3rd Specialty Conference on Material Engineering & Applied Mechanics
3e Conférence spécialisée sur le génie des matériaux et mécanique appliquée

Montréal, Québec
May 29 to June 1, 2013 / *29 mai au 1 juin 2013*

Pull-out Resistance of Composite Connections with High Performance Concrete

S. Kazemi[1], J.J. Roger Cheng[2,*]
Department of Civil and Environmental Engineering, University of Alberta, Edmonton, Canada
[1] Graduate Research Assistant; [2] Professor

Abstract: There have been increasing interests in using the conventional fiber-reinforced concrete (FRC) and ultra-high performance fiber-reinforced concrete (UHPFRC) in composite connection systems between steel webs and concrete flanges. This paper presents research from a study on the experimental pull-out test results of composite connections made of embedded steel plate secured in concrete beam via mechanical interlock. Two different types of concrete were used for the beam: UHPFRC material containing 2% volume-fraction of short steel fibers; and FRC material with 1% steel fiber content. An Ω-shaped hole, cut through the embedded plate, was used as the mechanical interlock system between the connection components. The influence on the pull-out behaviour and capacity of the composite connections from the different concrete types was of primary interests. The load-slip response, load-carrying capacity, and failure mode were investigated and the results are discussed in this paper. It was observed that the pre- and post-peak response, pull-out cracking load (PCL) and peak pull-out load (PPL) of composite connections are strongly influenced by the mechanical properties of the concrete.

Keywords: Fiber reinforced concrete (FRC), ultra-high performance FRC (UHPFRC), high performance concrete (HPC), pull-out tests, composite connections, load-slip response

1 INTRODUCTION

There has been a significant advancement in the use of ultra-high performance fiber-reinforced concrete (UHPFRC) in the structural composite sections in the last few years (Schmitt et al. 2005, Hechler et al. 2006, Feldmann et al. 2007, Hegger et al. 2009, Heinemeyer 2012). Several unique performance characteristics, including high load carrying capacity and stiffness, large displacement ductility capacity as well as excellent durability (structures with extended service life and low life-cycle costs) were reported for structural composite members made of UHPFRC material (Richard and Cheyrezy 1995, Rossi et al. 2005, Habel et al. 2006, Charron et al. 2007, Kazemi and Lubell 2011 and 2012). In addition, these members have the potential to significantly reduce dead load and to produce slender and attractive structural elements with lower maintenance cost and longer service life (Hegger et al. 2006, Feldman 2011).

Significant researches have been conducted over the past decade to investigate the mechanical properties of UHPFRC material (Chanvillard and Rigaud 2003, Rossi et al. 2005, Habel et al. 2006, Reineck and Greiner 2007, Graybeal and Davis 2008, Kazemi and Lubell 2011 and 2012). UHPFRC is a new class of advanced cement-based composite material that exhibits very high tensile and compressive strengths, exceptional post-cracking strain hardening and a high deformation capacity to the peak tensile strength through the use of discontinuous short steel fibers (Rossi et al. 2005; Habel et al. 2008). In addition, compared to the conventional fiber reinforced concrete, UHPFRC material was found to have significant shear strength, particularly for those with high fiber content (Kazemi and Lubell 2012).

While numerous studies in the past few decades investigated the response of the composite connection with conventional material, there is limited research on those constructed with FRC or UHPFRC material. The investigation of load transfer mechanism in the composite connection systems constructed with high performance concrete is of particular importance, as its higher load carrying capacity would result in higher stresses (e.g. shear, compression and tension stresses) along the interface between concrete and embedded steel. Thus, the connection detailing between the concrete and steel has to be carefully designed to meet higher demands for resistance to shear, compression and tensile stresses. Hegger et al. (2006) studied the response of composite connection with two different connection systems, i.e., conventional headed studs (HS) and direct embedment of steel web (DESW). They indicated that the headed studs attached to a steel plate that welded to web is not as efficient as the DESW with puzzle-strip holes. This phenomenon is more pronounced for the composite connection made of high performance concrete (Hegger & Rauscher 2006 and 2009, Feldman 2011).

