STATIC AND DYNAMIC BEHAVIOUR OF HYBRID PANELS AND BEAMS MADE OF UHPFRC, WOOD AND FIBER REINFORCED POLYMER BARS

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Abstract

The main objective of the research project reported in this paper is to develop a new type of high performance light beams or wood panels that will increase the performance of usual beams (timber steel or RC beams) by combining FRP rebars cast in a ultra-high-performance concrete with short fibre reinforcement (UHPC-SFR). The beam is obtained to get a light beam with a high compressive and tensile capacity to sustain high bending moment and to be also shear resistant. The hybrid beam thus obtained possesses a higher bending stiffness than a glulam beam and with a higher ultimate load capacity. The load-displacement and moment-curvature relationships are obtained from 30 large scales beams specimens and 5 wood panels. The results illustrate the potential interest of such composite beam configurations. The dynamic behavior is studied based on the vibration criteria. The technique used to verify vibration criteria is based on EN 1995-1-1 and Eurocode 5. The dynamic behaviour is improved allowing getting higher beams span.

Résumé

L'objectif principal du projet de recherche rapportée dans cet article est de développer un nouveau type de poutres hautes performances ou de panneaux de bois qui permettra d'accroître la performance des poutres habituelles (acier/bois ou poutres en béton armé) en combinant armatures en PRF coulé dans un béton ultra-haute performance avec renforcement de fibres courtes (BFUP-SFR). La poutre est obtenu pour obtenir un poutre légère avec une forte résistance en compression et à la traction pour obtenir un moment résistant plus élevé et d'être aussi résistantes au cisaillement. La poutre hybride ainsi obtenu possède une rigidité de flexion supérieure à une poutre lamellé-collé et avec une capacité de charge ultime plus élevée. La relation charge-déplacement et la relation moment-courbure sont obtenues à partir de 30 poutres de grandes échelles et 5 panneaux de bois. Les résultats montrent l'intérêt potentiel de ces configurations de poutres composites. Le comportement dynamique est étudié sur la base des critères de vibration. La technique utilisée pour vérifier les critères de vibration est basé sur la norme EN 1995-1-1 et l'Eurocode 5. Le comportement dynamique est amélioré permettant d'obtenir des poutres plus performantes.

1. INTRODUCTION

Construction with glued-laminated (glulam) timber structures has increased significantly in Europe in recent years. Since wood is a natural material with a capacity to mitigate the harmful effects of greenhouse gases, its increased use is predictable when sustainable development principles are taken in consideration. As a consequence, the consumption of wood has increased significantly for construction in Europe, to such a level that new ways to optimize its use are now necessary. The greatest opportunity for expanding the use of wood products such as glulam in construction may not be a stand-alone product, but in combination with other materials such as composite or hybrid elements (e.g. fiber-reinforced glulam). According to K.J. Fridley [1], it is necessary to "develop hybrid systems that capitalize on the economy and flexibility of wood and the unique characteristics of other materials to create economy and efficiency in the final product." The main objective when designing such a hybrid section is to make use of the best characteristics of each material. Recent developments in short fiber reinforced concrete (UHPC-SFR) have led to a new cementitious materials [2] with a compressive strength of about 60 MPa, tensile strength of 10 MPa and a young's modulus of 30 GPa [2]. These interesting properties can be useful for casting thin elements in the shape of planks which can be bonded to the upper and lower faces of a glulam section to improve its bending properties, as will be shown in this paper [3, 4]. The fact that UHPC has a high tensile strength allows the use of steel or FRP reinforcement bars in the bottom plank [5]. Saadatmanesh and Buell [6] have noted that when glass FRP reinforcement bars are used to strengthen a glulam beam, they have a positive effect on its bending stiffness and on its ultimate load. It can thus be expected that when FRP reinforcement bars are used to reinforce the bottom of the hybrid beam tested here, they will have a similar effect. FRP reinforcement bars have a tensile strength value between 1200 and 2500 MPa and their Young's modulus in the range of 40,000 to 160,000 MPa. These mechanical properties, combined with their lightness and resistance to corrosion, make them highly suitable for this application. This paper presents an experimental investigation of a new type of hybrid beam. As shown in Figure 1, the hybrid beam is obtained by bonding lamellae of concrete with short fibre (UHPC) to a laminated wood section.

