NEW SYSTEMS OF PRECAST BRIDGE DECKS MADE WITH ULTRA-HIGH PERFORMANCE FIBRE-REINFORCED CONCRETE

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Abstract

This research project aimed to develop various precast bridge slabs including ultra-high performances fiber reinforced concrete (UHPFRC), and a UHPFRC field-cast connection adapted for these precast slabs. Phase 1 of the project provided three innovative bridge slab designs: a reference slab made of high performances concrete (HPC), a hybrid slab incorporating high and ultra-high performances fiber reinforced concrete (HPFRC and UHPFRC), and a UHPFRC slab. Test conducted in laboratory demonstrated that slabs made with UHPFRC fulfilled easily requirements of crack openings and ultimate strength specified in the CSA Bridge Code. The UHPFRC field-cast connection developed in Phase 2 of the project was combined with precast slabs developed in Phase 1 and tested in laboratory. The tests confirmed that HPC slabs linked with the UHPFRC connection provided similar maximum crack openings, stiffness and ultimate strength as the equivalent cast-in-place HPC slab. Moreover, utilization of the UHPFRC connection between precast hybrid slabs provided smaller crack width and superior ultimate strength than specifications of the CSA Bridge Code.

Résumé

Le projet de recherche avait pour but de développer des dalles préfabriquées pour les ponts incorporant du béton fibré à ultra-hautes performances (BFUP) et un joint de clavage en BFUP coulé sur chantier. Trois concepts de dalles de pont innovateurs ont été conçus en Phase 1: une dalle de référence en béton hautes performances (BHP), une dalle hybride comprenant des bétons fibrés à hautes et ultra-hautes performances (BFHP et BFUP), et une dalle en BFUP. Les essais en laboratoire ont démontré que les dalles incorporant du BFUP ont respecté les exigences de fissuration et de résistance ultime du Code des Ponts CSA. Le joint de clavage en BFUP développé en Phase 2 a été combiné aux dalles de pont développées en Phase 1 et a été testé en laboratoire. Les essais ont confirmé que des dalles en BHP reliées par le joint en BFUP procurent des ouvertures de fissures, une rigidité et une résistance ultime similaires à celle d'une dalle en BHP coulée en place. De plus, le joint de clavage en BFUP entre dalles préfabriquées hybrides conduit à des ouvertures de fissure inférieures et à une résistance ultime supérieure aux exigences du Code des Ponts CSA.

1. INTRODUCTION

Decks are the most severely loaded bridge components in service conditions. They are exposed to aggressive environment and high level of cyclic loading, thus they are frequently affected by corrosion, delamination and cracking problems. Throughout North America, decks present extensive deterioration related to de-icing salts sprayed on their surface, and to the increase of traffic volume and intensity. Many bridge decks have reached the end of their service life and need a rehabilitation [1, 2], and billions of dollars are spent each year in North America to repair or replace these critical structural elements [3].

Outstanding mechanical and durability properties of ultra-high performances fiber reinforced concretes (UHPFRC) make them ideal materials to repair or replace existing bridge infrastructures. In North-America, UHPFRC applications on bridges were till today mainly field-cast joints connecting precast slabs in reinforced concrete [4, 5, 6]. For most precast bridge decks, UHPFRC connections allow elimination of post-tensioning in the slab and reduce significantly formwork size for casting the joint. Moreover, configuration of rebar lap splice in the joint can be simplified by using straight bars without bend. Despite these simplifications, in some cases there is still a congestion with the two reinforcement layers of the HPC slab, the rebar added sometimes along the joint and the shear connectors of the girders. Precast bridge decks can be further optimized.

The research project objectives were to design and evaluate the mechanical behavior of various precast bridge slabs including UHPFRC (Phase 1), and then design a UHPFRC field-cast connection and measure the mechanical behavior of bridge decks with this connection (Phase 2).

2. EXPERIMENTAL PROGRAM

2.1 Design of precast slabs and UHPFRC connection

The selected reference structure in this study was a simply supported 30 m long and 11.7 m wide bridge supported by 4 longitudinal welded wide flange steel girders (depth = 1400 mm, width = 348 mm) spaced at 3 m. The slab thickness is 200 mm, asphalt thickness is 65 mm and barriers cross-section is 450 mm wide by 350 mm height.

