Fostering composite structures of UHPC and timber

Luca Sorelli[1], Nicolas Naud[1], Serge Lamothe[1], Catherine Joly-Lapalice[1], Pierre Blanchet[2]

[1] CIRCERB and CRIB Université Laval, Department of Civil and Water Engineering, Quebec, Canada

[2] CIRCERB Université Laval, Department of Forestry and Timber, Quebec, Canada

Abstract:

Timber-Concrete Composite (TCC) structures are emerging in bridge and multi-storey buildings as they allow optimizing multiple performances, such as the structural stiffness and strength, enchanted vibration behavior, improved durability, and lower environmental impact in terms of carbon dioxide emission. The composite action consists of a couple of axial forces that significantly contribute to the resistant moment. This work aims at fostering the use of UHPFRC slab for TCC structures by taking advantage of the high compressive strength and shear resistance. In particular, two kinds of TCC structures are considered: (i) UHPFRC slab connected to a GLULAM (Glued Laminated) timber beam; (ii) UHPFRC slab connected with a Cross Laminated Timber slab. The threefold methodology consists of : (i) a multi-criteria design optimization, which considers vibrational effect and long term deflection; (ii) experimental characterization of shear behavior by push-out tests; (iii) vibrational and structural tests on four point bending tests on long span TCC beams; (iv) non-linear Finite-Element analysis. The present results show the important potentials of UHPFRC for reducing the weight and increasing the slenderness of TCC structures.

Keywords: composite slab, residential floor, composite action, serviceability limit state, vibration.

1. Introduction

Timber-Concrete Composite structures (TCC) are emerging as an structural system as they offer several advantages in terms of lightness, structural performances (i.e., stiffness and load-bearing capacity), vibrational behaviour, acoustic insulation, and eco-friendly footprint (1,2). Additionally, TCC have been employed in civil engineering applications, such as: prefabricated decks (3), composite bridges (4,5), vertical panel (6), and resilient modular buildings (7). The connection, which transfers the horizontal shear force between concrete and timber, affects the entire structural response of a TCC structure. In the last decades, several connectors have been developed which can be broadly classified into discrete connectors (screws, dowel, nail plates, etc.); and continuous connectors (glued interface, steel perforated plates, etc.). The connector behaviour is characterized in terms of the relationship between the shear force and the slip (V-s) by experimental push-out tests. Lately, connectors with a ductile shear behaviour have been developed, e.g.: continuous perforated steel plates (8); elongated Ultra High Performance Fiber Reinforced Concrete (UHPFRC)-steel composite dowel connectors (9); special grooved connections designed for timber failure in compression (10). Note that the connection ductility is not sufficient condition to guarantee the structural ductility. Indeed, the later requires that the connections undergo to significant inelastic deformations before that the timber beam breaks under a combination of bending and tension.

The composite action engenders a couple of counterbalanced axial forces acting in the two members which greatly contributes to the overall stiffness and resistance moment of a TCC structure. Since the concrete member is under a combination of compression and moment, recent works have attempted to minimize the thickness of the concrete slab of a TCC beam by exploiting the high compressive strength ($f_c \approx$ 120-180 MPa) and high elastic modulus ($E_c \approx$ 50-60 GPa) of Ultra-High Performance Fiber Reinforced Concrete (UHPFRC). Pham et al. has investigated the flexural response TCC beams of short span (1 m) composed by a thin UHPFRC slab of 40 mm thickness connected with a Glulam Timber (GLT) beam (11). Their results showed a greater structural stiffness for continuous connections (i.e., steel mesh or glue). Furthermore, they tested 3-m span GLT-UHPFRC beams with glued connection under 2 millions of flexural fatigue cycles without loss of structural stiffness. Notably, it was found that the low creep of UHPFRC slab can reduce the long-term deflection of a TCC beam by 50% with respect to an equivalent timber solution (12). Recently, an innovative solution for medium span bridges was developed which consists of a posttensioned TCC structure made of a UHPFRC slab of 110 mm thickness and GLT beams (13). The UHPFRC slab remarkably increases the overall stiffness and strength, while protecting the timber beams from external aggressive agents of the environment. Remarkably, this lightweight and cost-effective solution allows for fast construction without need of temporary beams or complex molds.

This work aims at further developing TCC floor for residential buildings with two possible configurations: (i) slab-on-beams system composed by GLT-UHPFRC; (ii) slab-on-slab system composed by combining a flat UHPC slab with a Cross Laminated Timber (CLT) slab. The research methodology consists of a simplified multi-criteria approach; experimental shear tests and structural tests.

