

EXPERIMENTAL INVESTIGATION OF PULL-OUT RESPONSE OF COMPOSITE CONNECTION MADE OF UHPFRC MATERIAL

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Abstract

In the conventional composite connection systems, the headed stud assembly was adopted to transfer the forces between the concrete and structural steel members. This paper describes research that investigated the use of an alternative mechanical connection system between the embedded steel plate and the ultra-high performance fibre-reinforced concrete (UHPFRC) beam for enhancing its pull-out response. The influence on the peak pull-out load carrying capacity and failure mechanism of the connections from the addition of 2 % volume-fraction of short steel fibres was investigated. The results of experimental tests indicated that the peak pull-out load carrying capacity of the connections tends to significantly increase, as the fiber contents were increased from 0 % to 2 %. Instrumentation based on the 3-D digital image correlation (DIC) technique allowed for a detailed study of the variation of crack width during the test and its relation to the pull-out loading. A substantial improvement in the connection's load-slip response and stiffness was found for specimens made of UHPFRC material with fibre over those without fibres.

Résumé

Parmi les systèmes de connexion traditionnels, les goujons sont souvent adoptés pour transférer les efforts entre le béton et les éléments de charpente en acier. Cet article décrit une recherche explorant l'usage d'un système alternatif pour connecter une platine métallique noyée dans une poutre en béton fibré à ultra-hautes performances (BFUP) pour améliorer sa réponse à l'arrachement. On a étudié l'influence de la force d'arrachement au pic et le mécanisme de rupture de la connexion avec un BFUP comportant 2 % de fibres métalliques courtes. Les résultats des essais montrent que la force ultime d'arrachement augmente de façon importante quand le pourcentage de fibres passe de 0 à 2 %. Une instrumentation basée sur la corrélation tridimensionnelle d'images numériques a permis d'étudier en détail la variation d'ouverture des fissures pendant l'essai et sa relation avec l'effort d'arrachement. On obtient une amélioration substantielle de la réponse effort-glisement de la connexion, et de sa rigidité, pour les spécimens en BFUP par rapport à ceux ne comportant pas de fibres.

1. INTRODUCTION

With the ever increasing concerns about the structural adequacy of buildings and infrastructures, particularly in harsh environments with limited funding for ongoing maintenance, a significant need exists to develop highly durable and rapidly constructed structural systems. To this aim, recent advances in the development of high-performance materials allow for the introduction of innovative girder configuration systems using the UHPFRC material as flange and steel plate as web. The proposed composite member is anticipated to result in a durable building or bridge superstructure construction with reduced life-cycle cost, longer life spans, and enhanced environmental sustainability. To cope with the higher cost of the high performance material, innovative designs should be implemented in detailing of composite members to make sure that the material is best used where it was required.

There has been a significant advancement in the use of UHPFRC in the structural composite sections in the few recent years [1], [9]. Several unique performance characteristics, including high load carrying capacity and stiffness, large displacement ductility capacity as well as excellent durability were reported for structural members made of UHPFRC material [14, 15]. These members have the potential to significantly save dead load and to produce slender and attractive structural elements with lower maintenance costs [9].

Several recent researchers have investigated the detailed behavior of the composite connections between embedded steel plate and the concrete members made of conventional and high-performance concrete material. However, very limited research studied the pull-out response of these types of connections under pull-out load, particularly for those made of UHPFRC material [1], [10].

The primary objective of the current study was to examine the influence of UHPFRC mixes with two different fiber volume-fractions, i.e., $V_f = 0\%$ and 2% , on the pull-out response of composite connections. Total relative slip between embedded steel plate and concrete beam, crack pattern, and crack width was measured through the DIC system, and were evaluated against each of the specimen.

2. EXPERIMENTAL INVESTIGATION AND TEST SETUP

The fabrication and testing was conducted at the I.F. Morrison Structural Engineering Laboratory at the University of Alberta. The experimental program is described in this chapter. The connection fabrication process is described first, followed by a discussion of the material and the test setup. The specific details of connection and instrumentation are then presented. Finally, the loading procedure is described.