Precast slabs were designed by Lachance [7] following the CSA Canadian Highway Bridge Design Code [8]. Industrial partners of the project asked for the development of reinforced concrete slabs avoiding pre-stressed components. Thus, the reinforcement was optimized for three designs in reinforced concrete (Figures 1a to 1c): a HPC deck, a Hybrid deck including a 170-mm HPFRC bottom layer and a 30-mm UHPFRC top layer, and a ribbed UHPFRC deck. The total reduction of conventional reinforcement in comparison to the HPC deck was 55 % and 64 % for the Hybrid and UHPFRC designs respectively.

The design of the UHPFRC field-cast connection was carried out by Verger Leboeuf [9] using nonlinear finite elements (NLFE) models. Based on parametric studies, the connection joint selected for this project (Figures 1e to 1g) had a closed shape, exposed aggregates interfaces and was 200 mm wide due to the rebar lap splice of 10 d_b (150 mm for 15M rebars).

2.2 Materials properties

Table 1 presents the 28 days mechanical properties of the four self-consolidating concretes used in the project. A HPC was used as a reference because it is commonly used in bridges. A HPFRC-1%, having a water/binder ratio of 0.3, 10 mm coarse aggregates and 1 %-vol. of 35 mm steel fibers, was selected for the bottom layer of the hybrid slab to allow a reduction of the reinforcement. A UHPFRC-2% was considered for all field-cast connections due to his very high mechanical strength and adhesion to existing concrete. A UHPFRC-4% was selected for the top layer of the hybrid slab for its exceptional water-tightness and durability characteristics. The UHPFRC-2% and UHPFRC-4% had a water/binder ratio of 0.2, maximal aggregate size of 0.6 mm, respectively 2 %-vol. and 4 %-vol. of 13 mm steel fibers. They both present a strain-hardening behavior under uniaxial tension (ε_{ft}, Table 1). These UHPFRC were developed at Polytechnique Montreal and are distributed by King Packaging Materials.

All reinforcing bars were 400W steel grade. Yield strength of 15M bars were measured at 438 MPa and 400 MPa respectively for Phase 1 and Phase 2 of the project, similarly yield strength of 20M bars were 438 MPa and 415 MPa.

2.3 Experimental programs

Phase 1 experimental program included ten slabs with a length of 3 m and a total width of 0.6 m (Figure 1). Three identical specimens were built for the HPC and hybrid slabs and four were built for the UHPFRC slabs. The first two specimens of each group were subjected to a quasi-static loading up to failure, the first one in positive bending and the second one in negative bending. The remaining specimens were submitted to cyclic loading, however this part of the experimental program is not discussed in the paper.

Phase 2 experimental program included five deck systems with a length of 3 m and a total width of 1.2 m. The deck systems were one reference cast-in-place HPC slab without connection joint (Figure 1d), two precast HPC slab systems (Figure 1e) and two precast Hybrid slab systems (Figure 1f) with a transverse UHPFRC joint. The precast systems were including 2 precast 0.5 m wide slabs and a 0.2 m wide field cast UHPFRC connection. The first specimen of each precast systems was subjected to quasi-static loading up to failure, while the second specimen was subjected to a one-million cyclic loading prior to the quasi-static loading to failure.

Table 1: Measured mechanical properties of concretes at 28 days

Properties	HPC	HPFRC-1%	UHPFRC-2%	UHPFRC-4%
f_c (MPa)	61.0	96.3	131.4	134.8
f_t (MPa)	4.07	4.90	7.56	10.5
ε_{ft} (%) *	-	-	0.25	0.17
E (MPa)	40 000	40 000	38 300	38 500
ν (-)	0.209	0.271	0.228	0.218

* : Strain measured at the maximum tensile strength (f_t) for hardening materials

