Shear strengthening of concrete T-beams with lateral layers of UHPC

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Abstract. Concrete T-beams are commonly used in building slab systems and bridge decks. They may require strengthening in shear when they are deteriorated or when loading requirements increased. This research project studied the shear behaviour of concrete T-beams using cast-in-place Ultra High-Performance Concrete (UHPC) layers as a lateral strengthening method avoiding beam depth modification. Three UHPC strengthened beams together with one reference reinforced concrete beam were tested in monotonic three-point bending. Parameters investigated include the thickness of UHPC layers and the presence of steel anchors at the UHPC-concrete interface. A digital image correlation (DIC) technique was used to investigate the strain distribution of T-beams during the testing. Strain distribution, failure modes and strengthening effects provided by the UHPC lateral strengthening were analyzed. Results show that UHPC strengthening can substantially improve the stiffness and shear capacity of concrete T-beams, 25 and 50 mm lateral layers increased by 102% and 113% the T-beam shear capacity, respectively. Typical bending-shear behaviour were observed on each strengthened beam with UHPC layers. A final shear failure was observed in the T-beam with 25 mm UHPC layers and 50 mm UHPC layers without anchors, while a combination of shear and bending failure was noted in the T-beam with 50 mm UHPC layers and steel anchors. The steel anchors at the UHPC-concrete interface can further increase the ultimate shear capacity and beam stiffness, but at a limited extent. Therefore, experimental results confirmed that cast-in-place UHPC lateral layers are an effective way to strengthen existing concrete T-beams with inadequate shear capacity

1 Introduction

Concrete bridges owners in Canada as well as in North America are facing the challenge of execute durable repair and strengthening. National Research Council of Canada Institute for Research in Construction reports that about 40% of all bridges operating in Canada are more than 30 years [1]. A proportion of approximately 30 ~ 40% of them are in urgent need of replacement or rehabilitation in North America [2]. The rehabilitation work on beams (or girders) is one of the major focuses for maintaining or improving their structural behaviours, particularly in bending and shear.

The repair and strengthening methods on deficient beams consist generally to use high performance construction materials including steel, concrete, or fiber reinforced polymer (FRP) [3, 4]. Steel plates and FRP both have high modulus and tensile strength, providing a high strengthening effect with small increase on the size of the original cross-section of the structural component. However, some drawbacks were observed through decades of research. Firstly, premature failure of such strengthening methods is observed and governed the ultimate capacity of the repaired components due to high possibilities of delamination at the interface between the repair layer and concrete substrate [5]. Secondly, steel plates may significantly increase the beam weight in some cases and thus are install only locally, they also require significant effort for installation (weight, anchors). FRP have a low weight, but requires multiple steps of installation (surface, grout, layers, etc.) and may experience degradation due to environmental effects. Besides, the epoxy resins used for connecting the steel or FRP to the concrete substrate are sensitive to the temperature variation and thus have a low fire resistance [6].

Cement-based materials perform better in terms of compatibility with the concrete substrate. However, normal strength concrete or fiber reinforced concrete strengthening require a considerable increase of the cross-section of the original structure and still have limited strengthening effect due to their limited compressive and tensile strengths. Debonding may also occur due to the limited bond strength at the interface.

Recent studies indicated that ultra-high performance fiber reinforced concrete (UHPC) has outstanding mechanical properties including large strain capacity, and extremely low porosity and transport properties that provide an

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exceptional durability [7]. The high compressive and tensile strengths of UHPC can improve the structural capacity with limited increase on the cross-section of the structural component. Moreover, the smaller difference of modulus of elasticity in UHPC compared with steel and FRP plates and their greater adherence and bond strength compared with concrete and fiber reinforced concrete leads to a much lower possibility of delamination between the repair layer and the concrete substrate. Furthermore, more durable repairs can be achieved through the superior durability properties of UHPC [7]. Therefore, rehabilitation of concrete beams using UHPC is expected to have promising performance and needs to be investigated.

Various research groups have investigated the feasibility and efficiency of UHPC in repairing and strengthening existing reinforced concrete components. Available research results focus mainly on the improvement of bending and shear behaviours of bridge decks, beams or slabs repaired by UHPC layers on bottom or top side [8]. However, the shear behaviour of the beams repaired by lateral UHPC layers to avoid beam depth increase are scarcely studied, although this solution seems more effective for enhancing the beam stiffness and capacity [9]. The quantitative improvement and related influencing parameters of beam lateral strengthening need to be further investigated.

