC reinforced by two CFRP bars, called BLC-P20-PC25. All cross-sections of the three types of hybrid beams studied are illustrated in Fig. 1.
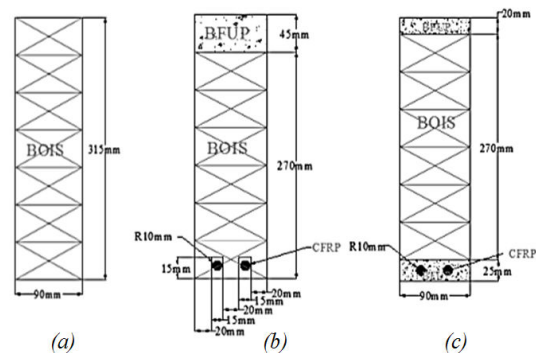

Fig. 1 Cross-sections of the beams (a) Reference, (b) BLC-P45-C, (c) BLC-P20-PC25

B. Flexural Long-Term Test Setup

A total of eight beams were tested to investigate the creep behaviour of hybrid beams under a constant load from 20 % to 40 % of the failure loading of reinforced beams. Five beams were examined in a sheltered environment (Fig. 2).

The other three beams were tested out-house environment (Fig. 3). All beams were tested in 4-point bending according to ASTM D198 [7]. Throughout the tests, the mid-span deflection, strains in the concrete layers, wood and CFRP composite were measured. The relative humidity and temperature were continuously monitored. The mid-span deflection was measured by using an LVDT and strains were measured by using a strain gauge extensometer. The results were obtained twice a day for over a year. Before the tests, the beams were conditioned to a mean moisture content of 12% and a temperature of 20 °C.

Sheltered environment-experiments started under a constant load of 24 kN in the laboratory with temperatures from 20-25 °C and a relative humidity between 40 and 60%.
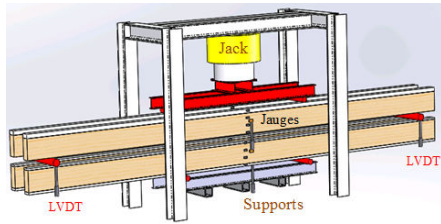
Fig. 2 Creep test setup in a controlled environment

These climatic conditions can be considered as Service Class 1, according to Eurocode 5 [10]. A non-reinforced and four reinforced beams were examined in this controlled environment by employing two series of the four adjustable linear supports creep setup. Each series was capable of loading two specimens at virtually identical constant loads. It should be noted that to make the testing more efficient, as seen in Fig. 2, two specimens of each series were set one on top of the other in the reverse direction. This means that the beam on top is bottom-up and the one on the bottom is upside-down; the beams were separated by two roller supports. As seen, these supports are the support for the top specimens; in contrast, the two roller supports act as the loading points for the bottom specimens. The load was applied by a hydraulic jack with a capacity of 300 kN, which was coupled to the top beam to transfer the same load to the between-beams support. The two roller supports now became the loading points and evenly distributed the load through the bottom beam to the bottom supports.
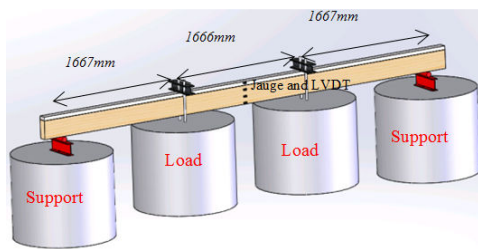

Fig. 3 Creep test setup in an uncontrolled environment

The total load applied to the creep test in an uncontrolled environment was 45 kN, as shown in Fig. 3. This load allowed a stress level in the wood of less than 25 % of the failure stress. Three hybrid beams were tested in uncontrolled laboratory conditions, which included minor changes in temperature and relative humidity during the testing period. The variations of the temperature and relative humidity of the wood recorded are given in Fig. 4.