The experimental responses of composite connection made of the embedded steel plate in ultra-high performance concrete (UHPC) under different loading configurations, including shear, tension and compression loading were investigated by Hegger et al. (2009). According to them, these types of connection are capable of carrying a significantly higher shear, tension and compression loads as compared with those made of the headed stud connection. This high load carrying capacity is attributed to the efficient mechanical interconnection between the UHPC and DESW. A high ductility was also reported for DESW connection (Hegger et al. 2009, Feldman 2011). It was indicated that the behaviour of these types of connections is governed by a series of variables including: concrete tensile strength, configuration of connection between embedded steel plate and concrete, the embedment length of plate, and the confining effect (Hegger et al. 2009, Feldman 2011, Heinemeyer et al. 2012).

In the current study a series of laboratory tests were conducted to examine the influence of two different concrete types on the response of the composite connections made of DESW with Ω-shaped hole. Ultra-high performance fiber reinforced concrete (UHPFRC) containing 2% volume-fraction of short steel fibers and fiber reinforced concrete (FRC) with 1% double hooked fiber were used for casting. This paper reports on the load-slip response, ultimate load-carrying capacity, and failure mode of the tested composite connections.

2 EXPERIMENTAL INVESTIGATION

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

2.1 Description of Pull-Out Specimens

The experimental work consisted of two groups of tests on composite connection made of embedded steel plate in FRC and UHPFRC materials. The geometry of the test specimens is schematically represented in Figure 1. The test specimens were constructed with a 150 x 150 x 600 mm concrete beam. The embedded steel plate overall dimension of 300 x 140 x 16 mm was selected in this study. The connections were designed to prevent any premature shear and flexural failure in the concrete beam. To prevent the flexural failure, the specimens were designed such that the flexural capacity of beam was at least 40% higher than the connection capacity prediction from the preliminary FEM modelling.

For composite connections made of UHPFRC material, a high performance EIRICH mixer was used. 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. For composite connections made of FRC, a 75 liter Gilson drum mixer was used. The mixer capacity allowed two specimens along with three 100 x 100 x 400 mm prisms and three 100 mm diameter x 200 mm long cylinders to be cast at the same time. The composite connection tests were conducted using two replicate test specimens for each type of composite connection. A 10M bar cage was used in all the specimens to improve the flexural capacity and prevent any potential failure modes in the FRC and UHPFRC concrete, as shown in Figure 1. A double headed stud was placed at the centroid of the Ω-shaped hole to improve the resistance of the concrete – surrounded by the hole – against the combined shear and splitting tensile stresses. The Ω-shaped hole was used as the primary component to transfer the tension load between embedded plate and concrete beam. The embedded steel plate was attached to the form by clamping a pair of angles to mold to firmly secure the plate in its proper location prior to concrete placement. Special care was taken to make sure a fixed embedment length (L_{em} = 100 mm) was used for all the connection specimens. The axis of each embedded plate was checked during the casting process to be perpendicular to the formed surface.

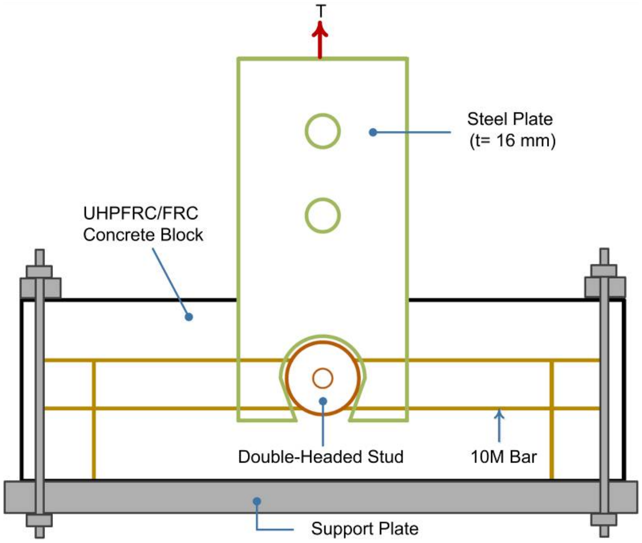

Figure 1: Overall pull-out specimen configuration.

2.2 Mix Composition

UHPFRC – A UHPFRC mix with locally available mix composition and low water/binder ratio (W/B = 0.18) which is suitable for in-situ casting was developed based on the mix compositions presented in Kazemi and Lubell (2011 and 2012), as detailed in Table 1. Type HE Portland cement was used in the mix as it was found to have the best compatibility with the other mix components. A high concentration of undensified Silica Fume (SF) was used in the mix having manufacturer specified properties of: bulk density = 250-300 kg/m^3; specific surface = 18-20 m^2/g; maximum particle size = 0.1 μm; greater than 98.9% SiO_2. The use of SF in UHPFRC material was found to significantly improve its mechanical properties in both tension and compression through the pozzolanic activity and by filling voids between the cement grains (Pfeifer et al. 2010). The SF also improves the rheological characteristics of the paste.