This research studied the shear behaviour of concrete T-beams using cast-in-place UHPC layers as a lateral strengthening method without increasing the beam depth. Three-point bending tests were conducted on both the reference reinforced concrete beam and three UHPC strengthened beams. Parameters investigated include the thickness of UHPC layers and the presence of steel anchors at the UHPC-concrete interface. Strain distribution, failure modes and strengthening effects provided by the UHPC lateral strengthening were analyzed.

2 Experimental program

2.1. Beam configuration

The investigation of the shear capacity of concrete T-beams included a reference beam (named as TS-R) having 3 meters long with shear span of 1 meter, 400 mm height, 500 mm flange width and 250 mm web width. Its design was based to obtain the next conditions: (1) typical shear span-depth ratio in the range of 2~2.5 corresponding to the usual bending-shear behaviour; (2) shear cracks and failure occurring mainly within the 1-meter shear span (critical shear region); (3) bending failure avoided in all the cases.

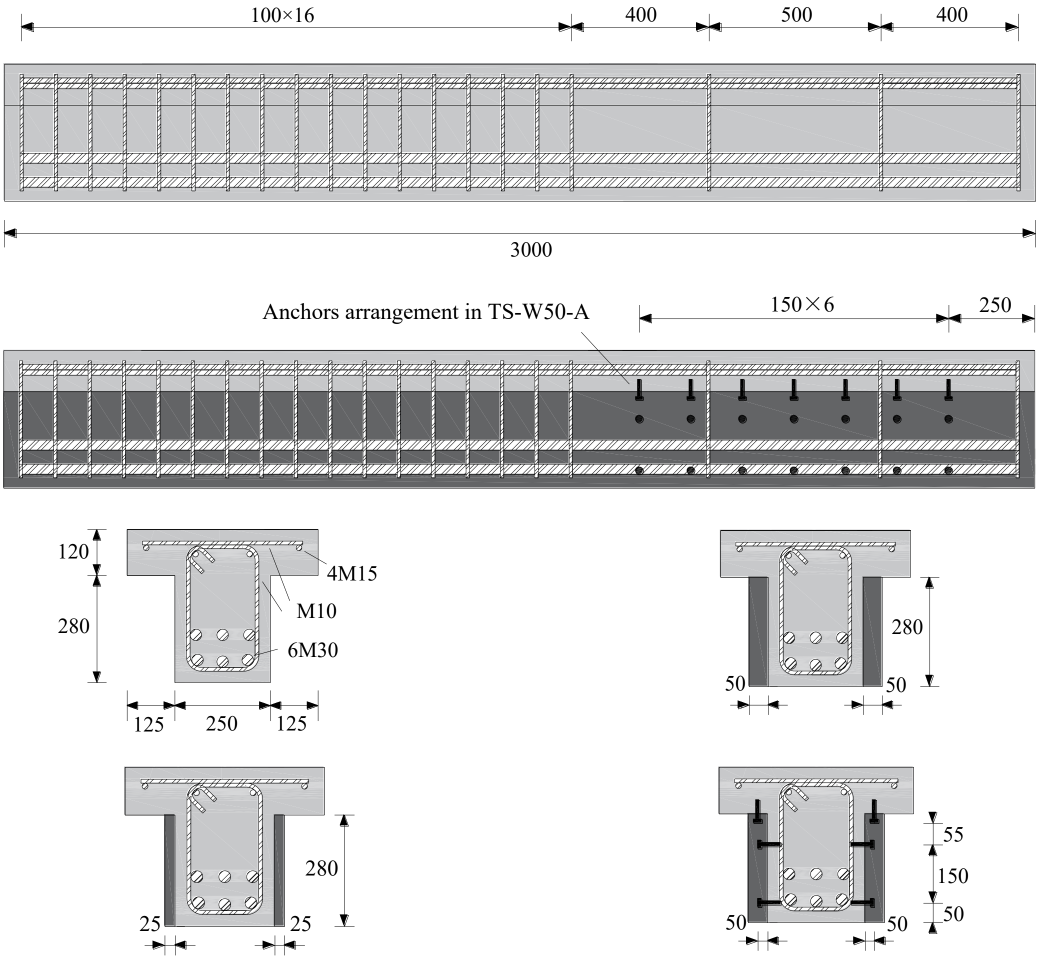


Fig. 1. Configuration of the four concrete T-beams tested: a) Lateral view of TS-R beam; b) lateral view of TS-W50-A beam; c) cross-section of TS-R beam; d) cross-section of TS-W50 beam; e) cross-section of TS-W25 beam; f) cross-section of TS-W50-A beam

