Composite Wood-Concrete panels: effect of cyclic loading and creep

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Abstract:

Since several years, composite structures emerged and are more and more studied and used in civil engineering. Wood-concrete structures have the advantage to improve the mechanical behavior on two points, the load capacity and the stiffness. The principle is to combine concrete which resists under compression and timber under tension. Several systems of connection exist to bond wood and concrete but an innovative system is used in this study based on a specific treatment of the wood and adhesives. Three configurations of hybrid panels are fabricated and tested under cyclic loads and creep. The results show that minimum and maximum loads, which represent the dead and live loads respectively, are quite constant during the cyclic bending test. The mid-span deflection evolves during the test. An analytical model based on the compatibility of the deformations is developed to predict the evolution of the displacement at the mid-span and integrates creep phenomena. Even if the panels are cyclically tested under the maximum nominal load (live load), the evolution of the mid-span deflection is governed by creep phenomena. Finally the composite panels are submitted to a residual bending test to failure. Panels with ordinary concrete present a progressive loss of bending stiffness during the 4-points bending test due to a progressive debonding of the concrete slab and a diminution of load capacity compared to panels that was not load cyclically. In the contrary, the panel with ultra-high performance fiber reinforced concrete has a similar mechanical behavior than the panel tested under static load.

Keywords: Panel, wood, concrete, gluing, rebar, cyclic loading, creep, analytical modelling

1. Introduction

Civil engineering is constantly researching improvements of material or construction systems or innovation in the fields. There is an objective to better build but without neglected environmental aspects, comfort of users and esthetic of the construction. Timber buildings are more and more popular since several decades in civil engineering thanks to the advantages of wood such as its good resistance, environmental impact or esthetic aspect. Unfortunately, timber structures are limited by the deformability of the wood and variability of its properties. Indeed, the Young's modulus of wood is lower than traditional concrete and consequently, wood shows more deformations than concrete under equivalent loads.

Subsequently, researches were conducted and different ways were proposed to improve the mechanical behavior of wooden structures. One of the most used improvement is the utilization of others materials in addition of timber. The purpose is to combine wood with stiffer materials to increase the rigidity of the structure and limited his deformability.

Several authors combined wood with timber to form a composite beam. The concrete is used in the compressive part of the section while timber is used under tension. The combination of wood and concrete allows improving the load capacity and rigidity of the hybrid beam compared to a

wooden beam. Then with the fabrication of more performing concrete as ultra-high performance fiber reinforced concrete (UHPFRC), a new concept of composite structure emerged which combined wood, concrete and steel rebars. Rebars placed in the tension zone of the cross-section with a near surface mounted method (NSM) combined with high performances of UHPFRC and improved even more the mechanical behavior of hybrid structures.
The interest of such composite structure is certain and more investigations were done to characterize hybrid structure under different conditions. The creep was studied by Kong and it was conclude that under controlled environmental conditions, the composite wood-UHPFRC beams present a reduced deflection compared to a reference timber beam. Moreover an analytical model was proposed to predict the evolution of the mid-span displacement.
Depending on the connection system of wood and concrete, it can be concluded that when bonding is used, no slip are measured between both materials and hybrid structure resist to cyclic loading, no loss of bending stiffness is observed. If local connectors are used for the wood-concrete connection, damages occur and a decrease of the bending stiffness is measured with an evolution of the deflection throughout the cyclic test.
The panels studied here are designed to office buildings or individual flat used and it will be interesting to predict the deflection of hybrid structures subjected to creep and cyclic loading. The connection systems used is based on adhesives and a surface treatment.
This paper describes the experimental protocol of fabrication of hybrid panels with their connection system, procedure of test and exposes the results obtained for the evolution of the deflection under creep and cyclic loads.

2. Experimental program

The mechanical behavior of hybrid panels under cyclic loads is characterized by four-point bending tests. The composite panels tested are presented in this section and details are given for fabrication and geometry.