2.1 Specimen configuration

The experimental work consisted of two groups of tests on composite connections made of an embedded steel plate in UHPFRC material incorporating 0% and 2% volume-fraction of short steel fiber. The mix composition is shown in Table 1. A UHPFRC mix with locally available mix composition and low water/binder ratio—suitable for in-situ casting—was developed based on the mix compositions presented in [11, 12]. The test specimens were constructed with a $150 \times 150 \times 600$ mm beam. The embedded steel plate overall dimension of $300 \times 140 \times 12$ mm (length \times width \times thickness) was selected in this research. The geometry of the test specimens is schematically represented in Figure 1. The connections were designed

to prevent any premature shear and flexural failure in the concrete beam. In each batch, one connection specimen along with three 50 x 50 x 150 mm prisms and three 50 mm cubes were cast at the same time. A 10M bar cage was used in all the connection specimens to improve its flexural capacity. A double headed stud (DHS) with the shank and head diameter of 15.9 mm and 50 mm was placed at the centroid of the shear connection to improve the resistance of shear key against the splitting tensile stresses (along the plate) in the concrete shear key.

An Ω -shaped hole through the embedded steel plate was used as the primary mechanism to transfer the tension load between the connection components. See Figure 1. The embedded steel plate was clamped to the steel form by a pair of angles at both sides of plate to firmly secure the plate in its proper location prior to concrete placement. Special care was taken to make sure a consistent embedment length was used for all the samples. The axis of each embedded plate was checked after the casting to be perpendicular to the formed beam surface.

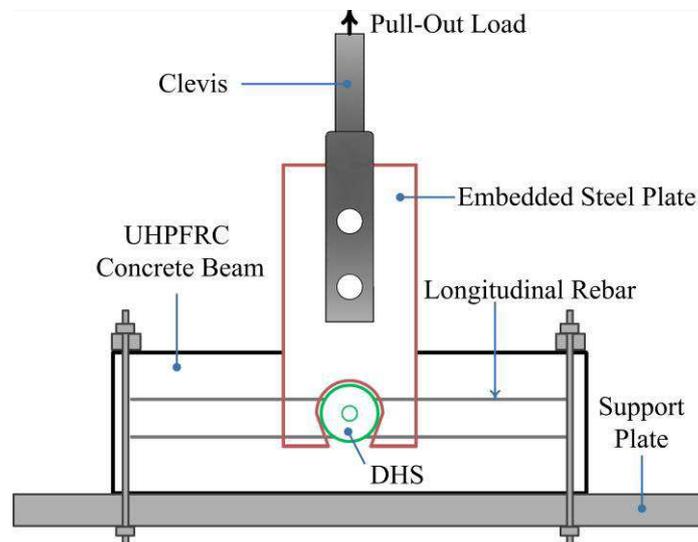


Figure 1: Overall pull-out specimen configuration.

Table 1: Mix composition of Alberta UHPFRC

Components	kg/m ³
Portland Cement	967
Silica Fume (SF)	338
Fine Sand	542
Fiber ($V_f=0\%$ or 2%)	0 or 312
Added Water	184
Superplasticizer (SP)*	20
Total Water**/Binder***	0.18
*Solid content of SP; ***Binder = Cement + SF	
**Total Water = Added Water + Water from SP	

2.2 Test Setup

An overall view of the test setup and a schematic diagram of the test assembly configuration are shown in Figure 1. The test setup was designed to simulate the composite connection under tensile loading. The pullout tests were conducted in the MTS 1000 universal testing machine equipped with hydraulic grips, and having a maximum load capacity of 1000 kN and an actuator range of 150 mm. Displacement-controlled loading was used to apply the quasi-static tensile load at a rate of 0.2 mm/minute. The concrete beam was tied to the bottom cross-head through the support plate. The embedded steel plate was bolted to the clevis which was held in the top grip of the machine. In order to prevent the slip of the assembly under the tensile load, a slip-critical connection between the embedded steel plate and the MTS grip was used.

The tensile load applied to pull-out specimens was monitored using the internal load cell integrated in the MTS 1000 test frame. A DIC measurement system along with a pair of LVDTs was used to measure the slip between the embedded steel plate and the concrete beam during the test. Data from different instruments was captured through a built-in data acquisition system using the DIC control system. All the horizontal and vertical LVDTs along with MTS load cells were connected to an internal data acquisition system in Vic-3D 2009.