The reference beam configuration is shown in Fig. 1a and 1c. Six M30 bars were used as longitudinal rebars in the tensile region to avoid bending failure, and M15 were used as longitudinal rebars in the compressive region. The stirrups in the shear span were M10 bars with 500 mm spacing, while the spacing decreased to 100 mm outside the critical shear span to avoid shear failure in this region. The configuration of the three beams strengthened with lateral UHPC layers are presented in Fig. 1d to 1f, where TS-W50 is the T-beams strengthened with 50 mm lateral layers, TS-W25 represents the T-beams strengthened with 25 mm lateral layers, and TS-W50-A is the same T-beams as TS-W50 except with the addition of steel anchors at the UHPC-concrete interface. The UHPC lateral layers cover all the web regions along the T-beams on both sides. The anchors were typical concrete screws used for this purpose (10 mm in diameter and 70 mm in length) and were installed at the interface with an electric drill, with 35 mm length in UHPC layers. The arrangement of the anchors is shown in Fig. 1b and 1e.

2.2 Materials

The normal strength concrete (NSC) used in this experimental program is the commercial product of Béton Préfabriqué du Richelieu (BPDR), it has a water/binder ratio of 0.37 and a maximum aggregate size of 14 mm. The UHPC used is a mix designed by Polytechnique Montreal and commercialized under the name UP-F3 by Sika Canada. It has a water/binder ratio of 0.2, a 3% of fiber in volume and aggregate with diameter less than 1 mm. The compressive strength of NSC and UHPC at 28 days were 26.8 MPa and 144.5 MPa, respectively A more complete characterisation was completed at the beam test day (200 days). The results are shown in Table 1, compressive strength and modulus of elasticity of NSC were measured on 102 mm × 204 mm cylinders while those of UHPC of UHPC were tested on 76 mm × 152 mm cylinders, tensile properties of UHPC were measured on dog-bones with 50 mm×100 mm in the central area. Besides, concrete retarder admixture was applied on the formwork before casting the NSC to obtain, after de-molding and cleaning the surface under high water pressure, a typical exposed aggregate surface prior the UHPC pouring. Longitudinal rebars and stirrups were both wieldable steel bars with Grade 400. The measured yield strength of M30, M15, and M10 rebar were 470.1 MPa, 414.4 MPa and 426.2 MPa, respectively.

Table 1. Material properties of NSC and UHPC at beam test day.

Properties	Concrete	UHPC
Compressive strength	29.8 MPa	150.8 MPa
Modulus of elasticity	27.4 GPa	41.1 GPa
Ultimate tensile strength	-	12.7 MPa
Tensile hardening strain	-	2449 mm/m

2.3 Test procedure

Monotonic static three-point bending tests were conducted on the four T-beams, as shown in Fig. 2. The critical shear span is 1 meter while the other shear span is 1.6 meters. The load was applied by a 1000 kN hydraulic actuator at a rate of 0.25 kN/s and was distributed on the 500 mm flange of T-beams through a transfer beam. It is important to mention that the support plates on both ends only support the 250 mm web of the original T-beam, rather than the enlarged width with UHPC layers, to represent that the repair layers are not supported in real practice. Load cell, strain gauges, as well as LVDTs shown on Fig. 2 were installed to obtain the load-deflection curves, and load-strain curves of rebars and stirrups. A DIC system was installed on one side of the critical shear span to monitor the strain distribution during the loading. The procedure included drawing of randomly distributed black dots on one beam lateral face, installation of two high-speed cameras, and analysis of results with the VIC3D computer program. The data of load cell, strain gauges and LVDT were recorded every 0.2 seconds, while the photos of the DIC system were taken every 3 seconds.