2.1. Materials and preparation of specimens

The materials used for the fabrication of the hybrid panels are wood, UHPFRC and/or Ordinary Concrete (OC), steel rebars (HA), and Eponal 371 V1 epoxy adhesive. The timber glulam used is a GL24h strength grade. This grade of glulam is widely used in civil engineering. Two kind of concrete are used an ordinary C40/50 mixture concrete and an Ultra-High Performance Concrete. Steel rebars is the common steel used in construction and diameter is 10mm (0.39 in).
The interest of such hybrid section is not to discuss, by combining each material where they are the most performing, the mechanical behavior of the global structure is increased. Concrete is hence used in compression part at the top of the section while rebars are used in tension at the bottom. Panels are made of three reinforced timber beams connected to a concrete compression slab. The wood-concrete connection is made by a specific treatment of the wood (Figure 1) that consist of applying a layer of adhesive and sprinkling sand on it before the polymerization of the glue. After 24h, the surface treatment is ready and concrete can be cast directly on treated timber.

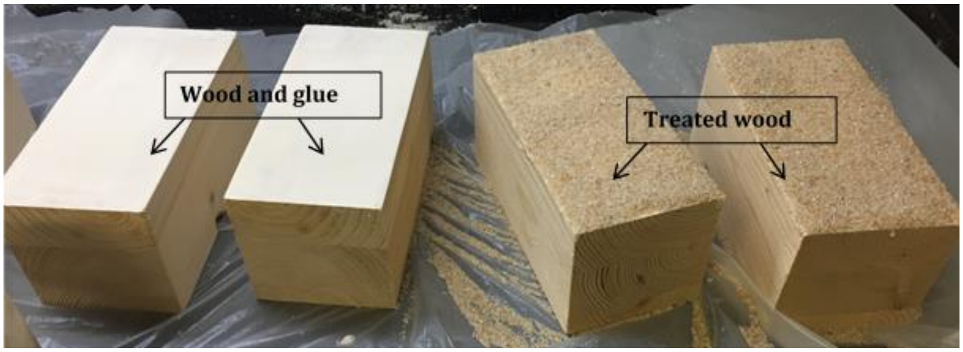


Figure 1. Specific treatment of the glulam

A near surface mounted (NSM) method is used to fix rebar at the bottom face of glulam beams. The methodology of fabrication is simple, glulam beams are reinforced and treated, and then the concrete is cast in the treated surface of the timber beams. In order to facilitate the handling of the panels and increase his stability, an oriented strand board (OSB) is placed in the bottom of the section to stabilize glulam beams. Moreover, timber braces are used at each extremity of panels. More details can be found in [11], which presents the instantaneous behavior of these panels.

At the end, three different configurations of composite panels are made and for each of them, two prototypes are fabricated.

The first configuration is made of wood, OC and steel rebars, and is called BO-HA. The second panel, named BFUP-HA, is fabricated with wood, steel and both concretes (OC and UHPFRC).

Figure ***2*** presents the section of panels tested. All panels have the same dimensions, a width of 1.2 m (47.24 in) and a height of 270 mm (10.63 in) for a length of 8.15 m (320.87 in).