The front face of the concrete beam was painted with a flat white latex paint. A random speckle pattern was then applied to the painted surface of the specimen using a flat black spray paint to produce small circular black dots covering approximately half of the specimen's surface. In order to highlight the slip between embedded steel plate and UHPFRC beam as well as the crack growth during the experimental test, the Vic-3D software was used (Correlated Solutions Inc., 2010). This was carried out by comparing the grey value pattern in each single image (taken every 3 second during the test) with that in the initial reference image. A Vic-3D image of the composite connection specimen after failure is given in Figure 2. All the specimens were cured under wet burlap and plastic immediately after painting was completed to prevent the formation of micro-cracking in the matrix [11]. The mean speckle diameter was measured to be approximately 2-3 mm and the spacing was 3-5 mm. Digital images were continuously taken by the digital image correlation system cameras throughout the loading process of each test.

3 EXPERIMENTAL RESULTS AND DISCUSSION

The overall pull-out load-slip response of the composite connection specimens during testing is provided in this section. In order to capture the post peak behaviour of composite connections, all the specimens were loaded well beyond the peak pull-out. The results of the experimental tests are summarized below.

3.1 Composite Connection with UHPFRC Material without Fibres

Figure 2 provides an overall view of the crack on the surface of the concrete beam for the composite connection made of UHPFRC material with $V_f = 0\%$ after failure. For each test series, two connection specimens were tested along with a series of concrete cubes and prisms—designated as companion specimens—to characterize the mechanical properties of concrete in compression and tension.

The compressive strength of 50 mm cubes was determined according to ASTM C109 and an average peak compressive strength of 135 MPa was recorded. The results of the unnotched

prism specimens—tested under third-point loading— were used to derive the equivalent tensile strength of the UHPFRC material [11, 12]. An inverse analysis technique originally proposed by AFGC and further developed by the first author [12] was used and an average peak equivalent tensile strength (PETS) of 7.9 MPa was derived for UHPFRC material with $V_f = 0\%$. More information about the mechanical properties of the UHPFRC in compression, and flexure can be found in the literature [11, 12].

The pullout load-slip behavior of the composite connection with UHPFRC material with $V_f = 0\%$, is given in Figure 3(a). The formation and propagation of the cracks in concrete beam was monitored by the DIC system and the results are presented in Figure 3(b). No microcracks were observed in the concrete beam during the initial loading stage until a load level of 45 kN was reached. A linear elastic response was observed during this first stage of loading. Once the cracking load was reached, a series of microcracks were formed and propagated downward along the longitudinal axis of the embedded plate. As a result, a pair of vertical macrocracks was formed in both sides of the specimen. Immediately after the formation of these cracks, a series of longitudinal cracks (parallel to beam longitudinal axis) were formed in the mid-height and at mid-span of the beam and rapidly propagated toward the top reactions. As a result a breakout crack was formed in both front and back sides of the specimen. See Figure 3(b). The rate of propagation of these cracks was much higher than those observed in the composite connection specimens with $V_f = 2\%$ fiber content.

A large fluctuation in the pull-out load-slip response of the connection was observed. See Figure 3(a). This is mainly associated to the rapid crack growth in the UHPFRC material without fibers, as there are no randomly distributed steel fibers to bridge the cracks and sustain the load once the stresses in the matrix exceed the cracking tensile strength of the UHPFRC matrix.