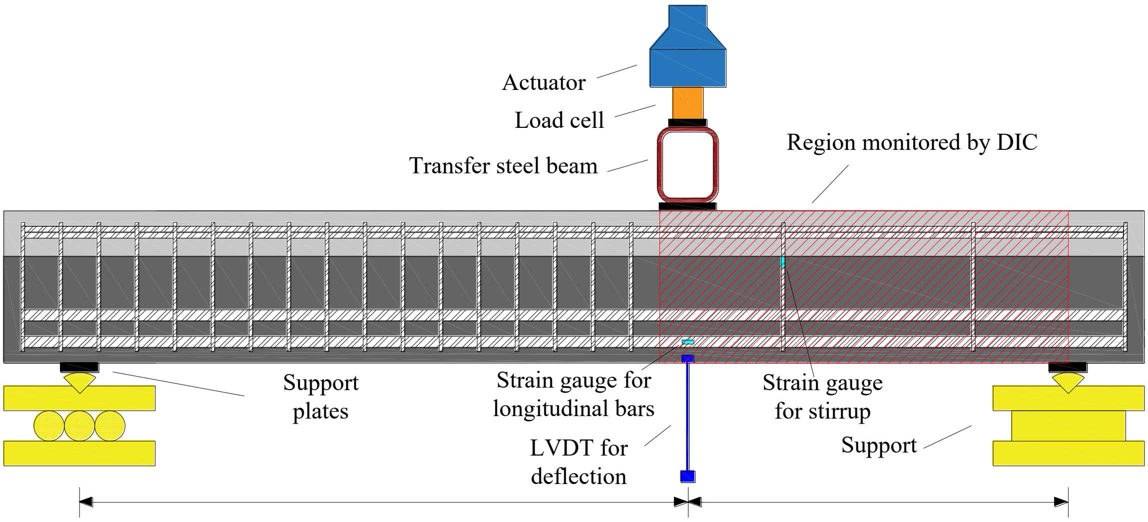


Fig. 2. Test setup of concrete T-beams.

3 Results and discussion

3.1. Load-deflection curve

The load-deflection curves of the four concrete T-beams are presented in Fig. 3.

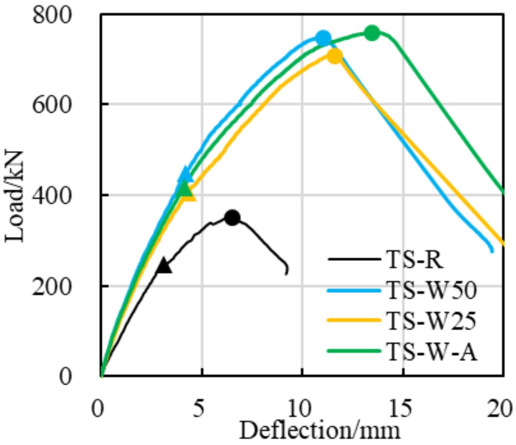


Fig. 3. Load-deflection curves of the four concrete T-beams

Five stages can be identified on each curve of T-beams. First, an elastic stage takes place without visible crack on the beam. Second, a bending crack stage starts with several cracks perpendicular to the horizontal axis at the bottom of the T-beams. Third, a shear crack stage occurs with diagonal cracks detected at mid-height of the web that propagate towards the near support and the loading plate. The triangular markers on Fig. 3 indicate the 1st shear cracking observed (load values shown in Table 2) and thus identify the start of this stage accompanied by a more obvious decrease of the beam stiffness. The 1st shear crack of the reference beam TS-R can be easily detected from the load-deflection curve. However, the 1st shear cracks of strengthened beams were determined with the DIC, from which the initiation of 1st shear cracks can be detected when the principal tensile strain of diagonal shear cracks exceeds the tensile hardening strain of UHPC (Table 1). Fourth, the shear failure stage starts, with the connection and widening of the shear cracks. When the critical shear crack was formed, the beam stiffness was largely decreased until the peak load was reached. The shear peak load is indicated by circle markers in Fig.3 (load values shown in Table 2). Fifth, the post-peak stage initiates with a sudden decrease of load and an increase of deflection. The residual loads supported by the strengthened beams after the sudden reduction were around 200-300 kN, which was similar to the residual load of the reference beam TS-R, indicating the total loss of the effect of UHPC layers at that point.