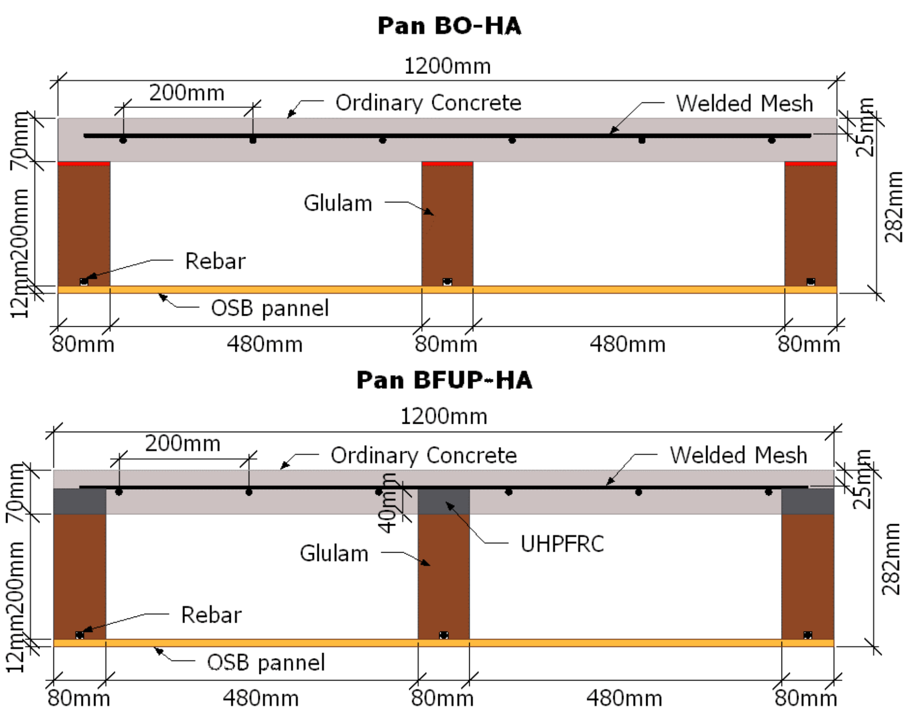


Figure 2. Cross-sections of the hybrid floors

2.2. Bending test setup

The purpose of this paper is to investigate the mechanical behavior of composite structure under cyclic loading and to take in consideration creep of materials. After the cyclic loads, the residual resistance of panels is also tested. Four-point bending test was conducted to determine the moment-displacement curve and compare the residual strength with Eurocode norms. The force and the displacement of panels are monitoring during the test with a strength sensor and a linear variable differential transformer (LVDT). Cyclic loading is assured by a pneumatic jack supplied by an 8 bar pneumatic network. Central load varies between 4 kN (899 lbf) to 20 kN (4496 lbf) that represents the dead load (flooring, ceiling and sealing) and the panels loaded with live loads for office building (2,5 kN/m² according Eurocode 1 [12]) respectively. Figure 3 represents the loading program used for the cyclic test. Panels have a weight of 2 kN/m² thus creep will occur during the test. The frequency of loading is between 0.25 to 0.5 Hz. Figure 4 presents the geometric configuration of the bending test and the deflection-measuring apparatus used.

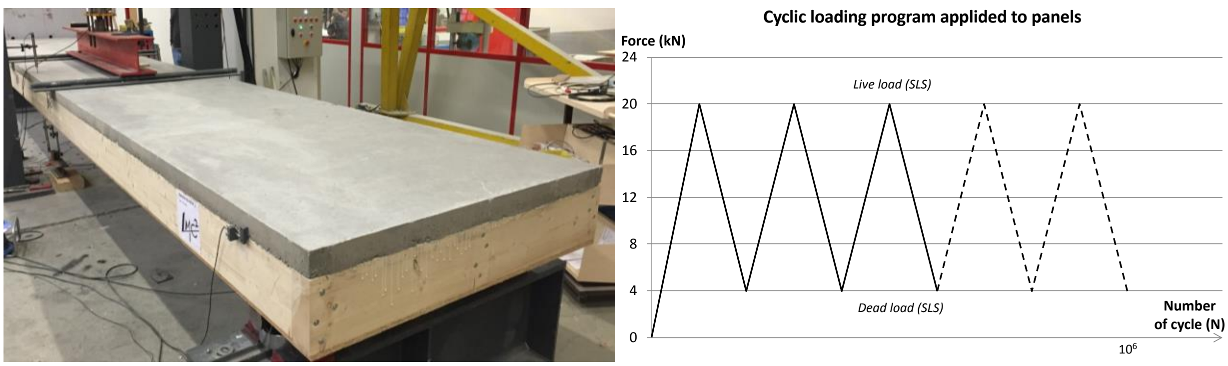


Figure 3. Four-point bending test & Loading program used during cyclic test of panels