2. Materials and Methods

2.1. Multi-criteria design approach

In this work, the application target was a TCC structure with a long span *L* of about 9 m as relevant for timber multistory buildings in Canada. Considering a simplified design approach, we consider the following criteria: (i) initial deflection; (ii) long-term deflection; (iii) fundamental flexural vibration; (iv) safety factor of the ultimate moment; (v) structural ductility; (vi) total weight; (vii) floor thickness; and (viii) material cost. In this study, the loads and combinations specified in the National Building Code (NBC) of Canada were considered (14). For office areas located in floors above the first storey, the live and permanent loads (including the self-weight of the beam) can be estimated as w_L = 2.4 kPa and w_D = 2 kPa, respectively. For the ultimate limit state (ULS), the load combination of 1.25 w_D + 1.5 w_L was considered. For the total long-term deflection, this estimation must consider the effect of creep on both materials and the creep in the connection. Theses reductions will result in a reduced bending stiffness calculated with the reduced Young's modulus and the reduced connection stiffness. The creep coefficients used in this work are: Φ_{UHPFRC}=0.8 for UHPFRC (15); Φ_{CLT}=2 for CLT (16) and Φ_{conn}=2 for the connection (17,18). The admissible maximum total deflection in the NBCC is L/180. Based on the Eurocode 5 and Canadian technical guides, the fundamental frequency should be higher than 6-8 Hz to be acceptable for a TCC floor.

2.2. Materials

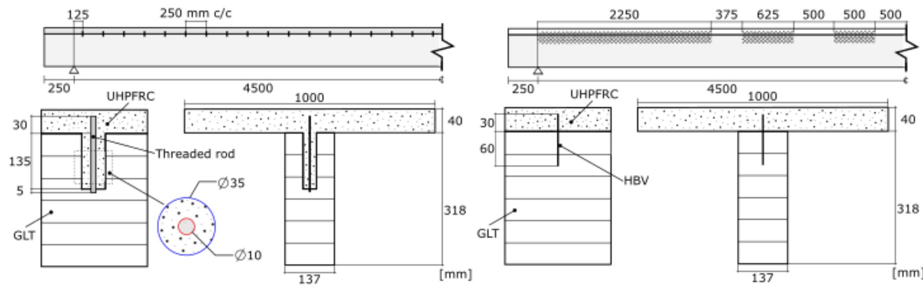
As for the GLT-UHPC1 beam, the GLT beams were made of an engineered wood product which commercially available under the name of Nordic-Lam 24f-ES/NPG (19). The UHPFRC1 employed in this work is a commercial brand under the name of Ductal® GM2 with 2% of steel fiber volume content (12 mm length and 0.20 mm diameter). Table 1 summarizes the average mechanical properties of the materials used in the experimental program. As for the composite slab CLT-UHPFRC2, a commercially available CLT known under the commercial name Nordic X-Lam 175-5s was employed (19). The CLT is made of 5 layers of 35 mm for a total thickness of 175 mm. The mechanical properties of the Nordic X-Lam are reported in Table 1 (19). The employed UHPFRC2 is commercially available under the name UP-F2 by King Materials with steel fibers at a volume content of 2%. The steel fiber has a length of 12.7 mm and a diameter of 0.2 mm. Table 1. Average mechanical properties of the materials used for the push-out and structural bending tests.

Table 1. Average mechanical properties of the employed materials.

Flexural system	Component	Product	Young's modulus E [GPa]	Confined compressive strength f_b [MPa]	Tensile strength f_t [MPa]	Compressive strength f_c [MPa]
GLT-UHPFRC1	Timber beam GLT	Nordic-Lam 24F-ES/NPG	12.4	45.9	30.8	54.8
	Concrete slab	UHPFRC1	60.2	n.a.	9.5	153
CLT-UHPFRC2	Timber slab CLT	X-Lam 175-5s	11.7	44.1	24.1	30.2
	Concrete slab	UHPFRC2	41.2	n.a.	8.0	119.6