Based on the experimental results, it can be concluded that considerable strengthening is achieved on both shear capacity and beam stiffness by using UHPC lateral layers. Moreover, the decrease of stiffness after the 1st shear crack formation was mitigated by the strain-hardening behaviour of the UHPC on the lateral layers.

3.2. Load-strain curve

The strain developments in longitudinal rebars and in stirrups are shown in Fig. 4a and 4b, respectively. Unfortunately, the gauge on the rebar of the TS-W25 beam was damaged during the beam production. The symbol “x” at the end of the curve indicates the breakage of the strain gauge, which may be due to an excessive deformation measured. When the M30 rebar and M10 stirrups of beams yields at approximately 2350 µm/m (f_y= 470 MPa) and 2100 µm/m (f_y= 420 MPa) respectively, the strain increases continuously with negligible increase of load.

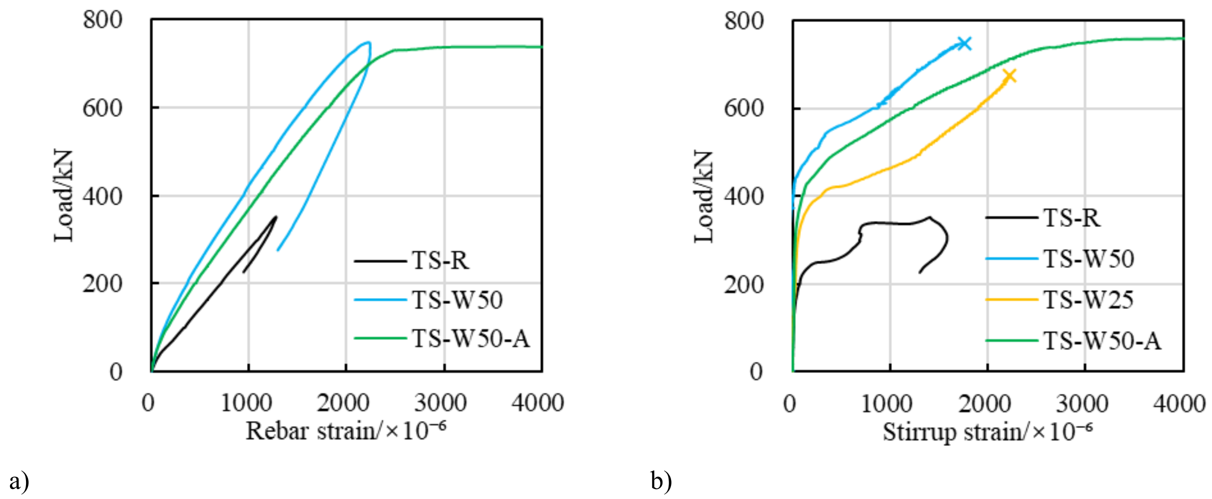
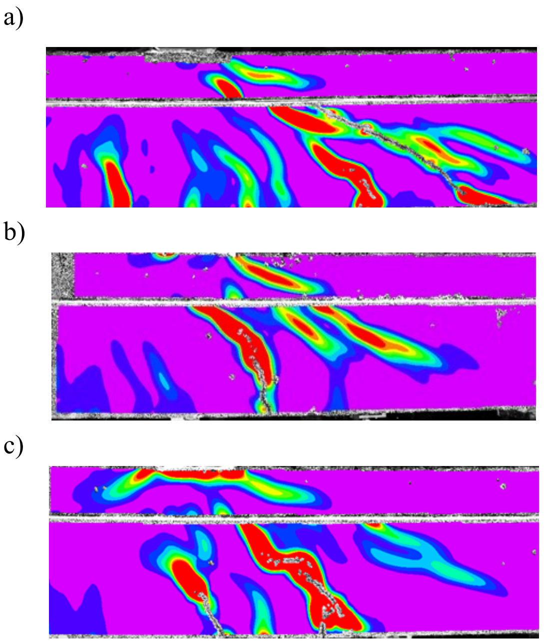