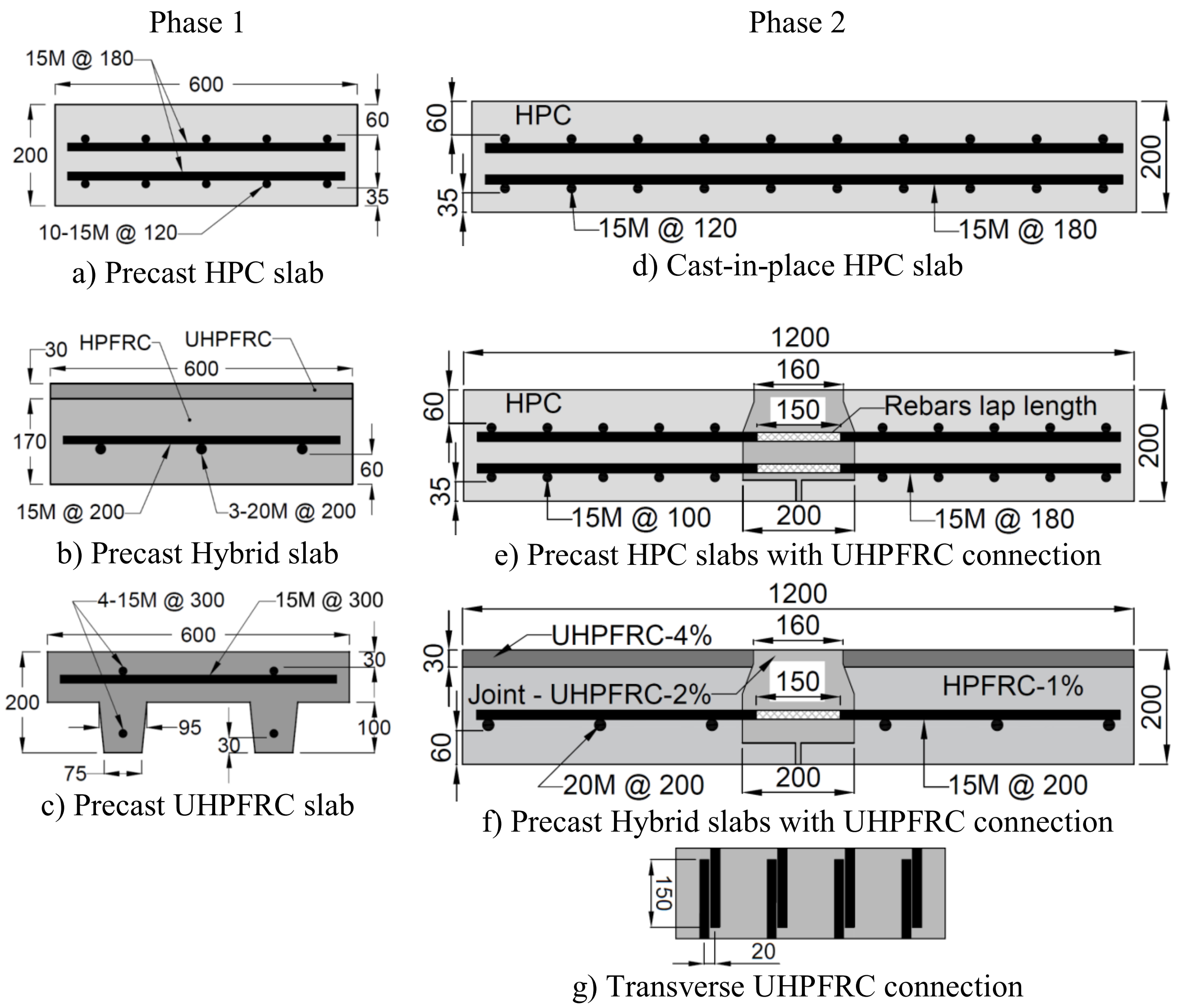


Figure 1: Slab cross-sections and UHPFRC connection, Phase 1 : a) to c), Phase 2 : d) to g)

2.4 Test setups

Two similar test setups were used for the project with the objective to reproduce partially the reference bridge conditions. The specimens were tested in simply supported conditions using a set of rollers spaced at 2.8 m representing the longitudinal girders (Figure 2).

A 490-kN actuator was used to apply the load at a loading rate of 0.2 kN/sec for the quasi-static tests. In Phase 1, the load was applied in two points and provided a four-points bending condition. In Phase 2, the load was applied at the deck midspan (third-points bending condition), but slightly eccentric in the longitudinal bridge axis (at 275 mm of the center of the UHPFRC joint). This critical configuration was adopted to verify the capacity of the rebar lap splice in the UHPFRC joint to transfer shear and bending loads between the precast slabs.

During the tests, set of instruments detailed in Figure 2 recorded mid-span deflection, strain in transverse reinforcement, crack opening at slab bottom face and crack opening at slab-joint interfaces when applicable.