III. Static Behaviour of Glulam-UHPFRC Beam

Comparisons of the experimental of the behaviour of the hybrid beams with the reference beam are shown in the curve (Fig. 5). The analysis of the load-displacement curves indicates that there are two or three distinct stages of behaviour during the test, corresponding to the configuration of beams and the level of damage in the constituent materials (concrete, reinforcement bars, and wood). For all beams, the

first stage of behaviour was the linear behaviour of the structure, from the beginning of loading to 70 % of the final failure. In this stage, the section was uncracked when the beam exhibited considerable bending stiffness. The second stage was counted from the moment when the first stage was finished to when the load reached approximately 85 % of the failure load. The behaviour of the beams was changed to slightly plastic (BLC-P45-C). At this point, the first cracking occurred by exceeding the compressive strength of the top UHPFRC plank. This failure can be observed by the discontinuity of the load-deflection curve (Fig. 5).
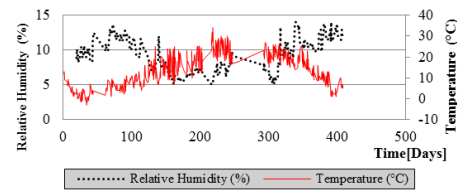

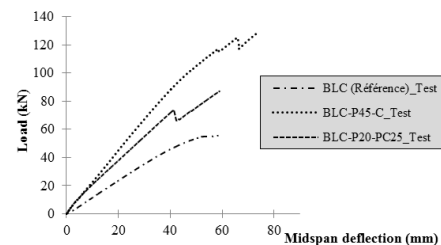Fig. 4 Internal relative humidity of the wood and outdoor ambient temperature

Fig. 5 Load-displacement curve at mid-span

Beyond this first rupture, the collaboration between the wood and concrete disappears and the system behaves as the glulam beam reinforced with only CFRP rebar. The final failure of the hybrid beam took place by exceeding the tensile stress in the fibre of the bottom layer of the beam section.

At the ultimate load level, various failure modes were observed, depending on the characteristics of the beam. In general, the reinforced beams permit higher stress at failure in each material and increase the performance of the beam. Compared to the reference beam, the increase in ultimate load varied between 50-130% and between 70-90% in bending stiffness, depending on the beam properties. Another common point for hybrid beams is a similar failure mode (Fig. 6), with no slip between the glulam/UHPFRC interface and UHPFRC/CFRP during the test.

Fig. 6 Failure modes (a) failure of UHPFRC plank, (b) failure of timber beams in tensile (c) failure of CFRP and collage

IV. Analytical Modelling

The iterative analytical method was developed to analyse

the creep behaviour of wooden beams reinforced by UHPFRC and CFRP based on the short- and long-term characteristics of individual components. Because the stress levels in the CFRP were relatively weaker than the ultimate strength of the CFRP, the creep of CFRP has been neglected. When the stresses are less than 40% of the short-term strength, the timber can be considered as a linear viscoelastic material in a controlled environment, while in an unstable environment, the viscoelastic behaviour of the timber becomes non-linear [11].

A. Simplified Analytical Approach

A model to analyse the wood-concrete long-term behaviour has been proposed by using a classic, simplified analytical approach [12] according to Eurocode 5 - Part 1-1 and 2 (CEN 1995, 1996) [10]. This approach has been improved by Fragiacomo [13], taking into account the mechano-sorptive creep phenomena, shrinkage of concrete. The creep coefficient depends on the moisture content, variation of the temperature and relative humidity of the environment [14]. The global creep behaviour is taken into account by using the effective modulus method with the replacements of the elastic modulus of the wood E_{gl} and concrete E_c with an effective modulus of wood $E_{gl,eff}$ (t) and concrete $E_{c,eff}$ (t) in the static calculation model.

The viscoelastic creep of UHPFRC, according to recommendations of the AFGC [15], is inserted into the calculation of the flexural stiffness (1).

$$E_{c,eff}(t) = \frac{E_c}{1 + \phi_c(t, t_i)} \tag{1}$$

In addition, the viscoelastic creep and mechano-sorptive of wood are also involved in the form of the rheological model, given by the Annex B of the Eurocode 5-Part 1-1 [10].

$$E_{gl,eff}(t) = \frac{E_{gl}}{1 + \phi_{gl}(t, t_i)} \tag{2}$$

where, ϕ_c and ϕ_{gl} are the creep coefficients of concrete and wood, respectively. The evolution over time of the concrete creep coefficient ϕ_c can be calculated by using the provisional recommendation formulas of the AFGC. For wood, the current version of Eurocode 5 suggests a final value (for 50 years of charging time) creep coefficient ϕ_{gl}, which is denoted by K_{def} for different classes of service.