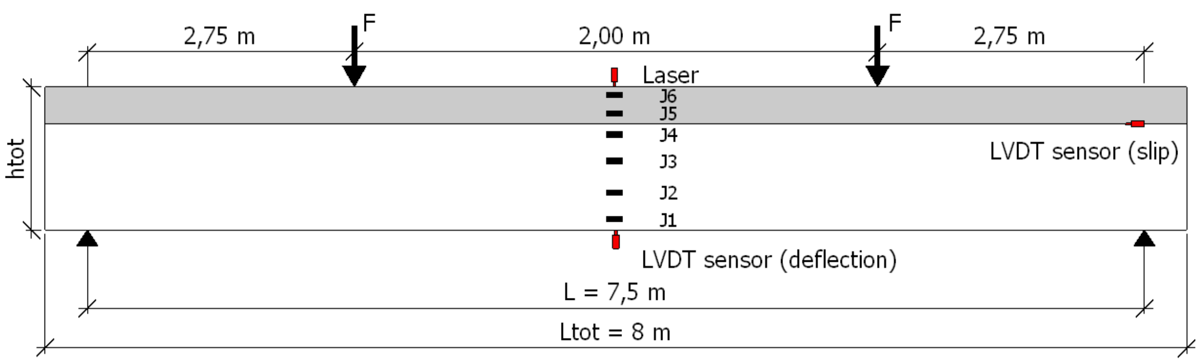


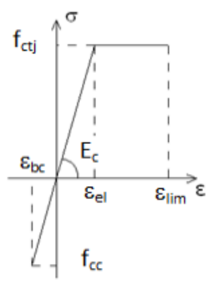
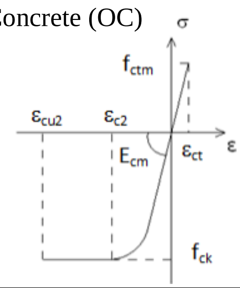
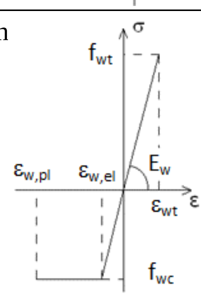
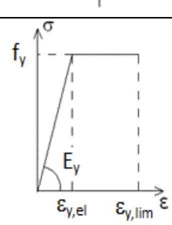
Figure 4. Panel loading and measuring apparatus

3. Analytical modelling

An iterative model was developed to predict the evolution of the mid-span displacement by including the creep of materials. This model is based on the iterative model developed by Kong. A creep coefficient is calculated which depends on time, this coefficient is integrated to calculate the effective modulus of elasticity. The minimal load and the weight of panels are used to integrate creep coefficient in the model. The effective modulus is used in the equilibrium of the section and to deduce the moment-curvature relationship. From the curvature, the deflection is calculated. This procedure is accomplished for each step of time and the evolution of the deflection is so obtained. Calculation is based on a cross sectional analysis and strain compatibility is assumed. For this approach of modelling, several hypothesis are supposed, firstly the strain distribution is linear and secondly Navier's hypothesis. The connection is consider to be perfect without slip between elements. Since the amount of rebars is quite low, around 0.2% of the volume of a panel, their creep phenomena is neglected. Furthermore, the amount of stress applied is small in front of the resistance of rebars.

The mechanical behavior of each material is considered and used in the model. Properties used for static behavior is listed in Table 1. Eurocode 2 supplies the stress-strain relationship under compression for the OC. In tension, the behavior is assumed elastic linear. The mechanical behavior of the UHPFRC comes from the "Association Française de Génie Civil" (AFGC) recommendations. The glulam is modeled with an elastoplastic behavior under compression and an elastic linear relationship under tension according Eurocode 5 and Fiorelli and Dias. Steel rebars are modeled by an elastoplastic behavior (Table 1).