2. EXPERIMENTAL TESTING

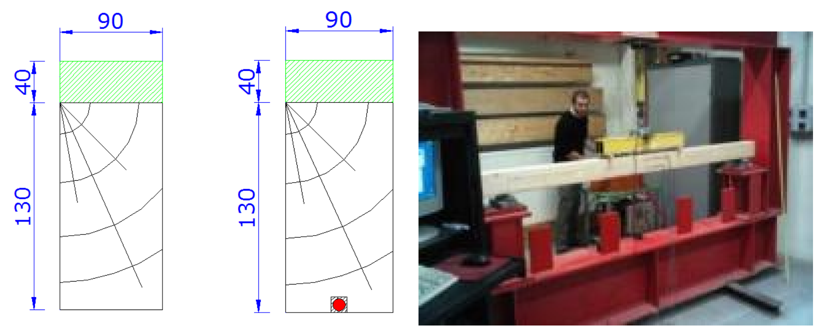
2.1 Beam description

For this part the high performance concrete was done based on a self made concrete in the lab. The high performance concrete lamellae, with a compressive strength of 110 MPa and a tensile strength of 10 MPa, are cast in layers varying in thickness from 1 to 4 cm. In order to increase the ultimate bearing capacity FRP rods were used in the tension part. An experimental program was performed on six hybrid beams and two reference glulam timber beams. The geometrical properties of the specimens are listed in Table 2. The investigated parameters are the span (2 meters), width (90 mm) and total depth (170 mm) of the beam. The core of each hybrid beam is a commercially available glulam timber beam made of Douglas pine with Glh 28 grade. The guaranteed tensile strength of the glulam section was 28 MPa and its guaranteed compressive strength was 30 MPa. The Young's modulus of glulam was taken as 13,400 MPa. The total depth of the hybrid beam was obtained by the addition of top and bottom UHPC-SFR lamellae to the core glulam beam. In order to facilitate a comparison with glulam-only sections, the thickness of the lamellae was chosen to obtain a total depth corresponding to that of the next higher commercially available glulam product. Experimental load-displacement and moment-curvature curves from the 2-meter spans are compared.

The wood-concrete composite beams used in this research were fabricated using the bonded connection as mentioned earlier. In order to increase the bond strength, a primer was first applied on the top and bottom faces of the glulam section. This primer will increase the adhesion between the concrete and the wood. The concrete plank was also sandblasted before bonding. Epoxy bonding system was applied on the concrete plank prior their placement on the glulam timber. To avoid bubbles and voids in the lap joint, pressure was applied on this assembly for about 24 hours. The assembly was cured for 7 days at 20°C room temperature. In total thirty glulam (GL) beams of dimension 2300 x 130 x 90mm were tested in this research.

Twenty beams were reinforced by a plank of high performance mortar and the remaining ten were used as control specimens. Ten out of twenty strengthened beams (BLC + UHPC) were equipped with carbon FRP reinforcement rod, of 10 mm diameter (Table 2), in the tension zone (BLC + UHPC + FRP). The mix design of concrete used in this research work is listed in Table 1.

The reinforcing element plank made of UHPC had a length equivalent to that of the glulam beam length and had a thickness and width of 40 mm and 90 mm respectively. Test beam had a total length of 2.3 m and a span equal to 2 m. The assembly of elements UHPCs and glulam beams is provided by an epoxy adhesive. The same epoxy adhesive was also used at the interface in between the 10 mm CFRP rods and timber by a grooving technique.