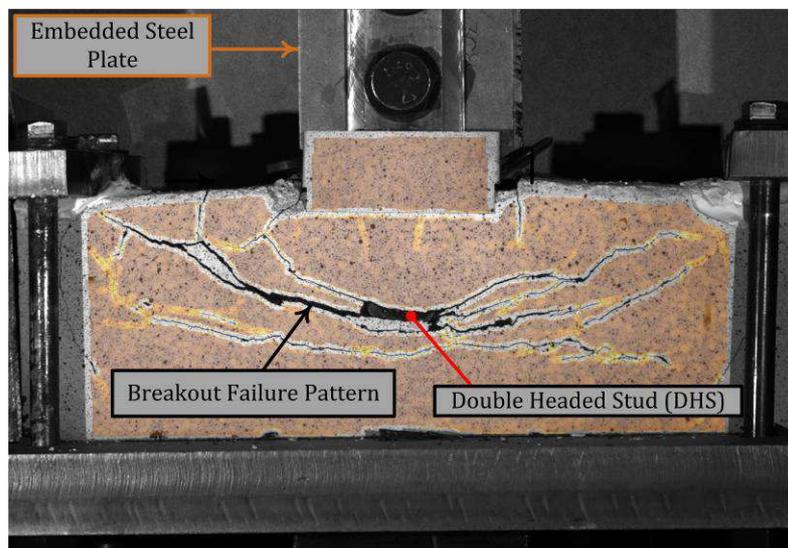


Figure 2: Failure of composite connection made of UHPFRC material with $V_f = 0\%$.

The variation of the inclined cracks at the edges of embedded plate and the breakout crack against the pullout loading is presented in Figure 3(b). As more displacement was applied, a series of microcracks was initiated around the head of the double headed stud (DHS) and the

concrete pieces were ejected from both front and back side of concrete beam. This is because the thin cover around the double headed stud—with thickness of 10 mm—was not able to accommodate the stress around the DHS. The inclined cracks at the top were further developed until they joined the breakout cracks. The maximum inclined crack width was observed to be less than 1 mm at the end of the failure. No significant slip (around 0.5 mm) between the embedded steel plate and top side of concrete beam was observed, which indicates that the proposed Ω -shaped connection provided a sufficient mechanical interlock between the concrete beam and the embedded steel plate. Instead the failure crack continued to widen, as the loading increased. See Figure 3.

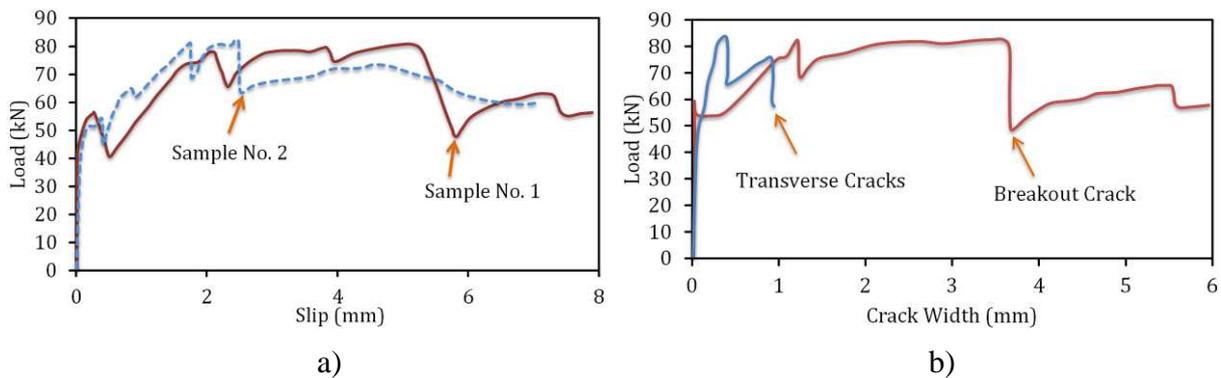


Figure 3: a): Load-slip response; b) Load-crack width response

3.2 Composite Connection made UHPFRC Material with $V_f = 2\%$

A general view of the composite connection made of UHPFRC material with $V_f=2\%$ after the failure is shown in Figure 4. An average peak equivalent tensile strength (PETS) of 8.4 MPa for UHPFRC mixes with $V_f=2\%$ were derived from the inverse analysis technique [12]. Unlike the composite connection made of the UHPFRC material without fibers, with an unsteady load-slip response under pull-out loading, a stable pull-out slip behavior was observed for the specimens made of UHPFRC with 2% volume fraction of short steel fibers. Compare Figure 3 and 4. This significant improvement is most likely attributed to the fiber bridging effect which acts as a secondary load transfer mechanism after the crack was formed and propagated.

The width of splitting crack at the level of the extreme tensile fiber—located at the top side of the beam—along with the breakout crack width at the midspan of the UHPFRC beam were extracted from the data recorded by the digital image correlation (DIC) measurement system during the test and the results are depicted in Figure 6.