Table 1. Mechanical properties of the materials used

Material		Parameters	Value
UHPFRC 	Tension	f_{ctk} [MPa] / Mpsi	9 / 29
		ε_{el} [‰]	0.16
		ε_{lim} [‰]	2.5
	Compression	ε_{bc} [‰]	4
		f_{cc} [MPa] / psi	180 / 26107
	Young's modulus	E_c [MPa] / Mpsi	45,000 / 6.52
Ordinary Concrete (OC) 	Tension	f_{ctm} [MPa] / psi	3.5 / 508
	Compression	ε_{c2} [‰]	2
		ε_{cu2} [‰]	3.5
		f_{ck} [MPa] / psi	50 / 7252
	Young's modulus	E_{cm} [MPa] / Mpsi	35,000 / 5.07
Wood (GL24 h 	Tension	f_{wt} [MPa] / psi	50 / 7252
	Compression	f_{wc} [MPa] / psi	24 / 3481
	Shear	F_{sh} [MPa] / psi	3.5 / 508
	Young's modulus	E_w [MPa] / Mpsi	12,500 / 1.81
Steel HA (Φ10) 	Tension	f_y [MPa] / psi	550 / 79771
		$\varepsilon_{y,el}$ [‰]	2.6
		$\varepsilon_{y,lim}$ [‰]	25
	Young's modulus	E_y [MPa] / Mpsi	210,000 / 30.45

4. Experimental observations and results

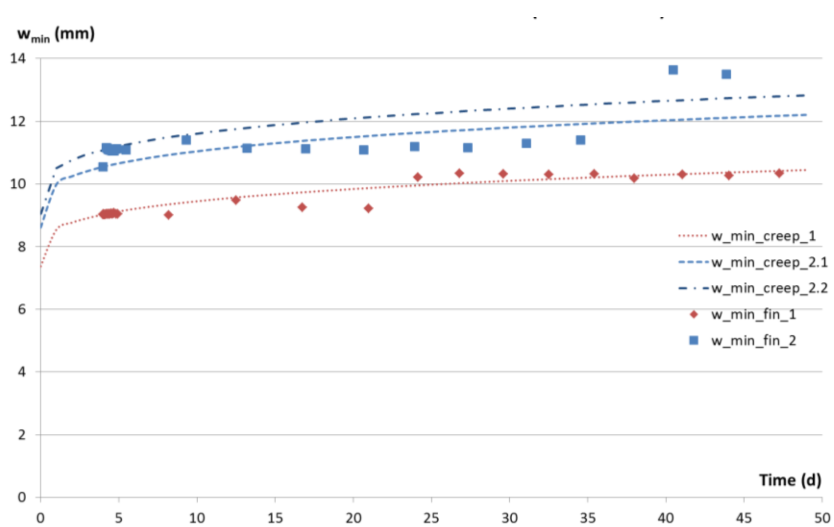
Results are discussed herein. First, the variation of the loads is observed during the cyclic test. Then, a discussion about the evolution of the deflection of panels is proposed and finally, the results of the residual strength are compared to monotonic test.