BLC-UHPC BLC-UHPC-FRP

Figure 1: Hybrid beams detail and test setup

Table 1: Mortar mix

Water [kg/m^3]	Cement 52.5 [kg/m^3]	Sand [kg/m^3]	Silica fume [kg/m^3]	Superplastiser [kg/m^3]	Accelerator [kg/m^3]	Fibers [kg/m^3]
220	550	1221	44	11	10	60

Table 2: Mechanical properties of CFRP bars

Average strength (MPa)	1899.29
Average Young's modulus (GPa)	144.78
Average ultimate strain (%)	1.312

2.2 Testing device

Figure 2 depicts the test setup used in this research. Test specimens were subjected to four point flexure load test according to ASTM standards D 3737-04 and D 4761-05. According to these standards the length of distance in between support and applied load was kept higher than twice the depth of beam. For a 2 m beam span, the minimum length is 0.7 m. Displacement-controlled load test were conducted, as requested by the standard ASTM D4761-05, and the total test duration was kept in between 10 s to 10 min. Load was induced at a rate of 9 mm/min for the beam with a span/depth ratio of 17 and 1 mm/min for the beams with a span/depth ratio of 7. Load and displacements data was measured with the help of load cells and LVDT transducers and recorded by a data logger at 1 s intervals.

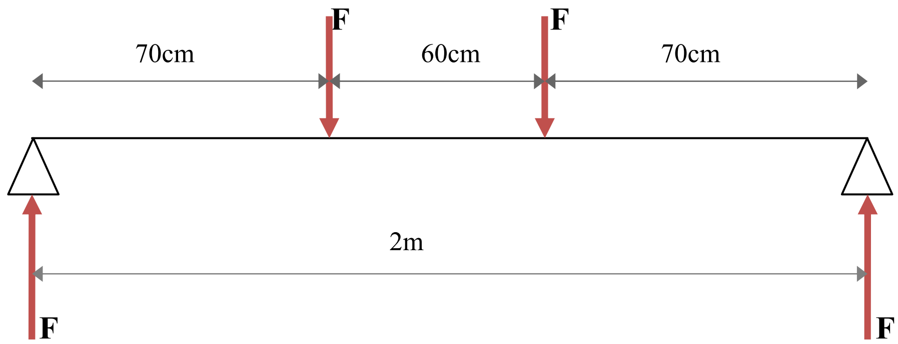


Figure 2: Tests description

2.3 Results and analysis

Experimental results are given in Fig. 3 and Table 4. The first ten (non-strengthened) beams used as reference beams showed a very high scatter in results regarding the failure load value.

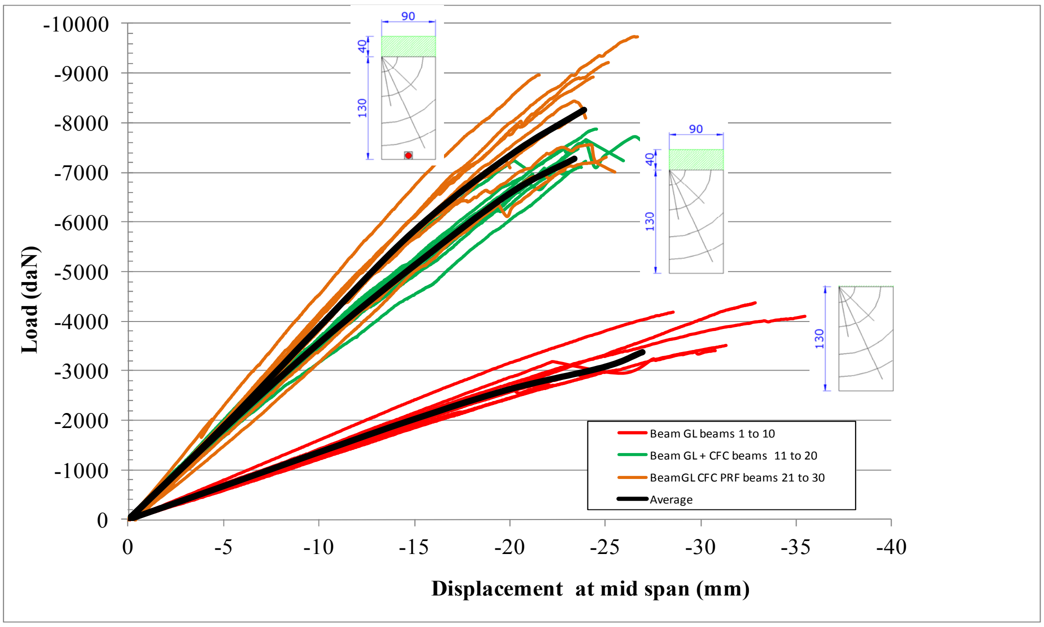


Figure 3: Load-displacement curves

The addition of a UHPC plank on the top brought allows improving the specimen mechanical behavior law. It increased the specimen load capacity from 34 kN to 73 kN or 115 %, slightly increased the overall modulus of elasticity of the structure and reduced the standard deviation of results (Figure 3 and Table 4).