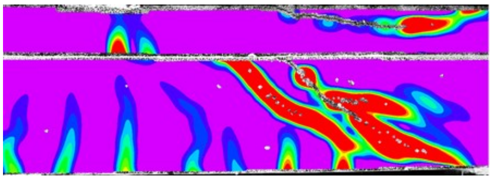
Fig. 4. Strain development of concrete T-beams: a) Strain in longitudinal rebars; b) strain in stirrups

The failure modes of the concrete T-beams can be distinguished with strain results of Fig. 4. In the reference TS-R beam, the strain in longitudinal rebar is far from the yield strain at ultimate load, confirming that the bending capacity was not reached. The stirrup achieved a higher strain but did not reach the yield strain too because the main shear crack propagates above the location of strain gauge, as shown by the DIC measurement in Fig. 5a). Therefore, it is concluded that the behaviour of the TS-R beam was controlled by a shear failure. Besides, TS-W50 and TS-W25 beams with UHPC thickness of 25 and 50 mm showed a similar failure. The strain in rebar of the TS-W50 beam approached closely the yield strain, however the shear failure occurred before leading to excessive deformation in the stirrup gauge and loss of its signal. Though longitudinal strain in TS-W25 was broken before the test, it is reasonable to estimate that the strain has not reach the yield strain as for the TS-W50 beam. Finally, the TS-W50-A beam with anchors presents yielding in both rebars and stirrups at the peak load, which indicates a mixed bending-shear failure mode. It can be concluded that the installation of anchors transformed the shear failure to a bending-shear failure.

3.3. Principal tensile strain distribution of concrete T-beams

The principal tensile strain recorded by the DIC system on the right side of the four concrete T-beams (Fig. 2) are depicted in Fig. 5 at peak load. The different colors in the figure indicate tensile strain ranging from 0 to 10000 με, it allows illustration of the bending and shear cracks in the concrete (TS-R beam) or in UHPC lateral layers (strengthened beams).





d)

Fig. 5. Distribution of principal tensile strain of concrete T-beams at peak load using DIC technique: a) TS-R; b) TS-W25; c) TS-W50; d) TS-W50-A

The cracking pattern and failure modes of the four beams can be observed and confirmed the strain measurements in rebar and stirrups. The reference TS-R beam showed clearly shear failure, with limited strains in bending cracks. All the strengthened beams experienced a bending-shear behaviour, showing very high strains in both bending and shear cracks. The TS-W25 beam failed in shear with limited effect by the bending-shear cracks. The critical shear crack propagates throughout the web and flange, leading to a direct stress transfer from the loading location to the support location. Besides, TS-W50 and TS-W50-A beams showed obvious bending-shear behaviour, in which the critical shear crack comes from the diagonalization of bending cracks. Considering both the DIC and the strain in rebars, it can be concluded that TS-W50 beam ended with a shear failure, while the TS-W50-A beam experienced a bending-shear failure, which is a more ductile failure with larger deflection at the peak load (Fig. 3).

3.4. Strengthening effect of UHPC layers

The improvement of the mechanical behaviour of strengthened beams using UHPC lateral layers can be evaluated by the increase of shear capacity and beam stiffness. Table 2 presents different parameters of the beams' mechanical behaviour, P_{1st} represents the 1st shear cracking load, P_u represents the ultimate shear capacity. The beam stiffness K_e represents the stiffness in the before the shear crack stage, calculated with load and displacement coordinates at 10% and 40% of the peak load, in this range the three strengthened beams are in elastic stage, while the reference beams TS-R is in the bending crack stage. The beam stiffness K_s represents the stiffness during the shear crack stage, evaluated between 60% and 80% of the peak load. δ values listed in Table 2 correspond to the difference between load P or stiffness K calculated for strengthened beams and the same value for the reference TS-R beam, values are in percentage. A positive δ represent an increase in comparison to the reference beam.

Table 2. Test results and strengthening effects measured on the concrete T-beams.