B. Dependence of the Creep Coefficient on the Moisture Content

When a mechano-sorptive effect is taken into account, the explicit dependence of the creep coefficient of the wood moisture content is assumed according to the model [16]:

$$\phi_c(t, t_i) = \left(\frac{t - t_i}{t_d}\right)^m + \phi^\infty \left[1 - e^{-c\frac{2\Delta u(t - t_i)}{100\Delta t}}\right] \tag{3}$$

where, t_d, m, ϕ^∞ and c are parameters of the materials taken to

be equal to 29500 days, 0.21, 0.7 and 2.5, respectively. Δu is the amplitude of the moisture content during the period of time Δt. $(t-t_i)$ is the loading time.

C. Shrinkage Effect

The shrinkage of UHPFRC is very low [17]; however, it is important to take into account the effect of concrete shrinkage in the long-term behaviour analysis of a composite beam. The hydro-viscoelastic solution, because of shrinkage of the concrete, is evaluated with the elastic formulas by using the effective data modules with (4):

$$\Delta\varepsilon_n = -\varepsilon_{cs}(t) + \varepsilon_{cs}(t_s) \tag{4}$$

$$E_{c,eff}(t) = \frac{E_{cj}}{1 + \phi_c(t, t_s)} \tag{5}$$

where, ε_{cs} is the concrete shrinkage deformation at a time t from the casting of the concrete t_s. Concrete shrinkage can be measured according to the formulas proposed by the recommendations of the AFGC on UHPFRC [9].

Effective shrinkage, according to (5), considers the difference between the creep caused by a constant external load and a variation of moisture.

D. Analysis Algorithm

As mentioned above, an analytical model was developed to simulate the creep behaviour of the hybrid beams based on the strain compatibility and equilibrium of internal forces in the section by using the effective modulus method. This simply means that the rheology behaviour of wood and UHPFRC is inserted in the model to identify the creep behaviour of the hybrid beams under constant loading in a period of time.

The laws of behaviour of wood, UHPFRC and CFRP and the geometric information, the constant loading, moisture content and the loading duration are input data. The relevant geometric variables are the height, the width of the beam, the quantity of CFRP, the thickness of the UHPFRC planks, the span and the position of external loads. To begin the calculation procedure, the initial value (t=0) is given. A curvature φ and position of the neutral axis z_g are assigned arbitrarily or can also start from a value φ_0 and z_0 calculated according to the elastic theory at time t=0.

The modules of the elasticity of concrete and wood that depend on time are obtained from (1) and (2). The strain is calculated at each increment of time steps and the constraint is derived by using the stress-strain relationship for each material. Multiplying the constraint by the area of the layer of material gives the compressive and tensile forces in a section. Once all the forces are calculated, the balance of the force section is checked with the following equation:

$$\sum F = 0 = F_r + F_c(t) + F_{gl}(t)$$
$$= A_r E_r \varepsilon_r + \sum_{i=1}^{n} A_c(i) E_{c,eff}(t)\varepsilon_c(i) + \int_0^h A_{gl} E_{gl,eff}(t)\varepsilon_{gl}(z)dz \tag{6}$$

The internal moment is determined to compare with the

external moment.

$$\sum m_{int}(t) = m_r + m_c(t) + m_{gl}(t) = m_{ext} \qquad (7)$$

with

$$m_r = A_r E_r \varepsilon_r (d_r - z_g) \qquad (8)$$

$$m_c = \sum_1^i A_c(i) E_c(t) \varepsilon_c(i)(d_c(i) - z_g) \qquad (9)$$

$$m_{gl} = \int_0^h A_{gl} E_{gl}(t) \varepsilon_{gl}(z) z dz \qquad (10)$$

If either or both (6) or (7) are untrue, then adjusting z_g and/or φ is needed and the equilibrium is checked again. The position of the neutral axis z_g is moved upward and the process is repeated until the sum of the compressive forces in the section balances the sum of the tensile forces. Likewise, the curvature φ is adjusted and the process is repeated until (7) is satisfied. Once the iterative procedure has converged to equilibrium, the distributions of strain and the mid-span deflection of the hybrid beams are determined in a period of time given. A flow chart of the calculation procedure is shown in Fig. 7.