In case of beams reinforced by a CFRP bar in tension and a UHPC plank at top, an increase of up to 83 kN was observed in failure load. The failure modes in this case depends on the bonding capacity of FRP bars in tensions. In this case a higher disparity in test results was observed. In comparison with the reference beam, the increase in ultimate load ranges from 115 % to 144 %, depending on the beam characteristics. Considering the variability of the mechanical properties of wood, it is difficult to reach a definitive conclusion on the most appropriate reinforcement for the UHPC plank in tension, but the third one with UHPC plank and FRP bars leads to best result.

Table 3: Ultimate load for the 30 specimens

Glulam Beam	N°1	N°2	N°3	N°4	N°5	N°6	N°7	N°8	N°9	N°10
Ultimate load (kN)	44	34	27	22	29	28	35	30	47	42
Average	Ultimate load : 34 kN – Standard deviation : 8,2 kN									
Glulam + UHPC	N°11	N°12	N°13	N°14	N°15	N°16	N°17	N°18	N°19	N°20
Ultimate load (kN)	73	59	79	72	75	77	73	77	71	42
Average	Ultimate load : 73 kN – Standard deviation : 5,8 kN									
GluLam + UHPC + FRP	N°21	N°22	N°23	N°24	N°25	N°26	N°27	N°28	N°29	N°30
Ultimate load (kN)	90	89	84	73	76	97	72	82	71	92
Average	Ultimate load : 83 kN – Standard deviation: 9,4 kN									

3. VIBRATION ANALYSIS OF A TIMBER FLOOR

3.1 The vibration and its stakes in wood construction

In current housing, vibration is an important comfort criterion. Wood is preferred as a constructive material because it has an aesthetic appearance, may be resistant to fire and is a very good thermal insulator. However, with respect to vibration it is not the best material. Indeed, wooden floors subjected to live load (users) can undergo large displacement because wood is a flexible material. It is necessary to check carefully the floor design criteria. Two things necessary in investigations of vibration criteria are (Ref. 20):

- Flexibility must be in between 1 and 1.6 m / MN
- The displacement rates during vibration should not be too large.

In this section the methodology adopted to obtain these parameters and its application to buildings is discussed. Finally, the suitability of these criteria is analyzed.

3.2 Presentation of the calculations of vibration

Floor structures are designed for ultimate limit states and serviceability limit state criteria:

- Ultimate limit states are those related to strength and stability;
- Serviceability limit states are mainly related to vibrations and hence are governed by stiffness, mass, damping and the excitation mechanisms.

For slender floor structures, as made in wood or composite construction, serviceability criteria govern the design. The Eurocode guideline gives regulation for:
• Specification of tolerable vibration by the introduction of acceptance classes, and
• Prediction of floor response due to human induced vibration with respect to the intended use of the building.

The technique used to verify vibration criteria is based on EN 1995-1-1 and Eurocode 5. Details of the computational part for constraint checks and displacements are not discussed here because these are beyond the scope of this research work. The spacing is chosen and the design of beams and displacement constraints has been achieved. For the prediction of floor vibration several dynamic floor characteristics need to be determined. These characteristics and simplified methods for their determination are briefly described. The calculations of vibrations have been made to a floor joists and decking wood boards. After evaluation of floor load, it is necessary to calculate the dimensional changes of the joists in order to take into account the stabilization of the beam relative to humidity in between the construction and functional stage (Temperature = 12 ° C and humidity 12 %). However, this variation can be equal to 1 mm on each dimension and has no influence on the following calculations. The next step is to evaluate the stiffness of the floor caused by the plank and the joists. It shall be calculated in both directions (transverse and longitudinal). However, longitudinal bending can be considered. The following formulas to obtain the stiffness of the floor due to the joists and the beams can be used:

$$EI_l = \left(\frac{E_s b_{s,d} h_{s,d}^3}{12} \right) \frac{1}{e_s} \tag{1}$$

$$EI_{plank} = \left(\frac{E_l 1 b_l^3}{12} \right) \tag{2}$$

with: $b_{s,d}$ and $h_{s,d}$ respectively the width and height of the joists; e_s the space between the joists; E_s and E_l the modulus of elasticity of the joist and the plank, respectively.

