CREEP BEHAVIOR OF COMPOSITE GLULAM-UHPFRC BEAMS CONNECTED BY BONDING

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Abstract

In wood-based structure design, in addition to the criteria of strengthening and stiffness, the criterion of deformability due to the creep of wood, especially in horizontal members, is a factor that often limits the availability of design. New developments have further improved structural performance, such as the strengthening of timber (glulam) beams 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. Glulam, UHPFRC and CFRP may be an interesting composite mix for responding to the problem of the creep behaviour of composite structures made of different materials with different rheological properties. This paper describes an experimental and analytical investigation on the short-term and long-term performance of hybrid beams in different environments. The results indicate beams provide an improvement in both strengthening and stiffness and can also effectively reduce the creep deflection of wooden beams.

Résumé

Dans la conception de structure à base de bois, en plus des critères de résistance et de raideur, le critère de déformabilité due au fluage du bois, en particulier dans les éléments horizontaux, est un facteur qui limite souvent la conception. De nouveaux développements ont encore amélioré les performances structurelles, comme le renforcement des poutres en bois (Bois Lamellé Collé) par collage de matériaux composites combinés avec un béton de fibres ultra-haute performance (UHPFRC) renforcé avec ou sans barres de polymère renforcé de fibres de carbone (CFRP). Le Bois Lamellé collé et le béton UHPFRC peut être un mélange de matériaux intéressant pour répondre au problème du comportement au fluage de structures composites faites de matériaux différents dont les propriétés rhéologiques sont variables. Le présent article décrit une étude expérimentale et analytique sur les performances à court et à long terme des poutres hybrides dans différents environnements. Les résultats indiquent que le comportement des poutres sont améliorés à la fois en résistance, vis-à-vis de la rigidité mais aussi du fluage.

1. INTRODUCTION

Glued, laminated timber, also called glulam, is a type of structural timber that has been and remains a widely used structural material. Glulam is more environment-friendly than many other materials because of advantages such as its availability and renewability. The use of glulam has increased dramatically after the commitment of the European Union to reduce greenhouse emissions. 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 design. As a result, design are often controlled by deflection limits. Furthermore, glulam beams must be deeply related to satisfy serviceability conditions. To fulfil the aim of improving the performance of the glulam's structure, including stiffness and ultimate bending load, reinforced glulam has been developed for several decades. In a beam bending stiffness can be improved by increasing the inertia or and by using material with higher Young modulus.

The first idea to ensure better performance in beams is to combine them with other materials, such as composite elements, as suggested by many authors [1], [2] and [3]. Furthermore, according to Ferrier [4], it is necessary to develop hybrid systems that focus on the ecology, economy and performance of the final product. The recent development of ultra-high performance fibre reinforced concrete (UHPFRC) shows that this concrete has better characteristics than ordinary concrete. This solution allows for reducing the height of wooden beams and can also increase the load capacity and stiffness of such hybrid structures. It has been shown from the results that reinforced beams could have considerably increased strength, by even as much as twice. On the other hand, the increasing the serviceability stiffness of glulam-UHPFRC beams due to the higher Young's modulus of UHPFRC as well as the presence of the short-fibre in concrete can decreases the elastic response and significantly reduces the long-term deflections. To improve the mechanical behaviour in flexure for large beam spans or high loading, one of the solutions corresponds to introduce carbon fibre-reinforced polymer (CFRP) on the lower part of the cross section of the glulam beam. The main advantages of using composite rebars compared to steel reinforcement are their resistance to corrosion and being lightweight, making them (CFRP reinforcements) highly suitable for strengthening wooden beams [5]. Furthermore, the incorporation of CFRP reinforcement allows the use of higher design stresses and could also reduce creep deformation. However, since the stress levels in the CFRP bars were relatively lower than CFRP's ultimate strength, the creep deformation in CFRP was ignored. In addition, the difference in creep response of beam components may cause the stress redistribution phenomenon in sections [6]. Several studies on the creep response of mixed wood-concrete beams or wood reinforcements, including [7] and [8], showed that the creep of wood was much more important than other reinforcement materials. One problem with using an hybrid system is the incompatibility between materials, especially timber (glulam); most notably, the differences in hydro-expansion and creep have resulted in failure in the bond-line between timber and a reinforcement, leading to delamination. Modern adhesives have minimized this problem and thus reinforcing timber beams is now a real possibility for improving the performance of timber structures [9]. New developments have continued, for example, [10] and [11-14], to further improve structural performance by integrating ultra-high performance fibre reinforced concrete (UHPFRC) and carbon fibre-reinforced polymer rebars (CFRP). An alternative solution is to carefully increase the tension stress in FRP bars at failure; this is the aim of mixing FRP and ultra-high performance fibre reinforced concrete (UHPFRC) [4]. The structural performance of wood, UHPFRC and CFRP are linked to the necessity to respond to the problem of the creep behaviour of composite structures made of different materials with different rheological properties.