The maximum deflection of a timber-concrete hybrid beam depend on time is given by (11).

$$f(t) = \frac{3L^2 - 4a^2}{24} \left[\frac{M_{ext}}{EI_{eff}(t)} \right] + \frac{M_{ext}}{(G_{gl} \cdot A_{gl})} \qquad (11)$$

where L is span length, a is the distance from the support to the loading point, G_{gl} is the shear modulus of the glulam and EI_{eff} is the homogenized flexural rigidity, which can be obtained from (12) according to [5].

$$EI_{ef} = E_{gl,eff} \cdot I_{gl} + \sum_{i=1}^2 E_{ci,eff} \cdot I_{ci} + E_r \cdot I_r + E_{gl,eff} \cdot A_{gl} \cdot (a_{gl})^2$$
$$+ \sum_{i=1}^2 E_{ci,eff} \cdot b_{ci} \cdot h_{ci} \cdot (a_c)^2 + E_r \cdot A_r \cdot (a_r)^2 \qquad (12)$$

V. EXPERIMENTAL–NUMERICAL VALIDATION

The above mentioned four-point bending creep setup in the different environments, both in- and out-house (Fig. 2 and Fig. 3), and procedure were employed to investigate the creep behaviour (time-dependent) response of the heterogeneous beams. The applied loads for the glulam and reinforced beams were not quite the same; however, the creep deflection vs. time curve and the evolution of strain as a function of time can demonstrate the phenomenon that affects the creep deflection.

A. Creep Behaviour in a Sheltered Environment

The principal measurement made during this test is the distribution of the strain and deflection at mid-span of the beam, which was caused by the constant load in a sheltered environment with an ambient temperature of 20-25°C and relative humidity between 40 and 60%. The load was equal to 18 kN for the non-reinforced glulam beam and 24 kN for

hybrid beams that were at almost 30 % of the failure load (Fig. 5).

Fig. 8 shows the evolution of the deflection versus time from measurements and analytical modelling. We found that the analytical method gives satisfactory results. It should be noted that this method takes into account the effects of the creep of wood and concrete as well as concrete shrinkage with relative humidity by using a simplified analytical approach based on the equilibrium beam section.
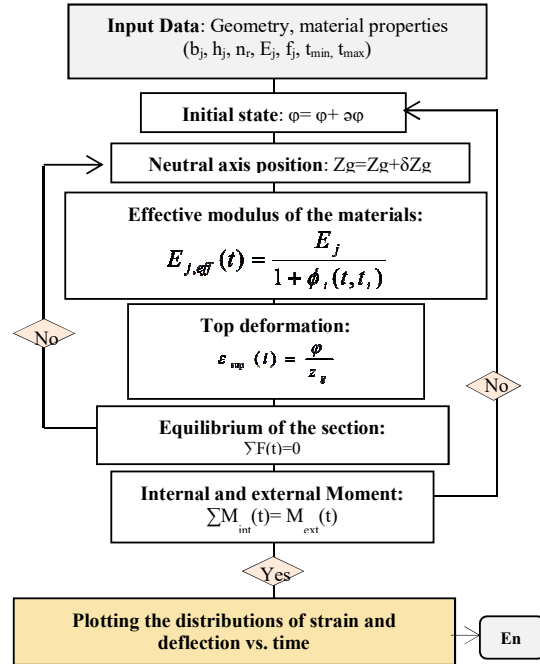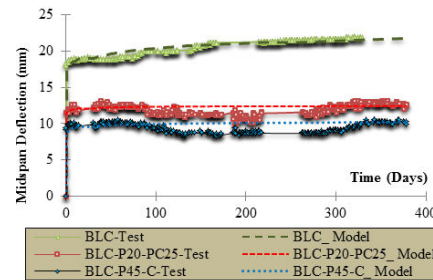

Fig. 7 Flow chart- Creep analysis

Fig. 8 Creep response of hybrid beams in a sheltered environment and comparison with analytical modelling

The first global remark is that the creep of heterogeneous glulam-UHPFRC beams is less important than that of the non-reinforced wooden beam, through the combined effects of the compressive UHPFRC and tensile CFRP. Indeed, the evolution of the deflection at mid-span of the glulam beams shows that it increases gradually until the end of the test. This deflection is increased by 30 % of its value at the beginning. The mechano-sorptive creep of the wood beam was not recorded due to a controlled environment. The creep deflection vs. time curve of the reinforced beam indicates that

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the delayed effects are relatively small. This is due to several simultaneous phenomena. We observed that the deflection increases during the early part of the test under the action of the creep of the wood and concrete. This deflection decreases dramatically from the hundredth day due to wood shrinkage induced by lower internal wood moisture in the sheltered environment of the laboratory. The deflection increases again when the creep effect of the materials is greater than the effects of shrinkage. This phenomenon is not visible for the glulam beams because the creep of wood is predominant.