The polycarboxyl-based superplasticizer (SP) with a density of 1.1±0.02 g/cm^3 and 30% solids content was used to enhance the consistency for mix workability and improve the compressive strength. High-purity crushed quartz sand with a maximum grain size of 1 mm was used as the largest aggregate. Straight, smooth steel fibers with tensile strength of 2500 MPa were used. The fibers had diameter of d_f = 0.2 mm, length of l_f = 13 mm and shape factor (l_f/d_f) of 65.

Table 1: UHPFRC composition

Components	kg/m^3
Portland Cement	967
Silica Fume (SF)	338
Fine Sand	542
Fiber (V_f=0% or 4%)	0 or 624
Added Water	184
Superplasticizer (SP)*	20
Total Water**/Binder***	0.18

*Solid content of SP;
**Total Water = Added Water + Water from SP;
***Binder = Cement + SF

FRC – A 75 liter capacity drum mixer with a constant mixing speed of 20 rpm was used for mixing the FRC material. The FRC mix composition is listed in Table 2. Gravel was first mixed with all the sand for approximately 3 minutes. Afterward, type HS cement was added and mixed dry for another 2 minutes before water was added. All the water, superplasticizer, and high range water reducer (HRWR) were mixed together before being added to the dry mix. The FRC became fluid after approximately 3 minutes of adding the water. Hooked end Dramix steel fibers, which are cold drawn fibers with yield strength of 1100 MPa, a length of 30 mm, and an aspect ratio of 55 were used in the current FRC mix. Fibers were added at around 3 minutes from the time of adding water to the mix over a period of 2 minutes to gain a uniform fiber distribution though the mix and prevent the fiber balling. All mixes contained a fiber volume fraction of V_f = 1%, as no significant improvement in flexural strength was reported for mixes with higher fiber volume fraction (Adebar et al. 1997, Dinh 2009, Shoaib 2012). The total time of mixing was about 10 minutes. The FRC slump was measured according to ASTM C143-10 standard during the casting and an average value of 118 mm was observed for all the three batches.

Table 2: FRC composition normalized by mass of cement

Components	Type	Weight
Cement	HS	391
Fine Aggregate	River Sand (4.75 mm)	796
Coarse Aggregate	Pea Gravel (14 mm)	990
Water		157
Steel Fibers	Double-ended Hooks†	78.6
Water Reducer	ml/m^3	250
Superplasticizer	ml/m^3	1800

†BEKARET Dramix ZP305

2.3 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 Digital Image Correlation (DIC) camera 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 instrumentations was captured through a built-in data acquisition system in 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, as shown in Figure 2. 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. 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 (Kazemi and Lubell 2012). 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 DIC system cameras throughout the loading process of each test.

3 EXPRIMENTAL RESULTS AND DISCUSSION

The overall pull-out load-slip response of the composite connection specimen during testing is provided in this section. In order to capture the post peak behaviour of composite connections, all the specimens were loaded until the pull-out force on the descending branch of the load-displacement relationship is dropped below 70% of the peak value. The results are summarized below.

3.1 Composite Connection with UHPFRC Material

Two connection specimens, constructed with UHPFRC material, 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 141 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 (Kazemi and Lubell 2010). An average peak equivalent tensile strength (PETS) of 8.4 MPa was derived from an inverse analysis technique originally proposed by AFGC and further developed by Kazemi and Lubell (2011). More detail about the mechanical properties of the UHPFRC can be found in the other publications by first author (Kazemi and Lubell 2010 and 2012).

Vic-3D software was used during the experimental test to highlight the slip between steel plate and UHPFRC beam during the pullout loading (Correlated Solutions Inc., 2010). This process 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. The Vic-3D DIC image of the composite connection specimen after failure is given in Figure 2.

As shown in Figure 2, a significant cracking after failure was observed in the concrete beam. The load-slip behaviour of composite connection specimens under pull-out loading is given in Figure 3. The results of experimental tests indicated that the composite connections tend to show a quasi linear-elastic load-slip response in tension until the pull-out cracking load (PCL) was reached. See Figure 3. A very small slip between the embedded steel plate and the concrete beam was observed in this stage. In addition, no visible micro-cracks initiated in this stage. An average PCL of 112 kN was observed for the connection specimens. The PCL is defined as the load where some micro-cracking was first observed and the bilinear load deflection curve began to deviate from the initial linear load-slip response.