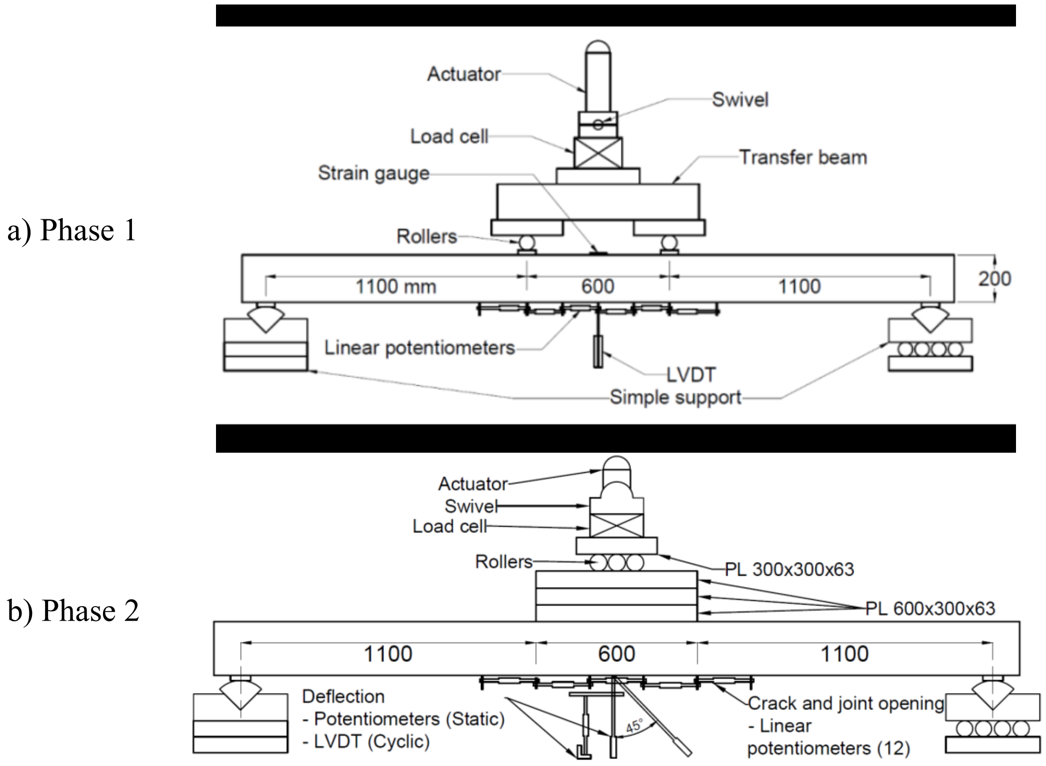


Figure 2: Laboratory test setups (dimensions in mm)

3. RESULTS AND ANALYSIS

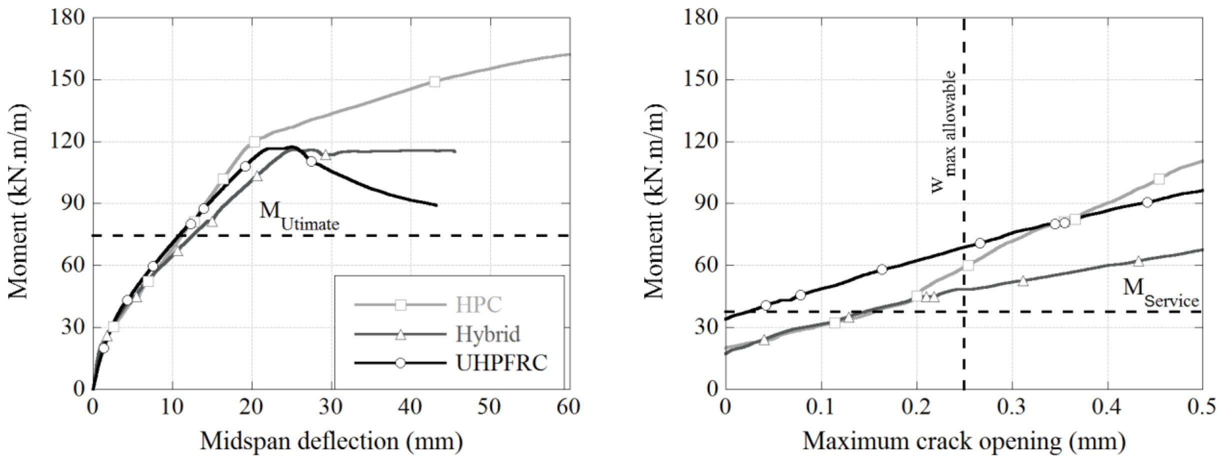
3.1 Precast slabs (Phase 1)