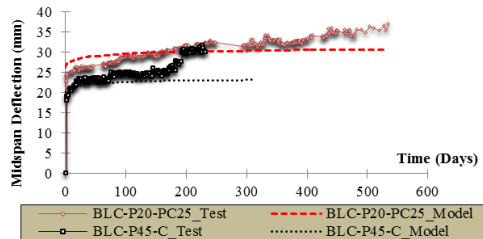*B. Creep Behaviour in an Out-House Environment*

Fig. 9 Creep response of hybrid beams in an out-house environment and comparison with analytical modelling

The relationship between fluctuations of the relative humidity and temperature was presented Fig. 4. In Fig. 9, the experimental and modelling results concerning the creep behaviour in an out-house environment are equally described. Conversely to the creep test results in the sheltered environment, creep behaviour in the variable environment outside the laboratory shows that the delayed effect of the wood and concrete plays a very important role in the evolution of the deflection of hybrid beams. The deflections are increased by 40% compared to their value at the beginning. Hygrothermal variation causes an increase in the deflection at mid-span of the hybrid beams. Furthermore, it should be noted that there was a failure of the beam named BLC-P45-C caused by instability of the whole system after 240 days of loading due to lateral movement. The reason behind this failure is the debonding between the concrete plank and glulam beam, which accrued approximately 170 days after loading. This debonding affects the global stiffness of the structure, which leads to the increase of deflection. Moreover, when the compression stress reaches a critical value, especially depending on the condition of the support and distribution of the bending moment, the lateral movement develops gradually until failure. However, this phenomenon was not considered in the analytical modelling as a result of simplifying the calculation. Table II contains a summary of the percentage increase of mid-span deflection as well as the comparison of the experimental and modelling results of the creep behaviour of the hybrid beam with the reference beam. The differences between the experimental determinations and numerical predictions of the mid-span deflections are between 5% and 15% at 360 days.

TABLE II
COMPARISON OF EXPERIMENTAL AND THEORETICAL VALUES

SPECIMEN		Percent increase of mid-span deflections (%)					
		Controlled Environment			Uncontrolled Environment		
		1 DAY	170 days	360 days	1 DAY	170 days	360 days
BLC	The	1.6	19.5	25.5	-	-	-
	Exp	1.7	16.1	30			
BLC-P45-C	The	1.1	12.4	14.6	6.5	24.7	35.5
	Exp	1.1	-5.9	10.3	7.2	31	40.1
BLC-P20-PC25	The	0.6	6.5	9.9	1.1	26.2	37
	Exp	4.1	-0.8	11.1	1.7	35.4	41

The = Theory, Exp = Experimental

VI. PARAMETRIC STUDY

The analytical model that was developed to simulate the long-term responses of the timber-concrete beam was then employed for conducting the series of parametric studies. The objective was to investigate the influence of the volume fraction of concrete and CFRP on the long-term performance of reinforced timber beams (BLC-P45-C) in an uncontrolled environment earlier (i.e., those in Fig. 3).

The influence of the volume fraction was examined by varying the thickness of the concrete layers. As shown in Fig. 10, the total width of the Timber-UHPFRC remained constant (i.e., 90 mm), equal to the timber beam's width shown in Fig. 1 and volume of CFRP is also constant (i.e., $2\phi10$ mm). Therefore, the volume (area) fraction of the concrete planks in the entire beam was 10, 20, 40, 50, and 60%, respectively.
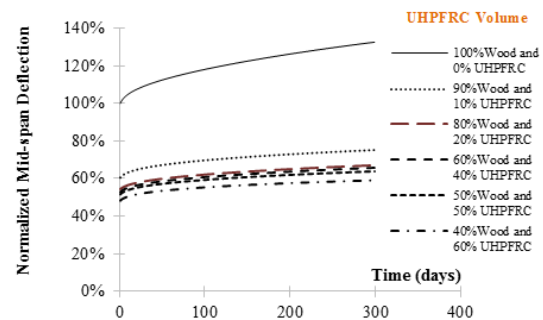

Fig. 10 Creep response of homogeneous beam with varying wood-UHPFRC sections

The Normalized mid-span deflection vs. Time curves in Fig. 10 show the influence of the properties of the material and the effect of the relative size of the UHPFRC section on creep behaviour of beams.