Beyond the PCL point, a hardening response up to the peak pull-out load (PPL) was observed for both specimens, as shown in Figure 2. During this stage, the pull-out strength continued to increase for additional applied displacement. Once the PPL point reached, a longitudinal crack was formed at the mid-span of the beam and propagated toward the top reactions at both ends of the beam to form a coneshaped failure in UHPFRC beam. After the PPL point, a descending branch with a steady softening behaviour was observed. The gradual softening part – immediately after the PPL point – was then followed by a series of sudden drops in the load carrying capacity. This is more pronounced when the vertical mid-span crack (splitting crack) propagated downward and joined the main breakout crack. See Figure 2. The breakout crack at the end of test was wide enough to easily see through the full specimen width. This indicated a complete breakdown of the fiber bridging mechanism. However a significantly small slip between the embedded steel plate and the concrete beam was observed at the end of the test. This is because the connection configuration provided a substantial mechanical interlock between the UHPFRC shear key and the embedded steel plate. The failure was characterized as a combination of breakout failure and splitting failure. Higher rate of crack opening was observed.

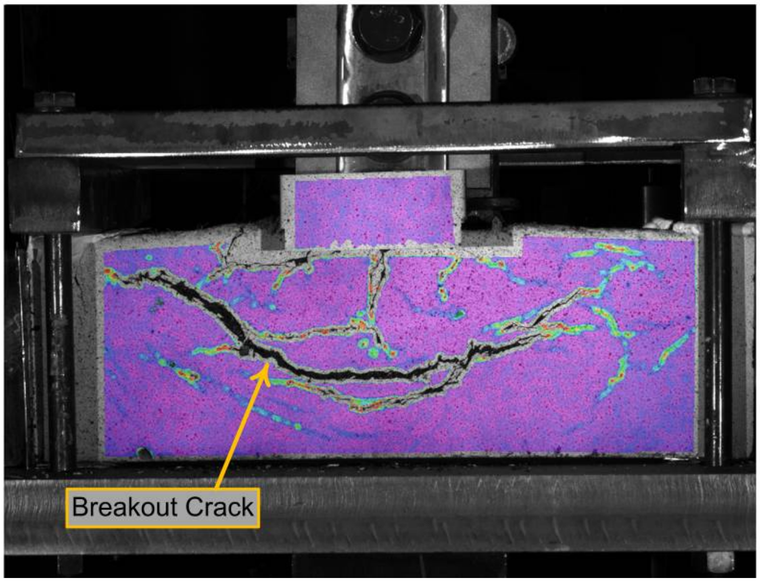

Figure 2: Failure of ΩS-U-70-16-2 specimen (Ω-shaped shear key, embedded length of plate = 100 mm, t_{pl} = 16 mm, UHPFRC material with V_f = 2%).

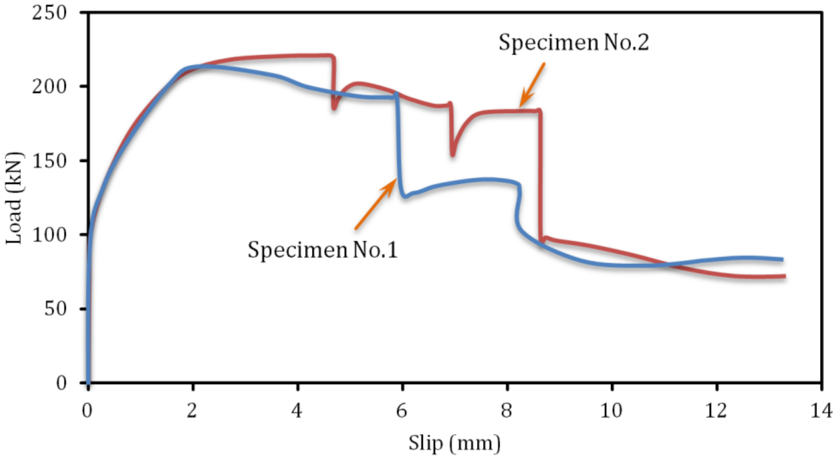

Figure 3: Load-slip response of ΩS-U-70-16-2 specimens.