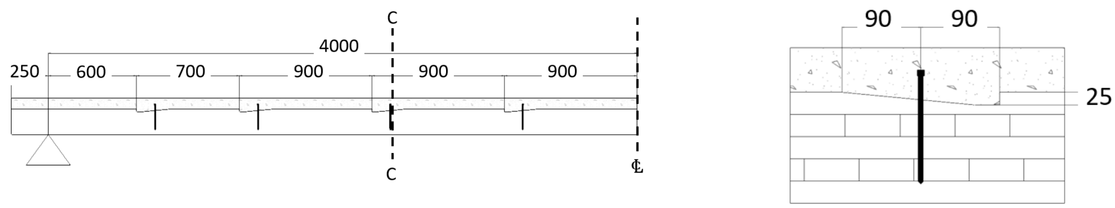
2.3. Beams and connections

Four GLT beams were cut with a length of 9000 mm and one CLT slab was cut with a length of 8500 mm by a CNC machine. Two GLT beams were connected to the cast-in-place UHPFRC1 slab with composite dowel connectors (UL), while other two beams were connected by the continuous steel plate connector (HBV). The former is a discrete connector recently developed at Université Laval (UL) which consists of elongated dowel connector composed by an external UHPFRC shell and a inner steel rod (9). The external UHPFRC shell controls the connection stiffness, while the internal steel threaded rod controls the connection strength. The later is a continuous connector made of a perforated steel plate which is available under the commercial name of HBV (8). As for CLT-UHPFRC2 slab, we employed a ductile TCC notch connector inspired by the works of Zwicky (20) and other recent studies (21). To avoid crossing the second layer of CLT, the notch is limited to a depth of 25 mm with 2 steel screw for avoiding uplift. In total, 8 connectors spaced at 700 mm are present in the beam as shown. Figure 1a and Figure 2 show the geometrical details of the GLT-UHPFRC1 timber and CLT-UHPFRC2 slab, respectively. No plastic sheets was employed to separate the materials as the water exchange between UHPFRC and timber is unlikely due to the low water content of UHPFRC. The TCC structures were covered with plastic to avoid early age cracking for 2 weeks curing. The the



(a) (b)

Figure 1. GLT-UHPFRC1 beam with (a) UL composite dowel connecter or (b) HBV steel mesh connector (22).



(a) (b)

Figure 2. CLT-UHPFRC2 slab with notch connectors and the indication of the position and sizes (23).

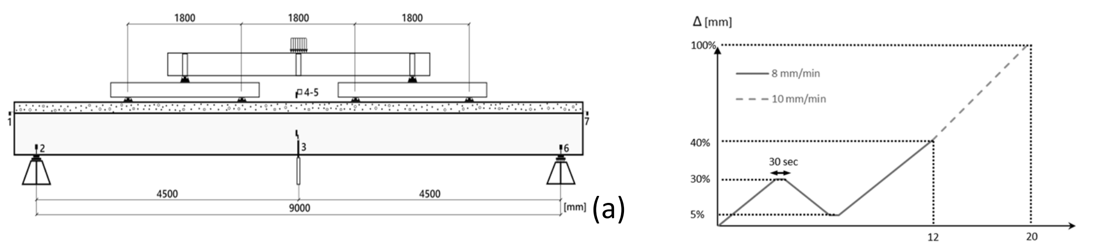
2.4. Test set-up

2.4.1 Push-out tests

Push out tests were employed to characterize the shear law of the connection in terms of shear force vs. the slip (V-s). The specimen length was 500 mm for both connectors. In total, three tests were carried out for the UL connector and 6 tests for the HBV shear connector.

2.4.2 Flexural test set-up

The structural response was measured in terms of load-deflection *(Q-Δ)* as well as the load-slip behaviour (*Q-s)* between the concrete slab and timber beam. Figure 3a shows the test setup of the flexural test. As done in a previous work (5,24), the test was controlled by imposing the displacement rate of the mid-span deflection within different load ranges as shown in Figure 3b.



(a) (b)

Figure 3. (a) Flexural test set-up; (b) Flexural test procedure and loading time history.

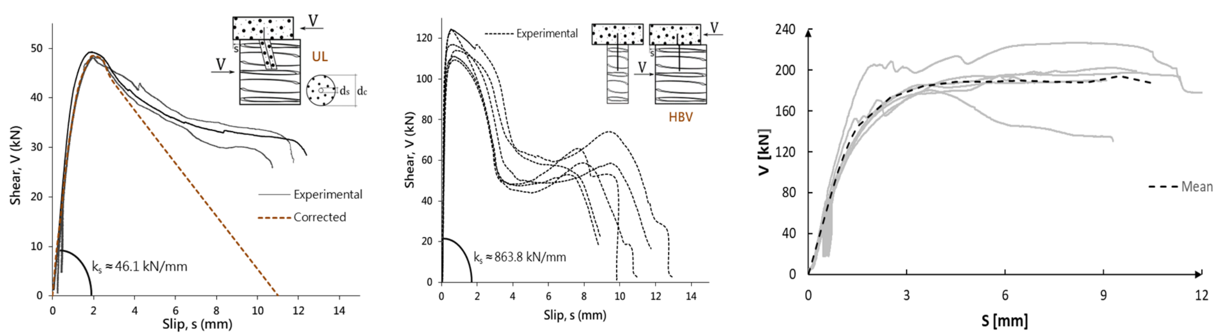
2.4.3 Vibration test

The natural frequencies of composite beams and slabs were measured by a conventional impact-response test (25). The accelerometer was fixed at the timber beam, which was excited with a hammer impact. A soft tip was used for the hammer so that the impact force would have a long duration and the impact force energy would be concentrated in a low frequency range of 2 Hz to 50 Hz. The signals were post-processed to determine the natural frequencies, modal damping ratios, and mode shapes.