The next step is to calculate the mass of the floor by using the reduction factor (α_A). For this we must first calculate a reduction factor for live loads (α_A). In fact in the calculation of the vibration effect, we consider the mass of the floor (dead load) and a reduction factor of 20 % of live loads (α_A) obtained by the following relation:

$$\alpha_A = 0.77 + \left({}^{A_0}\!/\!_{A} \right) \leq 1 \tag{3}$$

with A_0 = 3,5 m² and A the total surface of the floor

The second step is to calculate m, the load on the floor: $m = \alpha_A m_{qk} + m_{floor}$ (4)

We can then calculate the frequency of vibration depending on the span of the beam (l):

$$f_1 = \frac{\pi}{2l^2} \sqrt{\frac{(EI)_l}{m}} \tag{5}$$

The vibration velocity pulse corresponds to the speed of a point on the beam under a load of 1 kN. The first step is to calculate the number of Eigen modes for which the frequency below 40 Hz produces significant movement in the floor.

$$n_{40} = \left\{ \left(\left[\frac{40}{f_1} \right]^2 - 1 \right) \left(\frac{b}{l} \right)^4 \left(\frac{(EI)_l}{(EI)_b} \right) \right\}^{0.2s} \qquad (6)$$

The displacement rate in vibrations due to a unit impulse is given by the following formula:

$$V_{\max} = \frac{4}{mbl + 200} \left(0.4 + 0.6 n_{40} \right) \qquad (7)$$

This rate should be compared to the speed limit obtained by the following formula:

$$V_{\max,\lim} = b^{(f_1 \xi - 1)} \qquad (8)$$

with ξ the damping coefficient related to the material.

The factor b is obtained based on Eurocode and given by figure 5.

$$b = 120 - 40(a - 1) \qquad (9)$$

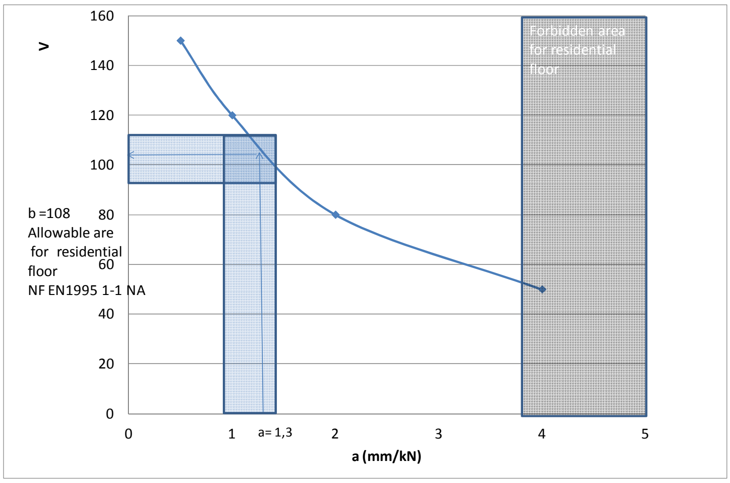


Figure 5: Values and ratio of factors a and b

This gives a maximum speed in mm / s and should be lower than $V_{\max,\lim}$. Thus, we have all the data to calculate the flexibility of the floor under a point load of 1 KN (regular case).

3.3 Calculation of the flexibility

According to the NF EN 1995-1-1 standard, stiffness factor is calculated as the ratio of the displacement (w) obtained for a point load (F) localized to get the higher displacement and is expressed in m / N. It is calculated as follows according to the standard based of stiffness of beams (k_s) and wood floor (k_p):

$$a = {}^{w}\!/_{F} = k_s.10^3 \left[\frac{36.(k_s^2) + 108.(k_s k_p) + 7.(k_p^2)}{180.(k_s^2) + 204.(k_s k_p) + 7.(k_p^2)} \right] \qquad (10)$$

with $k_s = \dfrac{l^2}{48E_sI_s}$ and $k_p = \dfrac{l^2}{48E_pI_p}$ (11)

This stiffness factor (a) must be between 1 mm/kN and 1.6 mm/kN.