As given in Figure 5(a), no microcracking was observed at the early stage of loading. However, for both specimens, a series of vertical microcracks near the mid-span and next to embedded steel plate were detected, as the tensile stresses exceeded the tensile strength of the UHPFRC matrix. The presence of short steel fibers on the microcrack surface introduces the fiber bridging effect which suppresses the localization of the microcrack at the early stage of loading. They also prevent the rapid propagation of the cracks and would result in a significantly higher resistance to microcrack growth. As a result, the connection specimens were observed to sustain more loads—yet with lower stiffness—as the higher displacement was applied. See the nonlinear pre-peak response of connection in Figure 5(a). Once the peak

pull-out load was reached, a single vertical macrocrack (called splitting crack) was formed in the mid-span, where the tensile stress is maximum. See Figure 4. This crack then extended downward and gradually increased as the pull-out load increased. A splitting crack width of 1.15 mm at the peak pull-out load (PPL) was observed. See Figure 5(b).

The breakout crack was formed at the mid-span of the beam and located at the level of bottom horizontal reinforcement. The crack was initiated at a load level of 143 kN and curved diagonally toward the top reactions at both ends of the beam. See Figure 4. The breakout crack width at the PPL was found to be 0.98 mm, both the splitting and breakout cracks rapidly widened. A significantly higher rate of crack growth was observed after the peak load was reached.

While no significant slip between the embedded steel plate and the concrete beam was observed before the formation of the splitting crack, a substantial slip was observed after the splitting crack substantially widened and the breakout failure occurred. This is mainly because the splitting crack deteriorated the mechanical interlock between the concrete shear key and the embedded steel plate, which allows the embedded plate to be pulled out.

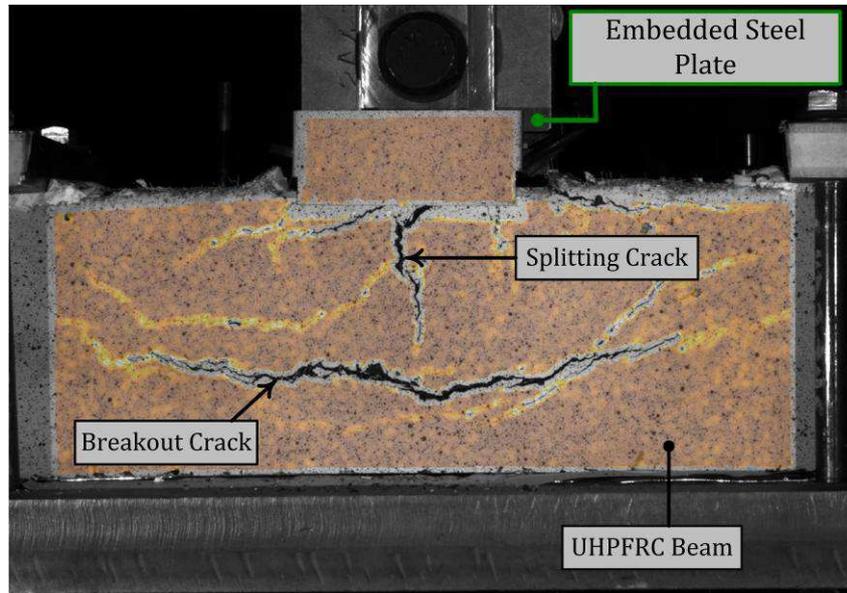


Figure 4: Failure of composite connection made of UHPFRC material with $V_f = 2\%$.