The moment-deflection behavior measured under quasi-static loading of precast slabs without connection (detailed in Figure 1a to 1c) is plotted in Figure 3 and 4 for positive and negative bending, respectively. The minimal static strength required by the CSA Bridge Code [8] is indicated with a dotted line. All precast slabs showed a linear elastic behavior, followed by a nonlinear behavior due to the initiation and propagation of bending cracks, ending by a stabilization of strength governed by the contribution of fibers (if applicable) and rebar yielding. All precast slabs exceeded easily the CSA factored design moment of 74.2 kNm/m ($M_{Ultimate}$).

The HPC slab showed rebar yielding at 120 and 94 kNm/m for positive and negative bending, and an ultimate strength of 163 and 112 kNm/m, respectively. The asymmetrical configuration of the Hybrid design led to a different behavior in positive and negative bending. In positive bending (UHPFRC layer in compression), cracking moment was reached at 17 kNm/m and the reinforcement yielded at 116 kNm/m. Under negative bending moment (UHPFRC layer in tension), the behavior remained elastic up to 64 kNm/m and the slab reached maximum resistance of 96 kNm/m. The UHPFRC slabs behaved similarly under positive and negative bending. When the elastic strength was reached at the tensile face of the slab (17 kNm/m and 25 kNm/m respectively for positive and negative bending), the UHPFRC entered the strain-hardening domain and a reduction of the slab rigidity was observed. This nonlinear stage continued until maximum strength was reached at 117 and 141 kNm/m respectively, indicating that the reinforcement yielded. A discrete macrocrack formed in the region of constant bending moment, and the specimen entered the final stage of its behavior, the strain-softening domain. A gradual reduction of resistance was observed toward the bending capacity provided by the reinforcement.

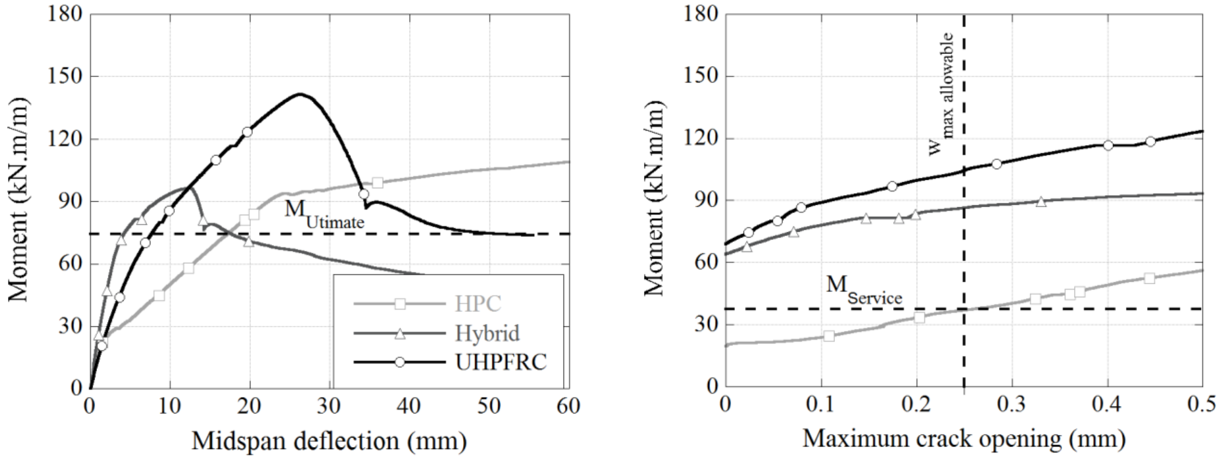
Figure 3b and 4b show the bending resistance according to the maximum crack width for positive and negative bending, respectively. The bending moment to consider in service conditions is indicated with a horizontal dotted line ($M_{Service}$), whereas the maximum crack width allowable of 0.25 mm specified in CSA Bridge Code [8] is indicated by a vertical dotted line. The curves begin at the cracking moment observed on the moment-deflection diagrams in Figure 3a and 4a. In positive bending, all designs presented a maximum crack opening inferior to the criterion in service conditions (w_{max} = 0.16, 0.15 and 0.02 mm for HPC, Hybrid and UHPFRC slabs, respectively). In negative bending, the HPC slab exhibited a maximum crack width of 0.26 mm, surpassing slightly the CSA limit, whereas Hybrid and UHPFRC designs showed no crack in service conditions.