4.1. Evolution of the cyclic loading

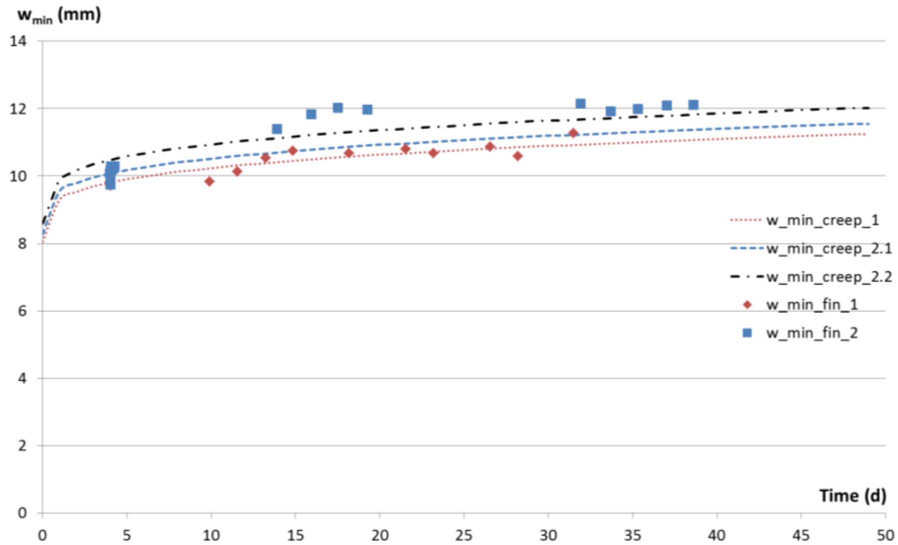
The loading, defined previously between 4 and 20 kN (899 to 4496 lbf), was monitored throughout the bending test. It was important to keep the loads constant, especially the minimum force of 4 kN (899 lbf) for the creep. For clarity only the results of one of each panel are exposed since the corresponding second panel shows the same result. Minimum and maximum loads are effectively near to the values imposed. Some variations can be observed and can be related to several causes. The pneumatic network that powers the loading system could be disturbed by several events. Indeed, this network was used during approximately 40 days without interruptions for the test and could be used by other users. Another explanation is the degradation of the panels throughout creep and cyclic loading. This deterioration has a direct impact on the rigidity of the structure that decreases with the increase of degradations. If panels creep, the initial position under the theoretical load of 4 kN (899 lbf) varies and so the minimum force applied, which decreases. If the loads observed were lower than expected, an adjustment was done to approach the values fixed. In general, the cyclic loading can ben supposed constant and equivalent to the limits even if some variations are observed.

4.2. Evolution of the mid-span deflection

The creep is characterized by an evolution of the deformation under a constant stress. This evolution leads to an augmentation of the deflection of the structure over time. In order to characterize this increase of displacement at the mid-span, the minimal deflection of panels is traced and presented in Figure 5 for panels BO-HA and BFUP-HA respectively.



(a) Evolution of mid-span deflection in function of time (panel BO-HA)



(b) Evolution of mid-span deflection in function of time (panel BFUP-HA)

Figure 5. Deflection of 2 panels, experimental data and theoretical creep

The creep analysis is integrated to these figures in order to appreciate these phenomena for each panel and compare the evolution of the mid-span displacement under creep and cyclic loading to the creep only. Several minimum loads for the creep analysis was modelled in order to better represent the experimental test. An instantaneous deflection marks the start of the model, and then the evolution of the creep deflection is important at the beginning before the augmentation decreases progressively and stabilizes. This evolution is in accordance with the literature review and the first and second phases of creep. Experimental data shows similitudes with the model. The deflection of the panels under cyclic loading increases over time but this evolution seems relatively constant. There is not this first step of quick raise before the stabilization. This particularity can be explain by the fact of the panels are put in place some days before the cyclic test. Therefore, panels begin to creep before the test and the deflection wasn't monitoring yet. This is why experimental data start at 4 days in the figures. It can be observed that the experimental deflection recorded seems to follow the creep modeling for each panel. This point is surprising since it is not what was expected. Indeed, the evolution of the mid-span displacement should increase over time, but more than the analytical model. The deflection can already be calculated by a combination of an instantaneous part and a creep part. It was expected that under cyclic loads, the deflection will be a combination of the elastic deflection, the creep phenomenon and a cyclic part. It seems here that the cyclic loading does not affect the evolution of the deflection.
In average, the diminution of the creep force is about 10% whereas the decrease of the deflection is approximately 7%.