This paper presents the experimental results to investigate the behaviour of glulam-UHPFRC-CFRP heterogeneous beams under short- and long-term loading. While the short-term behaviour of hybrid beams is evaluated by using a bending static test according to ASTM D3737 [12], the creep behaviour is obtained by conducting a bending test under constant long-term loading in different environments: in- door and out-house door conditions.

2. EXPERIMENTAL PROGRAM

The four-point bending tests were used to characterize the short-term mechanical behaviour of reinforced wooden beams. The properties of the materials used with the internal mechanisms of the redistribution of effort under a bending load were discussed to understand the behaviour of the glulam-UHPFRC beams. The concept of composite materials and glulam beams reinforcement techniques are presented. The detailed description of the geometry and fabrication of the specimen tested is also addressed.

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. The ultra-high performance fibre reinforced concrete (UHPFRC) 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 conception of such a hybrid section is to employ the best characteristics of each material to increase the ultimate bearing capacity. The carbon fibre-reinforced polymer rebars are used for reinforcement in the tension parts of glulam beams and have demonstrated their effectiveness by increasing flexural strength and stiffness.

Three different beams were studied, the first made only of glulam, the second consist in a compressive plank of UHPC and FRP on the bottom face placed with NSM technics, the last beam is similar to the second but the NSM technics is replaced by a UHPC plank internally reinforced by FRP bars. 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 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 epoxy for bonding was first applied to the concrete plank and then to the glulam timber. Pressure was applied for 24 h and the curing temperature was maintained at 20 °C for 7 days. 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 height x width of the section as 315x90 mm. Hybrid beams were manufactured in two configurations and were selected from the parametric study of Ferrier [4], with the UHPC representing 10 % of the section, for example, the initial bending is increased by 150%. The first configuration beam is constituted by an upper layer of 45 mm of the UHPFRC (15% of the total section), a glulam beam with cross-section 90x270 mm which has been strengthened by two CFRP bars. This CFRP reinforcement, in addition to reduce the influence of creep and shrinkage of wood, also improves the tensile strength parameters of timber beam, which leads to high performance composite system. This first configuration 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. The solution of UHPFRC reinforced to the bottom of the glulam beam is to eliminate the cracks of the lower layer of the beam and also to improve the long-term behaviour of the composite beam. All cross-sections of the two-three types of hybrid beams studied and a reference beam are illustrated in Figure 1.

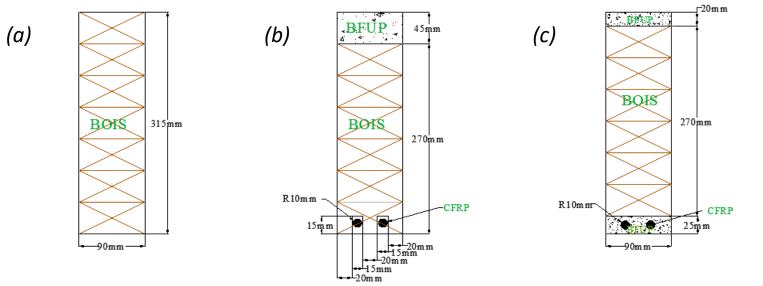

Figure 1. Cross-sections of the beams (a) Reference, (b) BLC-P45-C, (c) BLC-P20-PC25.