3.2 Composite Connection with FRC Material

A general view of the composite connection made of FRC material after failure is shown in Figure 4. A single vertical crack was initiated at the top side and at the mid-span of the FRC beam at an average PCL of 100 kN which is slightly less than that in the composite connection made of UHPFRC material. At a load level of 114 kN, a series of short inclined cracks was initiated at mid span and mid-height of the specimen (located near the top and bottom longitudinal rebars) as shown in Figure 4. These cracks were more rapidly propagated toward the reaction supports, as compared with those in specimens made of UHPFRC material. As the load increased, the vertical crack at mid-span was further propagated downward and joined the breakout crack. A circular crack was then formed around the double headed stud, as shown in Figure 4.

Compared to the specimens constructed with UHPFRC material, a nonlinear stage with significantly lower stiffness was observed for those specimens made of FRC material until the peak pull-out load (PPL) reached. The PPL of the specimens made of FRC material was compared with those made of UHPFRC material and it was found that the use of UHPFRC material was resulted in 60% increase in the PPL. The significant improvement in the PPL is most likely attributed to the higher tension and shear strength provided by UHPFRC material as compared with FRC material. These enhanced mechanical properties of UHPFRC material would significantly improve the mechanical interlock between the shear key and the embedded steel plate.

The average PCL occurred between 70%-75% of PPL for composite connections made of FRC material which is higher than those for UHPFRC material. This indicates that the degradation rate after the initiation of cracks in specimens made of FRC material is higher than those specimens made of UHPFRC material.

Unlike the connection specimens made of UHPFRC material with a deep breakout creak pattern, a shallow triangle breakout crack pattern was observed in those made of FRC material with 1% volume-fraction of double-hooked fibers. This is most likely due to the weak mechanical properties of FRC material in shear which cannot redistribute the stresses to the rest of the beam.

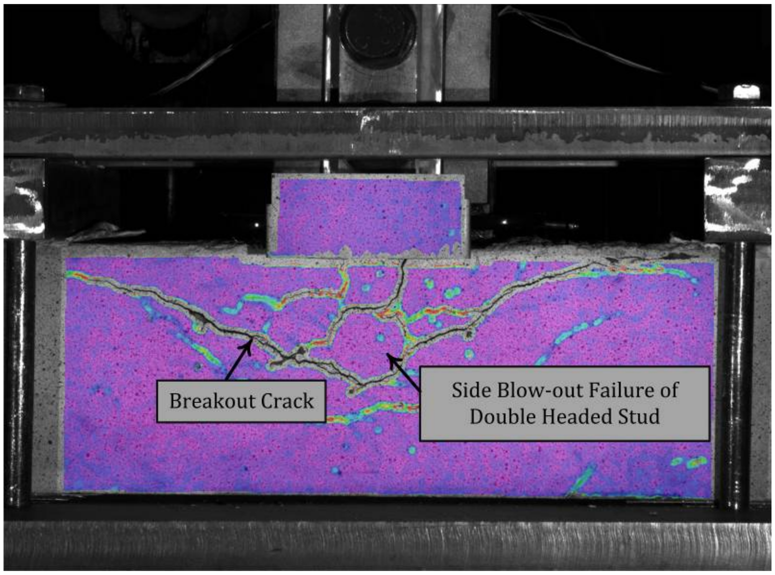

Figure 4: Failure of ΩS-F-70-16-1 specimen (Ω-shaped shear key, embedded length = 100 mm, UHPFRC with $V_f = 0\%$, $t_{pl} = 16$ mm).

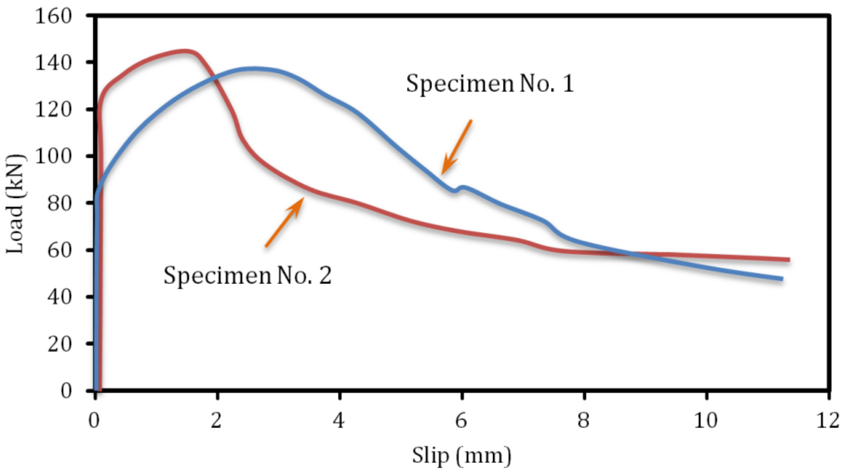

Figure 5: Load-slip response of ΩS-F-70-16-1 specimen.