Phase 1 of the project has demonstrated that precast Hybrid and UHPFRC decks with an important reduction of reinforcement developed in the project fulfill all requirements of CSA Bridge Code [8]. Phase 2 was then launched with the objective to develop and validate a UHPFRC transverse connection adapted to these precast slabs.



a) Moment vs. mid-span deflection b) Moment vs. maximum crack opening

Figure 3: Behaviour of slabs under positive bending



a) Moment vs. mid-span deflection   b) Moment vs. maximum crack opening

Figure 4: Behaviour of slabs under negative bending

3.2 Precast slabs with UHPFRC connection (Phase 2)

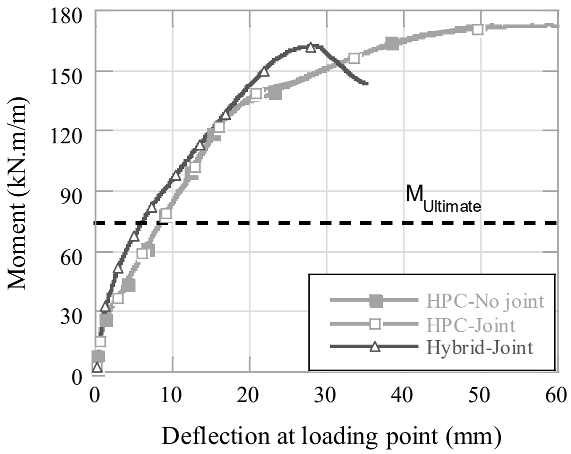
As shown in Figure 1d to 1f, the experimental program of Phase 2 is one step closer to a bridge deck configuration, since specimens included precast slabs connected with a transverse field-cast joint. The program included only the precast Hybrid slab along with the precast and cast-in-place HPC decks. The Hybrid slab was selected rather than the UHPFRC slab because it was considered more promising for rapid integration in bridge decks by industrial partners involved in the project. The configuration selected for the UHPFRC connection was described in Section 2.1 and illustrated in Figure 1g. The connection had only one layer of reinforcement in the Hybrid deck, instead of two layers in the HPC deck.

The moment-deflection behavior under quasi-static loading of the precast slabs connected with a UHPFRC joint is illustrated in Figure 5a with the factored design moment required by the CSA Bridge Code [8] at ultimate limit states. The moment-maximum crack opening behavior is plotted in Figure 5b with the service moment and the 0.25 mm maximum crack opening allowed in service conditions. All bridge decks showed a linear elastic behavior, followed by a nonlinear behavior due to the initiation and propagation of bending cracks. Finally, the HPC slabs ultimate strength was governed by rebar yielding, while the Hybrid slab maximum strength was determined by the combined action of fibers and reinforcement followed by a progressive strength reduction to the rebar yielding capacity only.

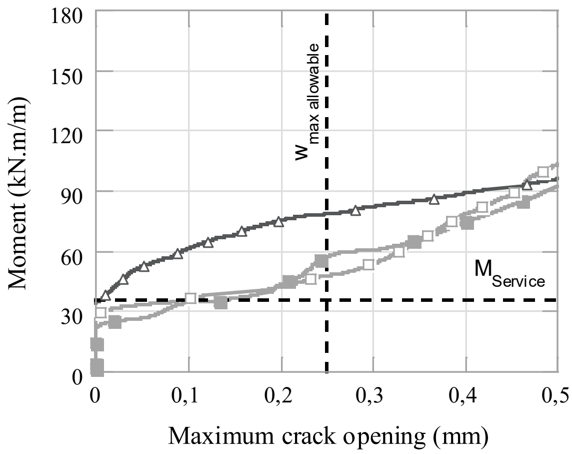
The precast HPC slabs with UHPFRC connection and the cast-in-place HPC slab (without connection) exhibited exactly the same stiffness and an ultimate strength of 170 kNm/m (Figure 5a). The precast Hybrid slabs with connection reached an ultimate strength of 162 kNm/m. Due to the better crack control provided by the HPFRC and UHPFRC layers, no crack were measured in the precast Hybrid slab at the service load level ($M_{Service}$), while the cast-in-place HPC slab had crack opening of 0.09 mm and the precast HPC slab with connection had crack width of 0.07 mm at the same load level (Figure 5b).