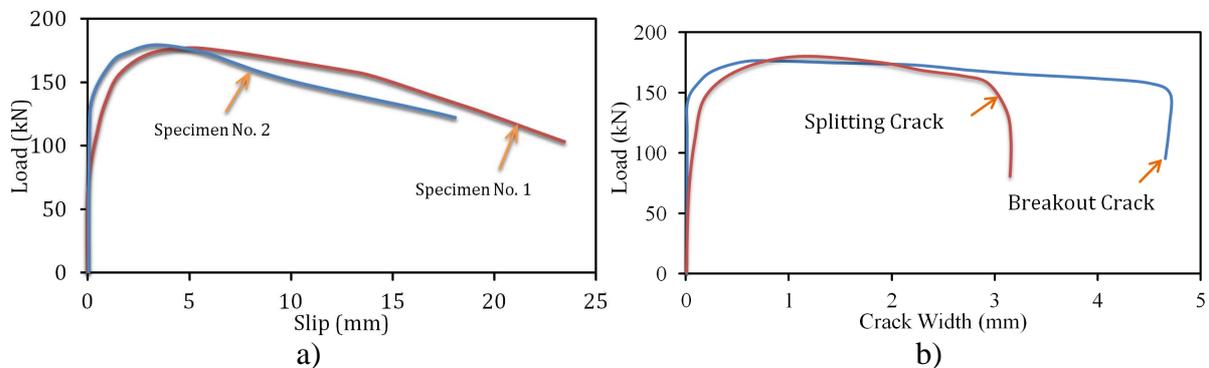


Figure 5: a): Load-slip response; b) Load-crack width response

3.3 Influence of fiber content on connection load carrying capacity

The results of experimental tests indicated that the failure of composite connection made of UHPFRC material without fibers takes place at a low deformation and is associated with a sudden drop in pull-out load-slip response. In contrast, the composite connection made of UHPFRC material with $V_f=2\%$ tends to show a ductile behavior under pull-out loading and can achieve significantly higher peak pull-out load. This feature is very beneficial in earthquake applications where the higher level of ductility in connections is essential.

Figure 6 shows the results of the changes in peak pull-out load (PPL) of composite connection, against the change in V_f for the composite connection with $V_f=0$ and 2 %. The results of experimental tests showed that the composite connection made of UHPFRC material with $V_f=2\%$ exhibited 130 % higher PPL than the connection made of UHPFRC material without fibers. This significant enhancement is mainly due to the improved mechanical properties of the UHPFRC material in tensile and shear which improve the mechanical interlock between embedded steel plate and the concrete shear key.

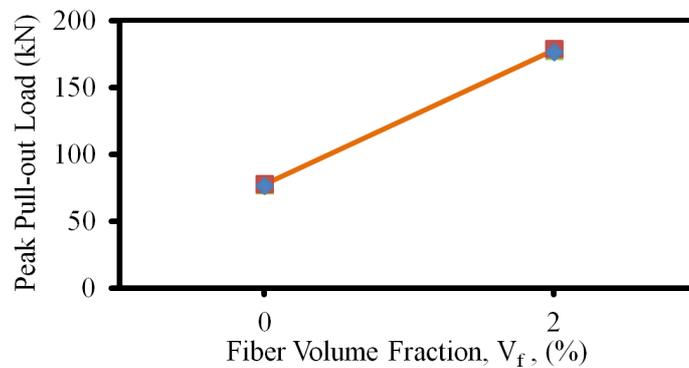


Figure 6: Influence of fiber content on load bearing capacity of composite connection.

4. CONCLUSIONS

The results of experimental tests on composite connections, made of embedded steel plate in UHPFRC beam, indicated that this connection is effective for many applications where a significant load carrying capacity and ductility under tension loading is required. This study established the following main observations and conclusions which are summarized as follows:

- The addition of short steel fibers to UHPFRC matrix was found to significantly improve the response of the connection under pull-out loading, mainly through the improvement in the mechanical properties of UHPFRC in tension and shear.
- The failure of composite connection was found to change from a brittle failure for specimens with UHPFRC material without fibers to a ductile failure for those with $V_f=2\%$. This is mainly due to contribution of steel fiber in limiting the crack propagation rate in the cracked sections.
- Compared to composite connections constructed with UHPFRC material without fibers, 130% improvement in the peak pullout load carrying capacity of the connection specimens made of UHPFRC material with 2% fibers was observed. This enhancement is mainly due to

the high mechanical properties of UHPFRC in tension and shears which significantly improve the mechanical interlock between concrete shear key and embedded plate.

- Compared with specimens made of UHPFRC material without fibers, a higher elastic stiffness with less degradation rate after the initiation of first crack was observed for specimens made of UHPFRC material with 2% volume fraction of short steel fibers.
- A large fluctuation in the load-slip response of the connections made of UHPFRC material without fibers was observed. In contrast a stable load deflection response was observed for those with $V_f = 2\%$. This is mainly because the UHPFRC material without fibers experiences a brittle behaviour under tension and shear.

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