4.3. Residual strength

After the cyclic test, all the panels are tested to failure in four-point bending. The residual mechanical behavior is therefore compared to the short-term behavior of panels which have not been submitted to cyclic loading. Residual mechanical behavior is modeled with marks whereas the short-term behavior is a single curve without symbol. Important observations can be drawn according these figures. For the configuration BO-HA, the residual behavior is similar to the instantaneous behavior at least for loads close to ULS. After this limit, the mechanical behavior can show some differences. Effectively, the panel BO-HA_2 present a first particularity at 48.8 kN (10971 lbf). A loss of strength is observed that corresponds to a debonding of a part the concrete slab to the timber. The same phenomenon appears for panel BO-HA_1 at 92.2 kN (20727 lbf). This debonding progresses during the test and is observed several times for the configuration BO-HA. The first incident of debonding can be relatively close to ULS and in this case, the value is 23 % above the ultimate bending capacity under static loading. It matches to a loss of load capacity of 64% compared to the maximal strength of the short-term behavior. This failure mode indicates that the joint between the concrete and timber degraded during the cyclic test. The debonding of the slab starts at the ends of panels, where shear are maximal and progresses to the center when the loading increases (Figure 6). A loss of the rigidity is also observed during the test and is related to the progressive debonding of the concrete. For classic loads ULS and SLS, both mechanical behaviors are similar, which is reassuring. Failure mode is a combination of debonding and bending of timber for panels which have been suggested to cycle whereas only bending of wood appears during the short-term test. The rupture is pseudo-brittle compared to the initial brittle failure.

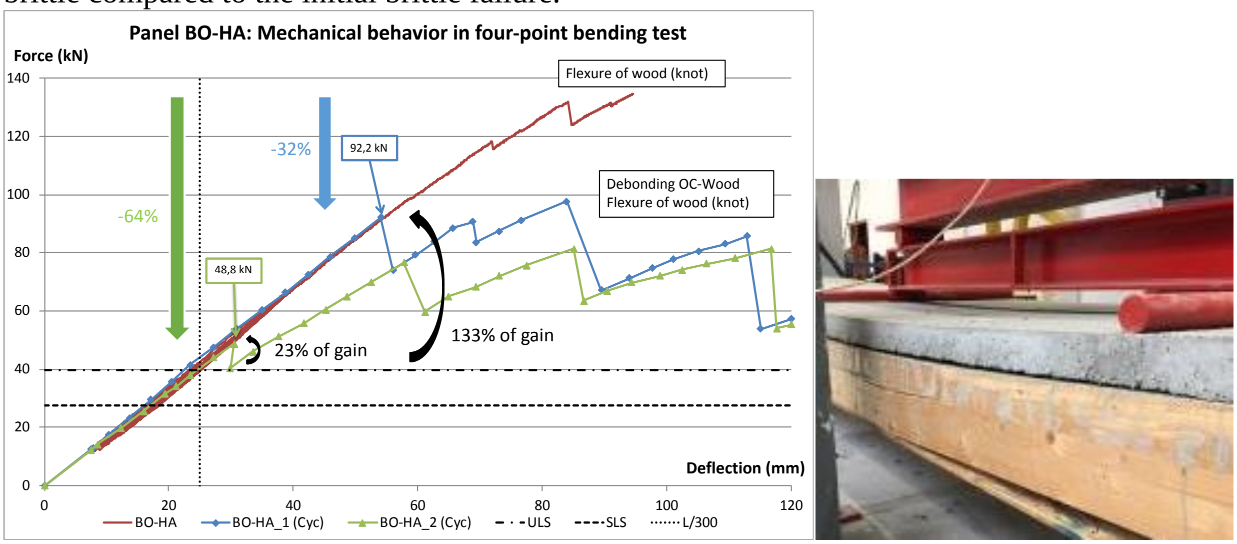


Figure 6. Mechanical behavior of BO-HA panels before and after cyclic loads and failure

The BFUP-HA panels in Figure 7 show some difference compared to panels BO-HA. Actually, no debonding was observed during the residual test for this configuration. The residual behavior is even improved. Indeed, the load capacity is better than the instantaneous bending test, with an average of 24% higher. The rigidity is slightly increased too, from 10 to 17%. However, these increases has to be put in perspective since during the short-term test, the compressive concrete slab was separated from the hybrid beams made of UHPFRC and timber, which means that the failure was premature. This residual test was also conducted a long time after the casting of concrete compared to the static test. The mechanical properties of concrete depend on time and more the time spends more the performance increases. This is why the rigidity is a little bit better for the residual test. Finally the BFUP-HA panels have a similar behavior before and after cyclic loading. No damages seem to appear for this configuration compared to panels with ordinary concrete. The use of UHPRFC has an advantage on the failure mode and allows having an additional safety.