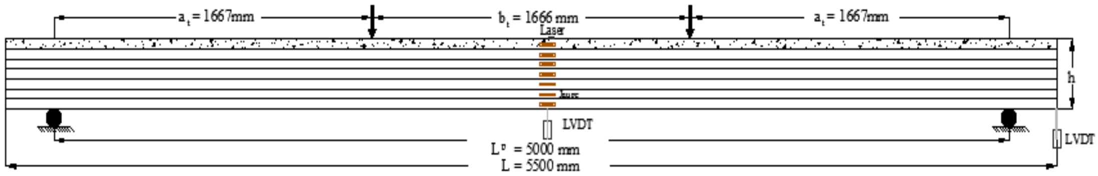

Figure 2. Beam Loading and the deformation-measuring apparatus.

3. SHORT-TERM BENDING TEST SETUP

To determine the load-deflection curve of the heterogeneous beams, the four-point bending test setup was used. The beam span-to-depth ratio Lspan/h was taken as 17 for all the beams tested; the high value for this ratio is anticipated to promote flexural behaviour rather than shear behaviour. The Lspan/h value of 17 corresponds to the standard value proposed by ASTM D3737 [12]. However, no instability occurred during loading in the similar study of Proulx [10]; thus, anti-instability is not necessarily needed. Figure 2 shows the geometry of the four-point bending and the deflection-measuring apparatus. The load was applied by using a hydraulic jack with a capacity of 500 kN. To control the loading, the speed of the displacement of the jack was proposed to be 2 mm/min. The maximum axial strain was located at the mid-span and measured by a strain gauge extensometer, which has a gate length of 30 mm and a resistance of 120 Ohms and was affixed to the CFRP rebars, UHPFRC planks and each layer of the glulam beams.

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 start when the load reached approximately 85 % of the failure load. 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 (Figure 3). Beyond this first failure, 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. The hybrid beams provided the increased bending stiffness due to the high Young's modulus of the UHPFRC planks. The combination with the UHPC, due to its high compressive strength allows a significant increase in the bearing capacity.

A total of eight beams, four of BLC-P45-C, three of BLC-P20-PC25 and a reference beam, 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 tested in a controlled environment. The other three beams were tested outside of the laboratory environment. All beams were tested in 4-point bending according to ASTM D3737 [12]. 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. Results were measured 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. 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 controlled environment with an ambient temperature of 20-25 °C and relative humidity between 40 and 60 %. As the specimens in the present work have the different ultimate load of the short-term test and the creep load levels were chosen to be the same (30 % of the failure load); thus the creep load was equal to 18 kN for the non-reinforced glulam beam and 24 kN for hybrid beams. The relationship between fluctuations of the relative humidity and creep deflection of the reinforced beam is presented in measured. Conversely to the creep test results in the controlled 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. This increasing is affected by the variation of the temperature as well as the wood humidity which firstly caused to increase of the creep strain of the components especially in wood. Therefore, the hydrothermal 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 occurred approximately 190 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. Controlled environment of 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 %. These climatic conditions can be considered as Service Class 1, according to Eurocode 5 [15]. Five beams were examined in this controlled environment by employing two series of the four linear supports creep setup. 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. The test setup was first let free to displace laterally. However, it was noted that there were some difficulties due to lateral movement which caused instability in the whole system after a few minutes of loading. 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 20 % 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 the delayed effects are relatively small. This is due to several simultaneous phenomena. 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.