All deck systems largely exceeded the factored design moment ($M_{Ultimate}$) of 74.2 kNm/m and exhibited cracks inferior to the maximum crack opening of 0.25 mm specified in the CSA Bridge Code [8]. The 200 mm UHPFRC transverse joint adequately transferred the applied load between precast HPC deck elements as no difference was noted with the cast-in-place

HPC slab behavior. Moreover, the UHPFRC joint transfer adequately bending and shear loads between precast Hybrid slabs having only one reinforcement layer instead of two (Figure 1).



a) Moment vs. deflection



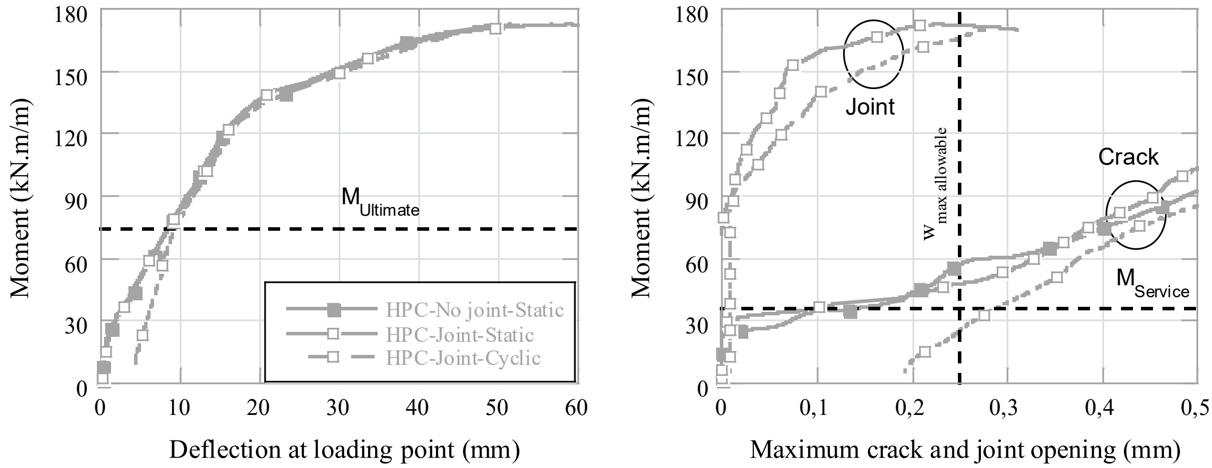
b) Moment vs max. crack opening

Figure 5: Behaviour of slabs with & without connection under positive bending

The second specimen of each deck systems studied in Phase 2 was submitted to a cyclic loading. The experimental setup for the cyclic tests was the same as in quasi-static tests (Figure 2b), except that the actuator was applying a cyclic load at a frequency of 4.4 Hz. The minimum and maximum loads were 20 kN and 100 kN respectively, which corresponded to the application of transverse moments of 10.4 kNm/m and 52.2 kNm/m respectively. The minimum load was related to the configuration of the loading system and was higher than the dead load moment in the reference bridge deck. The maximum load was selected equal to 120 % of the CSA truck axle to test the UHPFRC joint in a critical condition for both transverse and longitudinal moments. One million loading cycles was applied. After the application of the cyclic loading, the specimens were loaded in quasi-static condition up to failure.