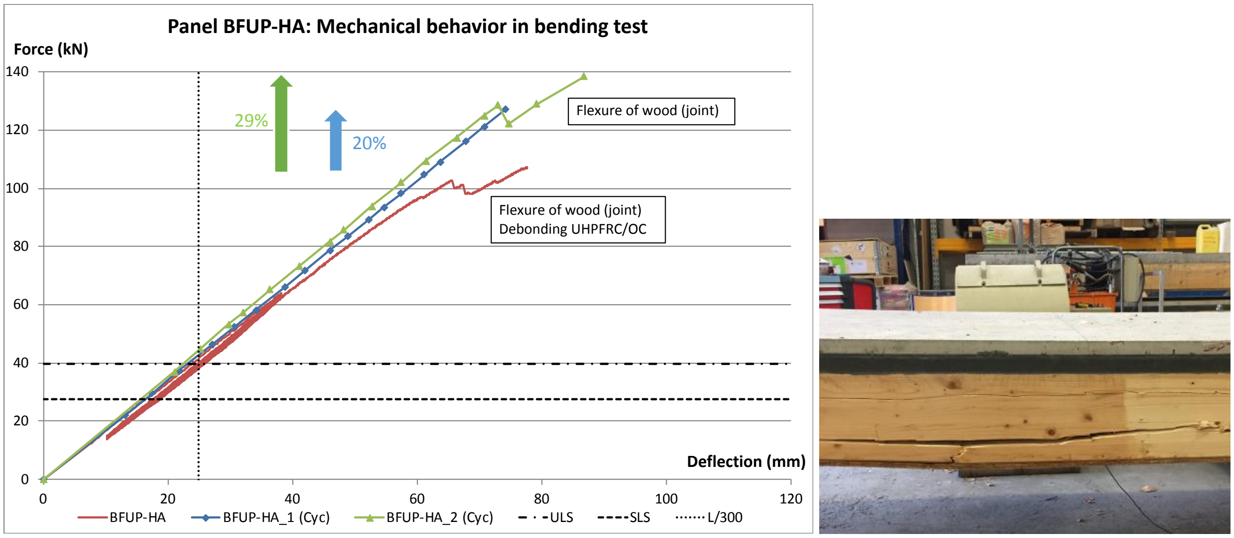


Figure 7. Mechanical behavior of UHPFRC-HA panels before and after cyclic loads and failure

5. Conclusions

Innovative hybrid panels were designed and submitted to cyclic loads. In total one million cycles was conducted between dead load and the live load for office buildings respectively. An analytical model was developed to predict the evolution of the mid-span deflection during the cycling.

Experimental results show that the deflection increases during the experiment due to two phenomena, creep and fatigue; in average, the diminution of the creep force is about 10% whereas the decrease of the deflection is approximately 7%.

The confrontation of empirical data with the modelling shows that finally, the evolution of the mid-span displacement seems to be governed by creep phenomenon only and that cyclic loading does not influence the deflection;

This can explain why the creep are predominant in the evolution of the deflection and that cyclic loading seems to have no influence;

Residual strength of hybrid panels is important and some particularities appeared. A debonding occurred between the timber and the concrete for both floors (BO-HA). By consequence, a progressive loss of rigidity was observed for these panels;

No damage was observed for the panel BFUP-HA during the residual bending test. The residual behavior was even better than the mechanical behavior without cyclic loading.

6. Acknowledgements

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