Test results	TS-R	TS-W25	TS-W50	TS-W50-A
P_{1st} (kN)	247.4	405.4	449.1	418.1
P_u (kN)	352.1	710	748.5	759.1
K_e (kN/mm)	84.7	101	111.4	118.8
K_s (kN/mm)	48.9	52.8	57.4	59.5
Strengthening effects				
δP_{1st} (%)*	-	+ 63.9	+ 81.5	+ 69.0
δP_u (%)*	-	+ 101.7	+ 112.6	+ 115.6
δK_e (%)*	-	+ 19.3	+ 31.6	+ 40.3
δK_s (%)*	-	+ 8.0	+ 17.4	+ 21.5

*: In comparison to the reference beam TS-R

For all parameters considered, UHPC lateral strengthening improve substantially the stiffness and shear capacity of concrete T-beams. For the load-carrying capacity, 25 and 50 mm UHPC lateral layers increased by 63.9% and 81.5% the T-beam 1st shear cracking load (P_{1st}), and by 102% and 113% the T-beam ultimate shear capacity (P_u). For the beam stiffness, the elastic stiffness (K_e) increased by 19.3% and 31.6% in TS-W25 and TS-W50 beam respectively, while the stiffness during the shear crack stage (K_s) is enhanced by 8% and 17.4%. The improvement in stiffness is approximately proportional to the UHPC layer thickness, 25 mm of the TS-W25 beam providing about half of the stiffness increase obtained with 50 mm in the TS-W50 beam. However, the improvement of shear load-carrying capacities is not proportional to the UHPC layer thickness. The first 25 mm of UHPC layer offered a very strengthening effect, while the increase to 50 mm layers brought a limited supplementary improvement. This observation may be linked to the transition from true shear failure in the TS-W25 beam to the bending shear failure in TS-W50.

The influence of anchors on the shear behaviour of T-beams with lateral layers is also noted in Table 2. The anchors installed on the interface between concrete substrate and UHPC layers at the spacing of 150 mm can help further increase the stiffness before the shear cracking stage (K_e), the stiffness during the shear cracking stage (K_s) and the ultimate load (P_u), while the load at 1st shear crack (P_{1st}) was not improved. However, the extent of these increases is limited, it may come from the two reasons. First, the bond performance of the interface between UHPC and concrete is substantial to provide a superior performance of the strengthened beams without anchors, the anchors contribution is thus limited with such bond performance of the UHPC. Second, the yielding of both longitudinal rebars and stirrups may limit the further increase of shear capacity of T-beam that could be obtained with anchors. The detailed effect of anchors needs further experimental or numerical investigations.

4 Conclusions

This research project has investigated the shear behaviour of concrete T-beams using UHPC lateral layers. One reference concrete and three UHPC strengthened beams with different layer thickness and anchor condition were tested through static three-point bending with shear span of 1 meter. Load, deflection, strain and cracking patterns were recorded and analysed to study the failure mode and the strengthening effect of UHPC lateral layers. Conclusions can be drawn as follows:

(1) UHPC lateral strengthening can substantially improve the stiffness and shear capacity of concrete T-beams. 25 and 50 mm lateral layers increased by 63.9% and 81.5% the T-beam 1st shear cracking load, and by 102% and 113% the T-beam ultimate shear capacity. For the beam stiffness, the stiffness before the appearance of shear crack increased by 19.3% and 31.6% in TS-W25 and TS-W50 beam respectively, while the stiffness during the shear crack stage is enhanced by 8% and 17.4%.

(2) Different failure modes are observed in UHPC strengthened concrete T-beams according to the thickness of UHPC lateral layers. All the strengthened beams experienced bending-shear behaviour, instead of a shear behaviour for the reference beam. The beams with UHPC layers of 25 mm and 50 mm without anchors led to a shear failure, while 50 mm layers with anchors conducted to a bending-shear failure.

(3) The installation of anchors can help further increase the strengthening effects of UHPC lateral layers in several aspects, but with a limited extent. Although the yielding of both longitudinal rebars and stirrups may influence the results, the limited improvements observed with anchors may indicate the substantial bond of UHPC on concrete interface is sufficient to obtain an adequate performance of the strengthened concrete beams without anchors.

It was demonstrated that UHPC lateral layers are very efficient to strengthen concrete T-beams with inadequate shear capacity without increase the beam height.

Acknowledgements

The authors would like to acknowledge the financial support obtained from NSERC and MITACS (Canadian granting agencies), and industrial partners involved in the research project (BPDL, City of Montreal, Euclid, Jacques-Cartier and Champlain Bridges inc., Sika and St-Lawrence Seaway). The authors also thank the technical team of Polytechnique Montreal Structural Laboratory.

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