3. Results and discussion

3.1 Connector shear behaviour

Figure 4a and 4.b show the shear behaviour measured by push-out tests for the GLT-UHPFRC1 for UL and HBV connectors, respectively. The mean value of the connection stiffness k_s for the single UL connector was 46.1 ± 1.1 kN/mm and its maximum shear strength V_{max} was 48.7 ± 0.5 kN. As for HBV shear connector performance, the mean value of the connection stiffness k_s was 863.8 ± 220.3 kN/mm. The maximum shear strength, V_{max} was 116.8 ± 5.9 kN. The difference in the stiffness of the two connectors (which is about 18 times) depends on the length of the specimen (500 mm in this case) and can be reduced by reducing the spacing of the discrete connectors. After the peak load, the HBV shear connector exhibits a rapid loss of strength. On the other hand, the UL discrete connector exhibited a lower stiffness and strength, but its post-peak behaviour was less steep and more ductile. Figure 4c shows the shear law behaviour of the CLT-UHPFRC2 notch connection. The CLT-UHPFRC2 connections has a mean connection stiffness (k_s) of 398 ± 22 kN/mm and a maximum shear strength (V_{max}) of 198.5 ± 13.8. As expected due to the design of the notch shape, the CLT-UHPFRC2 notch connection exhibited a ductile behaviour.



(a) (b) (c)

Figure 4. Results of shear tests in terms of shear vs slip for GLT-UHPFRC1 timber: (a) UL connector; (b) HBV shear connectors, and for CLT-UHPFRC2 slab: (c) notch connector.

3.2 Multi-criteria design of TCC beams

Figure 5a and 5b summarizes the performance of the GLT-UHPFRC1 beams and CLT-UHPFRC2 slab, respectively. Both types of GLT-UHPFRC1 beams and CLT-UHPFRC2 easily meet the SLS and ULS requirements. One can note that the long-term deflection (L/180) and the vibration are the design criteria that govern the design of such structures.

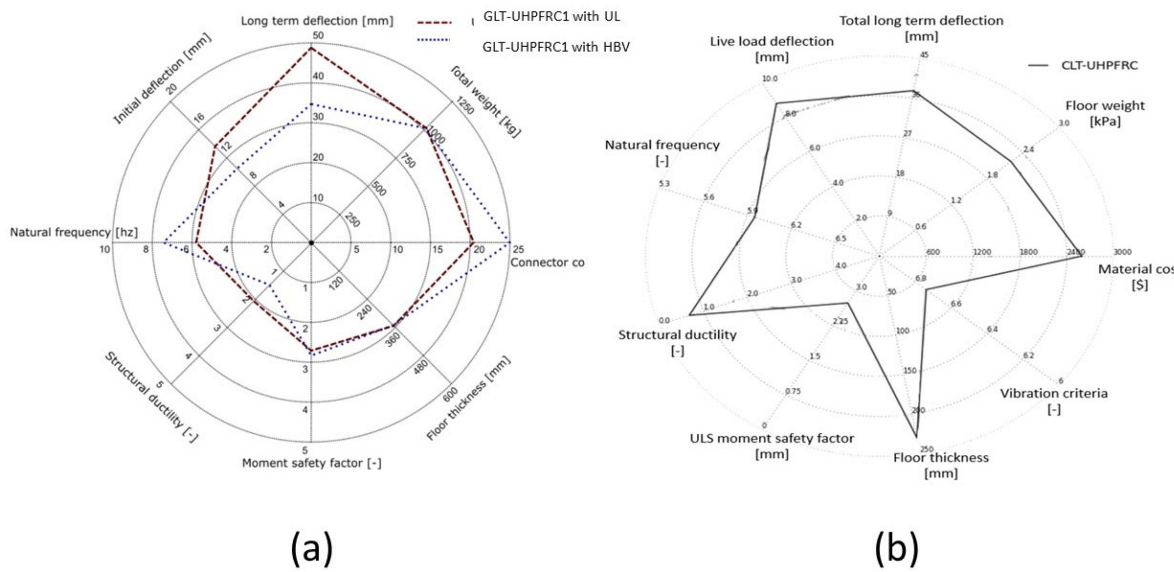


Figure 5. Radar graph of the multi-criteria design for (a) GLT-UHPFRC1 with two type of connections (UL or HBV); (b) for CLT-UHPFRC2 slab.