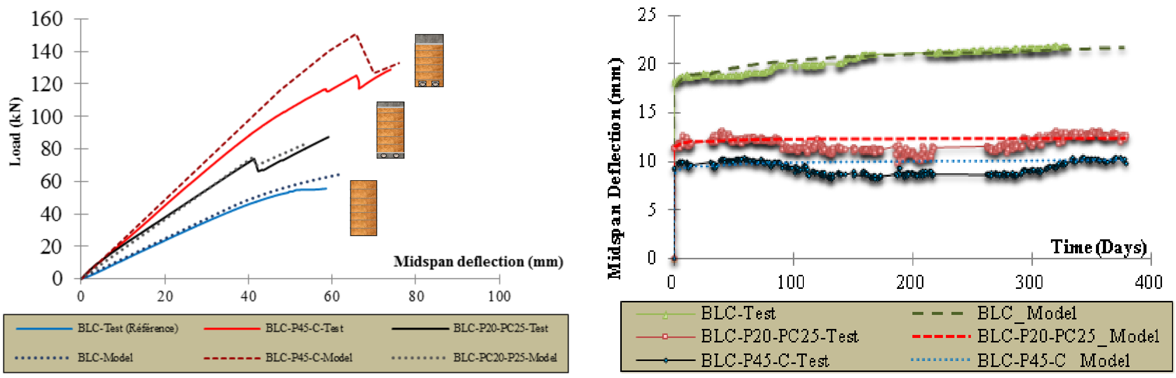

Figure 3. Load-displacement curve at mid-span and Creep response of hybrid beams

Figure 4 describes the evolution of creep strains for each component on more than one layer of the hybrid beams (h=0 corresponds to the bottom surface of a wooden beam). The strain of concrete in a compressive zone in the cross-section of beams increases lightly. The increasing of these strains is mainly affected by the deformation of shrinkage of the concrete. On the wooden side, three strains gauge extensometers were glued to different layers of each beam. The creep strain increases during the early part and decreases from the hundredth day due to wood shrinkage induced by lower internal wood moisture, as mentioned above. As the wood shrinks, the CFRP reinforcement in the tensile zone is compressed and imposes an equal and opposite tensile force on the wood at the level of the reinforcing. Additionally, the difference in creep response of wood and CFRP may cause the stress redistribution phenomenon in the sections; thus, the evolution of the creep strain of CFRP reinforcement follows the fluctuation of the creep strain of wood.   An elactic model using force equilibrium have been develop and used to compare the results, all details of the model is given by Ferrier *et al.* [11].

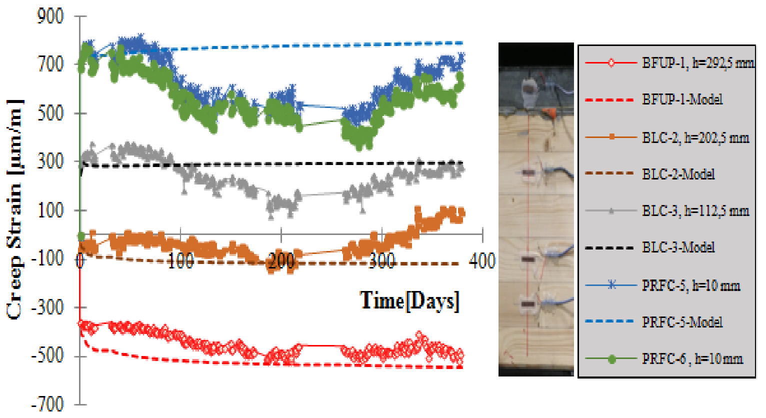

Figure 4**.** Evolution of creep strains for each layer of the hybrid beam (BLC-P45-C) in a controlled environment.

4. CONCLUSIONS

The objective of the present study was to address the short- and long-term performance of heterogeneous glulam-UHPFRC beams. A short-term experimental program was carried out to assess the instantaneous behaviour of the heterogeneous beams. The test results were used to identify the short-term performance of heterogeneous glulam-UHPFRC beams and to approximate the creeping load to apply in the long-term test. The long-term experimental tests were then performed in different environments to examine the creep behaviour of the glulam beams reinforced with CFRP rebars and the concrete planks internally reinforced with or without CFRP reinforcement bars.

- The short-term experimental study shows that the Glulam-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. Result described in this study is a consequence of the increased bending stiffness of the hybrid section 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 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 controlled 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 hydro-expansion, including mechano-sorptive creep, by taking into account the effect of temperature variations on the diffusion phenomenon. Fire behaviour can also be an interesting focus to deal with.

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