3.3 Summary of Influences of Concrete Generation

The influences of two different concrete generations, i.e. FRC and UHPFRC, on load carrying capacity of composite connections with Ω-Shaped hole are summarized in Figure 6. The tests results indicate that, compared to composite connection with FRC material, the use of UHPFRC material significantly increases the maximum load carrying capacity of connection by 60%. This significant improvement is attributed to the high mechanical properties of UHPFRC in tension and shear that enhanced the mechanical interlock between the embedded steel plate and the concrete beam.

The experimental test demonstrated that the connections made of UHPFRC material tends to exhibit a higher stiffness after the PCL point, compared to specimens made of FRC material, indicating that the stiffness of composite connections is highly dependent on the mechanical properties of the concrete.

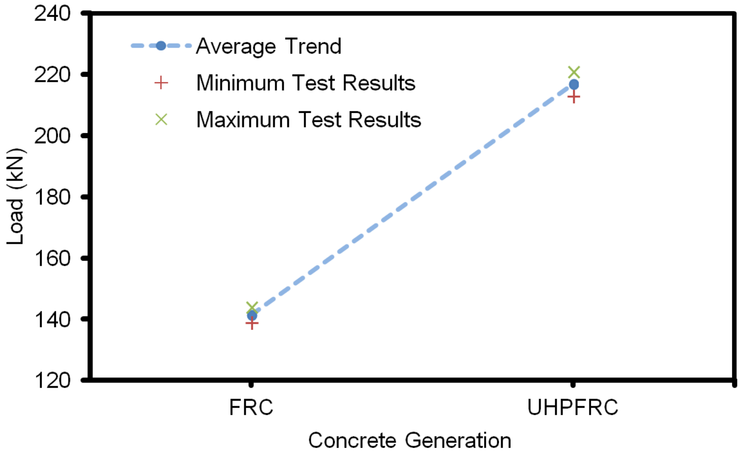

Figure 6: Influence of concrete generation on load bearing capacity of composite connection with Ω-shaped shear key.

4 Concluding remarks

Based on the experimental results of composite connections – made of embedded steel plate in UHPFRC and FRC beams – under pull-out loading, this connection is shown to be effective for applications where a significant load carrying capacity and ductility are required. This study established the following main observations and conclusions summarized as follows:

- Compared to composite connection with FRC material, a 60% improvement in the peak pullout load carrying capacity of the connection specimens made of UHPFRC material with 2% volume-fraction of fibers was observed. This significant improvement is attributed to the high mechanical properties of UHPFRC in tension and shear which significantly improve the mechanical interlock between concrete shear key and embedded steel plate.
- Higher elastic stiffness with less degradation rate after the initiation of first crack was observed for specimens made of UHPFRC over those made of FRC material. This is associated to higher fiber bridging effect in UHPFRC Material that retard the crack initiation and propagation in concrete beam.
- Unlike the specimens made of UHPFRC material with a deep curved-shape breakout failure, a shallow triangle-shaped failure was observed in specimens made of FRC material.

Acknowledgements

Financial support for this study was provided by the Natural Sciences and Engineering Research Council of Canada. Materials were donated by Waiward Steel Fabricators Ltd., Lehigh Inland Cement, Bekaert and BASF.

References

Association Française de Génie Civil. 2002. Ultra High Performance Fibre-Reinforced Concretes, Interim recommendations, Paris, France, 152 pages.

ASTM C1018-97. 1997. Standard test method for flexural toughness and first-crack strength of fiber reinforced concrete (using beam with third-point loading). *ASTM International*, West Conshohocken ,PA, USA: 7 pages.

ASTM C109/C109M. 2007. Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-inch or [50-mm] Cube Specimens), *ASTM International*, Philadelphia,PA, USA: 9 pages.

ASTM C1609/C1609M. 2010. Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam With Third-Point Loading), *ASTM International*, West Conshohocken*,PA, USA,* 9 pages.