3.3 TCC beam results

3.3.1 Vibration test

Table 2 presents the measured frequency which are in good agreement with the expected values.

Table 2. Average results of the vibration tests.

Structure	First frequency, f_1 [Hz]	Second frequency, f_2 [Hz]	Damping ratio for the first order frequency [Hz]
GLT-UHPFRC1 with UL	7.13	22.5	2.7
GLT-UHPFRC1 with HBV	9.38	32.9	3.7
CLT-UHPFRC2	5.95	21.3	1.0

3.3.2 Structural response under bending and analysis

Figure 6a and 6b show the structural response of the GLT-UHPFRC1 timber with UL and HBV connectors, respectively in terms of load-deflection curves Q-Δ. For both series of tests, the test repeatability is rather satisfactory. Figure 6 also show the upper and the lower bound responses for zero or full composite action (γ=0 and γ=1). The average initial structural stiffness was 1.4 kN/mm and 1.7 kN/mm for the GLT-UHPFRC1 beams with UL and HBV beams, respectively. The elastic response of the GLT-UHPFRC1 beams with HBV connector is stiffer and closer to the TCC response with the perfect composite action. As for the load bearing capacity, the GLT-UHPFRC1 beams with HBV connectors had an average ultimate load-carrying capacity Q_{ULT} = 130 kN which is 20% higher than that of the UL beams at 108 kN. However, the GLT-UHPFRC1 beam with UL connector exhibited a slightly greater structural ductility (μ = 1.6) with respect to the ones with HBV connectors (μ = 1.3).

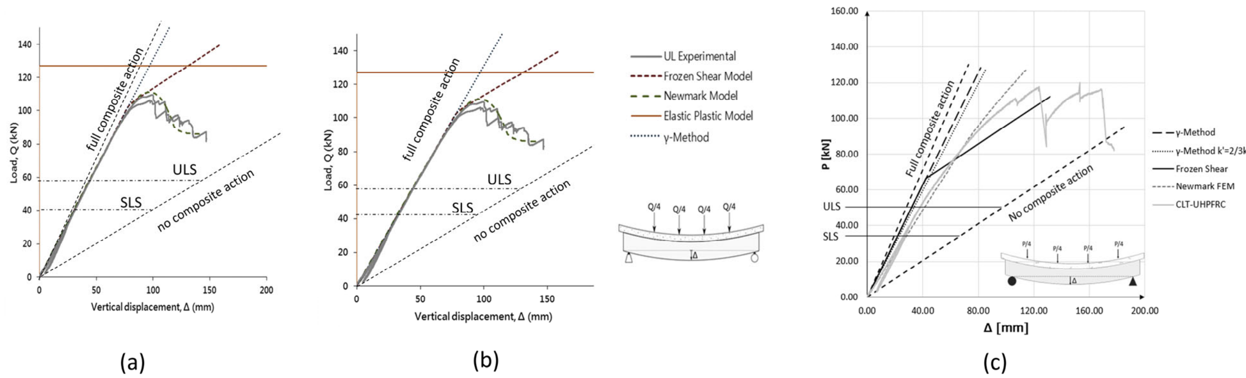


Figure 6. Comparison of load-deflection (P- Δ) curves for GLT-UHPFRC1 timber (a) with UL connector and (b) HBV connector; as well as (c) CLT-UHPFRC2 slab.

4. Conclusions

The present work investigates the use of UHPFRC in timber-concrete structures as for composite beam and slab. As original contribution, a multi-criteria design approach was presented and the flexural strength and vibration were experimentally validated in real scale. Based on the present results, the Timber-UHPFRC structures appear as promising system to reduce the self-weight and increase the slenderness.

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6. Acknowledgements

We would like to acknowledge the National Sciences and Engineering Research Council of Canada funding and the NSERC Industrial Research Chair on Eco-responsible Wood Construction (CIRCERB) for supporting the present research. We would like to acknowledge Mr. Keven Duran and Ms. Julie Frappier of Nordic Engineered Wood for the donation of timber beams as well as Dr. Dominic Corvez and Mr. Gaston Doiron of Lafarge North America Inc. and Mr. Julian Peña Cruz of King for the donation of the UHPFRC mix material and assistance in the casting.