3.4 Analysis of the influence of a beam reinforced

We have made several models in our Excel file to see the influence of reinforcement on the bearing behavior and vibration criteria. The calculations, displayed in Table 5, were performed using a constant cross-section of 90 x 170 mm.

Table 5: Interest of Beam reinforcement for dynamic loading

		GL	GL +UHPC	GL+UHPC+FRP
Beam spacing 40 cm	**Span**	**3.7 m**	**4.2 m**	**4.4 m**
	Stiffness (a)	1.6 m/MN	1.6 m/MN	1.566 m/MN
	Speed of vibration impulse (v_{max})	10.2 mm/s < 20 mm/s	10.6 mm/s < 18.5 mm/s	11.1 mm/s < 19.1 mm/s
Beam spacing 60 cm	**Span**	**2.6 m**	**3.9 m**	**4.1 m**
	Stiffness (a)	1.55 m/MN	1.59 m/MN	1.57 m/MN
	Speed of vibration impulse	6.6 mm/s < 19.7mm/s	8.8 mm/s < 17.0 mm/s	8.82 mm/s < 17.0 mm/s

The calculation results show that the use of FRP and UHPC plank allows the increase in beam span (from 3.7 to 4.4 m) with respect to the vibration design of floors.The gain in range is more important when beam spacing is increased. The span of beams may be increased from 20 to 50 %. Another solution is to increase the spacing of beams allowing decreasing the number of beams without need of change in beams depth.

4. MECHANICAL TESTS ON WOOD HYBRID PANELS AND RESULTS

The tests carried out are done to determine the bending stiffness and the load-bearing capacity of the hybrid composite panel illustrated in Fig. 6. The panel specimens constructed according to the procedure detailed above were subjected to a four-point loading. The panel is reinforcement with a compressive slab made with high performance mortar bonded onto wood and with a UHPC plank internally reinforced by FRP also bonded onto the bottom part.

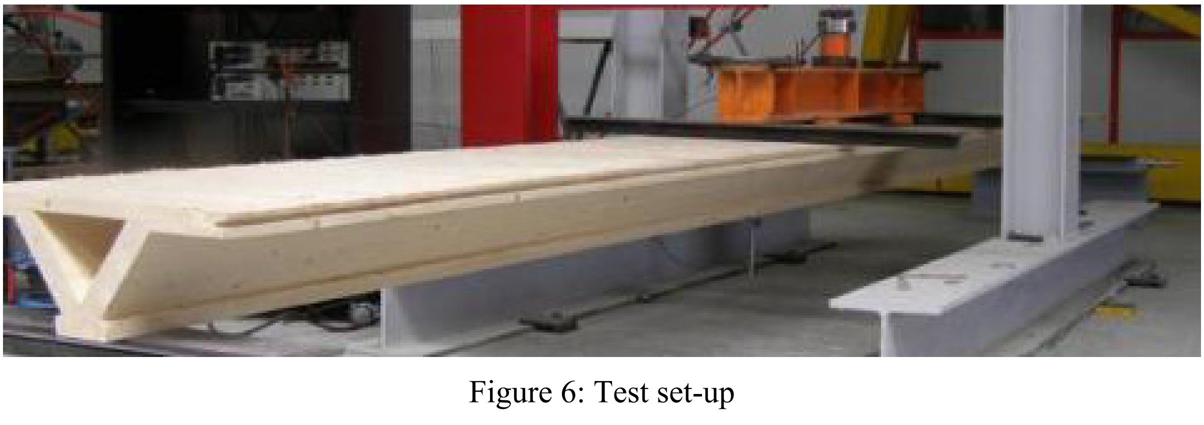


Figure 6: Test set-up

The analysis of the load-deflection curves indicates that there are two or three distinct stages of behavior during the test, corresponding to the level of damage in the constituent materials (concrete, reinforcement bars, wood). The curves showing the load-displacement relationship for the four 6-meter panels and the four 4-meter panels are given in Fig. 7. The behaviour of the composite panel remained linear but with a reduced stiffness. Panels reinforced with composite reinforcement bars had only two stages of behavior. Beyond the cracking load, the behavior remains elastic with constant stiffness until failure.