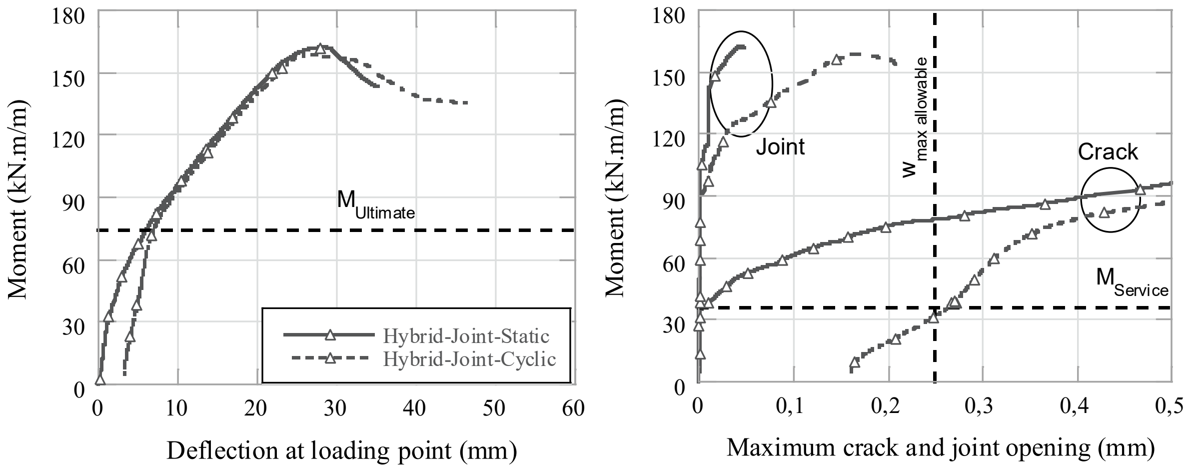
Figure 6a shows the moment-deflection behavior of the precast HPC slabs with a connection for the quasi-static tests following the cyclic loading, and its twin specimen as well as the cast-in-place HPC specimen, both loaded only under quasi-static loading. Figure 6b illustrates the moment-maximum crack opening behavior. After the cyclic loading, the precast HPC specimen with a connection showed the same mechanical behavior than the precast HPC slab with connection and the cast-in-place HPC slab subjected only to a quasi-static loading (Figure 6a). The ultimate strength of these slabs was equal to 170 kNm/m. The maximum crack opening of the precast HPC slab increased from 0.07 to 0.29 mm in service conditions after the cyclic loading, while the slab-joint interfaces remained closed. A transverse bending moment around 80 kNm/m (twice the service moment) was required to open the slab/joint interfaces.

The Hybrid slab behavior with the UHPFRC joint is illustrated in Figure 7a. The response to the two loading regimes (only quasi-static vs. cyclic & quasi-static loadings) was similar in terms of stiffness and ultimate strength. The ultimate strength of the Hybrid slab was 159 kNm/m with cyclic loading and 162 kNm/m with quasi-static loading only. The maximum crack opening measured in the precast Hybrid slab increased from 0.00 mm to 0.26 mm in service conditions and the slab/joint interfaces remained closed (Figure 7b). Again, a transverse bending moment around 80 kNm/m (twice the service moment) was required to open the slab/joint interfaces.



a) Moment vs. deflection b) Moment vs max. crack opening

Figure 6: Behaviour of HPC slabs with connection under positive bending after 1x10^{6} cycles



a) Moment vs. deflection b) Moment vs max. crack opening

Figure 7 - Behaviour of Hybrid slabs with connection under positive bending after 1x10^{6} cycles

4. CONCLUSIONS

The objectives for this research project were to design, build and evaluate the mechanical performance of precast bridge decks incorporating UHPFRC in slabs and connection joints.

Phase 1 of the project demonstrated that utilization of UHPFRC in precast slabs allows significant material reduction without compromising ultimate strength and ductility measured under quasi-static loading in comparison with the reference HPC slab. Reinforcement was reduced by 55 % and 64 % for the Hybrid and UHPFRC slabs, respectively. In the case of the hybrid design, major savings of workmanship can be further expected by the use of only one reinforcement layer. Additionally, the ribbed UHPFRC design led to a reduction of 36 % of concrete volume compared to full-depth slabs. All slab designs surpass easily the requirements of crack openings and ultimate strength specified in the CSA Bridge Code. Moreover, Hybrid and UHPFRC slabs showed thinner crack openings in service conditions in comparison to the reference HPC slab.

Phase 2 of the project confirmed that the proposed transverse UHPFRC field-cast connections between precast HPC decks provided similar crack openings, stiffness and ultimate strength as equivalent cast-in-place HPC decks subjected to quasi-static and cyclic loadings. Utilization of the proposed transverse UHPFRC connection between precast Hybrid slabs provided smaller crack width and superior ultimate strength than specifications of the CSA Bridge Code. Thus, the significant reinforcement reduction (55 %) in the Hybrid slabs and in the joint did not affect the mechanical performance. Finally, the transverse UHPFRC joint remained closed for a load level corresponding to twice the service moment. This observation should lead to a negligible water and aggressive ions infiltration through slab/joint interfaces and thus provide an extended durability of the joint.

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