The effect of high stiffness of concrete is to decrease the elastic bending stiffness EI of the hybrid beam, and this leads the global creep mid-span deflection decrease. When the UHPFRC component is relatively important, the mid-span deflections decrease, as well as the creep deflection. As can be seen, the initial deflection of beams decreases considerably with only 10% of concrete; this trend also continues when considering the beam's long-term performance. In the case of 20 to 50% of volume of concrete, however, the creep

deflections are decrease similarly. Therefore, the long-term response is dependent on the optimum volume of the concrete, whenever the adhesive is assumed to act perfectly between wood and concrete.
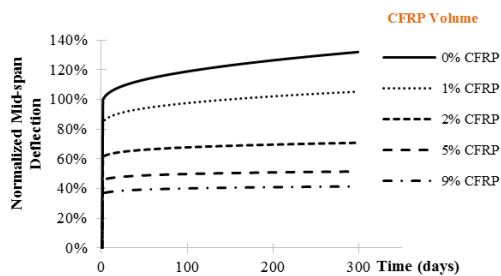

Fig. 11 Creep response of homogeneous beam for different volume fractions of CFRP

The influence of the volume fraction of CFRP was examined by varying the quantities and diameter of the CFRP rebars. Four configurations (i.e., $2\phi10$, $2\phi20$, $2\phi30$, and $4\phi10$), which are 1, 2, 5, and 9% respectively of volume of CFRP in the entire beam, were examined. The geometry and boundary conditions of the beams were kept the same as the beams studied.

The changes in mid-span deflection, normalized with respect to the initial deflection of unreinforced beam, over time increments for the heterogeneous timber-UHPFRC beams reinforced with CFRP at the abovementioned volume fractions are illustrated, Fig. 11. Similarly to concrete, the effect of high stiffness is decrease the creep response in hybrid beam. As can be seen, the initial mid-span deflection decreases considerably by increasing the CFRP volume fraction.

VII. CONCLUSION

The long-term experimental tests were performed in different environments to examine the creep behaviour of the heterogeneous Timber-UHPFRC beams. These experimental tests were also employed to examine the accuracy of the analytical model for predicting the instantaneous and creep response of heterogeneous glulam-UHPFRC beams based on their constituents. The results of the theoretical analysis correspond to the measured values of the deformation; the differences vary between 5% and 15%.

The Timber-UHPFRC beams provided the increased bending stiffness about 70-90% over that of the glulam section, due to the high Young's modulus of the UHPFRC planks. Additionally, the high tensile strength of the lower concrete plank, reinforced with CFRP reinforcement bars, leads to a significant increase in the ultimate capacity between 50 and 130% compared to that of a glulam beam of similar size.

In addition to the increasing in strength and stiffness of the glulam beams, the reinforced beam is also found to be improved and thus the deflection of the beam could be reduced; the reinforcement could even further reduce the long-

term deflection due to the very low creep effect on the reinforcement material. It can also effectively reduce the creep phenomenon of wooden beams, especially in low-stiffness wood species. The creep deflection vs. time curve in different environments demonstrates that the heterogeneous glulam-UHPFRC beams are sensitive to environmental conditions. In the sheltered environment, the creep deflection of the reinforced beam increases slightly and decreases occasionally throughout the test. In contrast, the deflections are increased by 40% compared to their value at the beginning.

This study should be completed by numerical modelling considering all the effects of hygro-expansion, including mechano-sorptive creep, by taking into account the effect of temperature variations on the diffusion phenomenon. These transfers affect the mechanical properties of wood. The present study was limited to the analysis of an isostatic of the mixed structure in particular climatic conditions. It is interesting to consider more complex structures with different combinations of hydro-mechanical loads, which would adapt the design criteria depending on the types of loading. The debonding between timber and concrete in an uncontrolled environment should be an interesting issue to investigate. Moreover, the study of the fatigue behaviour and under dynamic loads could be performed to complete the analysis of the mechanical behaviour of this type of hybrid beam.

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