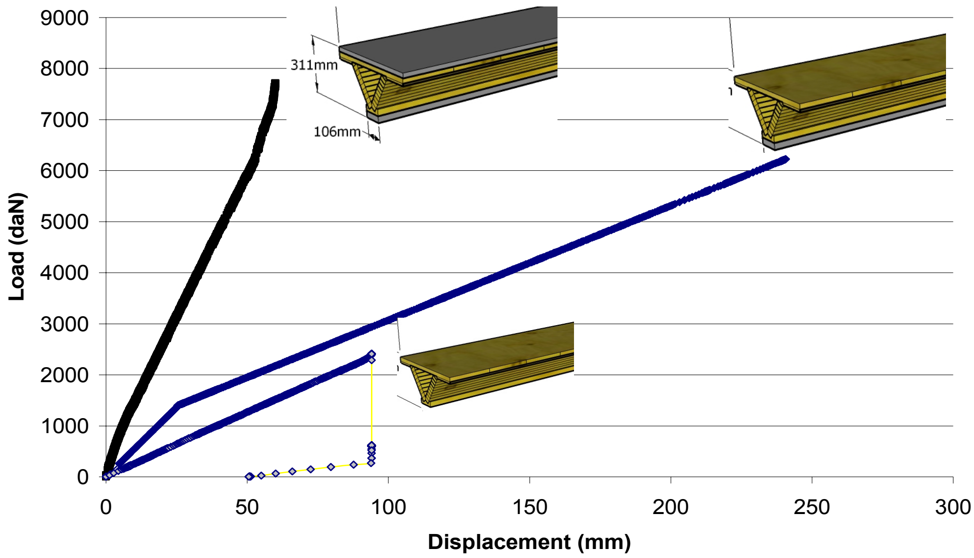


Figure 7: Load deflection curves for panels 2 to 4

Table 6: Tests results

Reference	F_{Elast} [daN]	δ_{Elast} [mm]	F_{Rupt} [daN]	δ_{Rupt} [mm]
Panel 1	-	-	45.22	79.85
Panel 2	-	-	2415	94
Panel 3	12.87	23.64	238	61.77
Panel 4	13.57	9	77.12	60
Panel 5	-	-	71.45	59.6
Panel 6	35.50	3.9	158.40	26.1
Panel 7	5140	26,2	7030	43,2

This emphasizes the interest of using FRP reinforcement bars to allow an increase in the tensile capacity of the lower plank and in the ultimate capacity of the panel (Table 6). The study shows that the reinforcement elements UHPFRC allows significant changes in the behaviour of a reference panel (Fig. 7). Indeed, strengthening multiplies the ultimate load that the panel can sustain by 4. The bending stiffness of the panel is greatly increased; it is multiplied by 6 in the first stage and 2.6 in the second. The load-displacement curve in

Figure 6 reflects an elastic behaviour of the structure to a value of 45.37 kN for the panel of 120 cm and a value of 24.15 kN for the panel of 60 cm and a tensile failure in the lower wood lamellae. The test shows that the reinforced panel (Panel 6) has a bi-linear elastic behaviour with two distinct phases of behaviour (Fig. 7). Failure occurs again at the bottom in tension.

5. CONCLUSIONS

This study presents an innovative hybrid beam made of glued-laminated wood, ultra-high performance concrete reinforced with short metallic fibres and FRP or steel reinforcing bars. The experimental results show that the increase in ultimate load capacity (that ranges from 115 % to 144 %) depends on the beam characteristics. The combination of materials allows a control of the ultimate load and displacement. The results of this study should be confirmed by an extensive experimental program with large-scale beams and more specimens. The dynamic behaviour is also investigated based on calculation. The dynamic behaviour is improved by allowing utilisation of higher beams span.

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