ASTM C39/C39M. 2010. Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. *ASTM International*, Conshohocken, PA, USA, 7 pp.

Kazemi, S. and Lubell, A.S., 2012. Influence of Specimen Size and Fiber Content on Mechanical Properties of Ultra-High-Performance Fiber-Reinforced Concrete. *ACI Materials Journal* 109 (6).

Kazemi, S. and Lubell, A.S., 2011. Size Effects on the Mechanical Properties of UHPFRC. *Proceeding of CSCE 2011 Annual General Conference*. Ottawa, CSCE.

Chanvillard, G. and Rigaud, S. 2003. Complete characterisation of tensile properties of Ductal® UHPFRC according to the French recommendations. High Performance Fiber Reinforced Cement Composites HPFRCC-4, *International Workshop High Performance Fiber Reinforced Cement Composites*, Ann Arbor, Michigan, USA, 21-34.

Richard, P. and Cheyrezy, M. 1995. Composition of reactive Powder Concretes. *Cement and Concrete Research*, 25(7):1501-1511.

Rossi, P., Arca, A., Parant, E., and Fakhria, P. 2005. Bending and compressive behaviours of a new cement composite. *Cement and Concrete Research,* 35(1): 27-33.

Habel, K., Viviani, M., Denarie, E., and Bruehwiler, E. 2006. Development of the mechanical properties of an ultra-high performance fiber reinforced concrete (UHPFRC). *Cement and Concrete Research,* 36(7):1362–1370.

Shoaib, A., Bindiganavile, V. S., and Lubell, A. S., 2009. Effect of steel fibers on the shear response of structural lightweight concrete. *Proceedings of CSCE 2009 Annual General Conference*, St. John's, NL: CSCE.

Feldmann, M., Hechler, O., Hegger, J., and Rauscher, S., 2007. Untersuchungen zum Trag- und Verformungsverhalten von Verbundmitteln unter ruhender und nicht ruhender Belastung bei Verwendung hochfesterWerkstoffe. FOSTA – Abschlussbericht zum AiF-Vorhaben AiF 13867 N, Aachen 2007.

Feldmann, M., Hechler, O., Hegger, J. and Rauscher, S., 2007. Neue Untersuchungen zum Ermüdungsverhalten von Verbundträgern aus hochfesten Werkstoffen mit Kopfbolzendübeln und Puzzleleiste. Stahlbau, 76: 826–844.

Hegger, J., Sedlacek, G., Döinghaus, P., and Trumpf, H. 2001. Testing of Shear Connectors in High Strength Concrete. *Proc. RILEM Symposium on Connections between Steel and Concrete*, Stuttgart, Germany,Sept. 9-12, 2001.

Hechler, O., Feldmann, M., Rauscher, S., and Hegger, J. 2006. Use of shear connectors in high performance concrete, Proc. intern. symp. *Stability and Ductility of Steel Structures*, D. Camotim et. al (ed.), Lisbon,Sept. 6-8, 2006.

Wurzer, O. 1997. Zur Tragfähigkeit von Betondübel, PhD the-sis. Institut für Konstruktiven Ingenieurbau, Universität der Bundeswehr, München, in German.

Hegger, J., Rauscher, S., and Goralski, C. 2005. Push-Out Tests on headed studs in high strength concrete. *Proceedings of the Seventh International Symposium on the Utilization of High-Strength/High-Performance Concrete*, Washington D.C./USA 2005, June 20-24, pp. 769-785.

Hegger, J., Feldmann, M., Rauscher, S., and Hechler, O. 2006. Load-Deformation Behavior of Shear Connectors in High Strength Concrete subjected to Static and Fatigue Loading. IABSE Symposium on Responding to tomorrow's challenges in structural engineering, Budapest, Hungary, 2006.

Hegger, J. and Rauscher, S. 2008. UHPC in Composite Construction. *2nd international Symposium on Ultra High Performance Concrete*, 2008.

Heinemeyer, S., Gallwoszus, J. and Hegger, J., 2012. Verbundträger mit Puzzleleisten und hochfesten Werkstoffen. Stahlbau, 81. pp 595–603, in German.

Hegger, J., Gallwoszus, J., and Rauscher, S. 2009. Load-Carrying Behaviour of Connectors under Shear, Tension and Compression in Ultra High Performance Concrete. *11th Nordic Steel Construction Conference NSCC 2009*, Swedish Institute of Steel Construction, Sweden, S. 486-493. ISBN 91-7127-058-2.