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Study of High Strength Reinforced Concrete Exterior Beam-Column Joints under Cyclic Loading

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ABSTRACT: This study investigates experimentally the behavior of full scale, shear deficient, exterior reinforced concrete beam-column joints. The research was conducted experimentally using four specimens with two being control specimens cast with normal concrete. The remaining two specimens were strengthened with ultra-high performance concrete (UHPC) in the joint region only, with other sections of these two specimens being cast using normal concrete. All the specimens had the same reinforcement detailing. The specimens were tested under monotonic and cyclic loading. The results showed that the load carrying capacity for the specimens with UHPC in the joint was enhanced by 65% as compared with specimens with normal concrete. The mode of failure was noted to change from shear failure in the joint to the preferred flexural failure at the beam column interface.

1 INTRODUCTION

Beam-column joints are one of the most common elements of existing buildings that collapse under shear forces, which mainly are caused by earthquakes. The damage in the joints region has been observed in the recent destructive earthquakes in many countries around the world. The beam-column joint in a moment resisting frame structure designed according to early codes may have insufficient shear reinforcement and inadequate development length. This is believed to be the main cause of joint failure. Therefore, other materials should be used in order to increase the strength and ductility of the reinforced concrete joints, such as CFRP (Carbon Fibre Reinforced Polymer), GFRP (Glass Fibre Reinforced Polymer), steel fibres, SMA (Shape Memory Alloys) and ultra-high performance concrete (UHPC).

Steel fibers is one of the materials that is used to enhance the ability of the structures to resist tensile forces such as seismic loads, blast and shock loads, splitting erosion and abrasion, and high temperatures by making the concrete tougher and more ductile. Steel fiber is a ductile material with high tensile strength and has different shapes and styles.Considerable research has been carried out recently on strengthening reinforced concrete beam-column joints e.g Ahmed et al (2012), Bedirhanoglu et al (2013), Gansen et al (2007), Gencoglu et al (2002), Halahla (2014), Keerthana et al (2014), Oinam et al (2013), Perumal et al (2011), Rohm et al (2012), Sarsam et al (2010), and Wang et al (2007). Bedirhanoglu et al (2013) investigated the seismic behavior of deficient exterior beam–column joints constructed with low-strength concrete and plain reinforcing bars before and after retrofitting with prefabricated HPFRCC (high-performance fiber-reinforced cementitious composite) panels. The HPFRCC panels bonded and anchored to the external faces of the deficient exterior joints enhanced the joint shear strength, limited the shear deformations in the joint core and delayed the development of shear damage. The beam framing into the joint reached its flexural capacity and there was a a significant enhancement in drift capacity.

The steel fibre reinforced concrete is normal concrete with a specific amount of steel fibres. The properties of the steel fibre reinforced concrete mainly depend on the concrete mix, steel fibre content, fibre shape and aspect ratio and also the bond characteristics. The workability of the concrete is affected when steel fibres are added to the mixture. Therefore, important requirements should be considered when the concrete mixture includes steel fibres like the amount of mortar, maximum aggregate size, and role of additives like super plasticizers.

This paper presents the results of an experimental program involving cyclic load tests on beam-column joints without transverse reinforcement in which the normal concrete in only the joint area was replaced by UHPC. The mode of failure was noted to change from shear failure in the joint in control specimen with normal concrete to flexural failure at the beam column interface in the UHPC joint specimen. Such a mode of failure satisfies the seismic design philosophy of strong column/weak beam. The idea of using UHPC in beam-column may allow for the elimination of transverse reinforcement in the joint leading to excellent damage tolerance.

2 SPECIMEN DESCRIPTION AND TEST SETUP

Experimental tests were conducted on four beam column joint specimens to study the behavior of reinforced concrete exterior beam-column joint cast using ultra-high performance concrete (UHPC). Table 1 shows the details of specimens for the monotonic and cyclic load tests. All specimens had the same reinforcement detailing. The specimens were reinforced with 18mm bars as longitudinal bars in both beam and column with 8 mm stirrups at a spacing of 75 mm as shown in Fig. 1. The NC-BCJ-18MM specimen was cast using normal concrete. The joint area of UHPC-BCJ-18MM specimen was cast using ultra-high performance concrete (UHPC) and the rest of specimen was cast using normal concrete as shown in Fig. 2. The mix design of UHPC is shown in Table 2 (Hakeem, 2014). The cross-section of beam and column was 250 × 300 mm. The column height was 1400 mm and the beam length was 900 mm.

Table 1: Specimens Details for Monotonic Test

S.No.	No. of Specimens	Specimens	Details	Test Method
1	1	NC-BCJ-18MM	Control sample with normal concrete	Monotonic
2	1	NC-BCJ-18MM	Control sample with normal concrete	Cyclic
3	1	UHPC-BCJ-18MM	Sample with UHPC in the joint	Monotonic
4	1	UHPC-BCJ-18MM	Sample with UHPC in the joint	Cyclic

Table 2: Quantities of Constituents for Producing 1 m3 of the UHPC Mixture

Cement Kg	Fine dune Sand Kg	Water Kg	Microsilica Kg	Steel Fibers Kg	Plasticizer Glenium Kg
900	1005	163	220	157	40

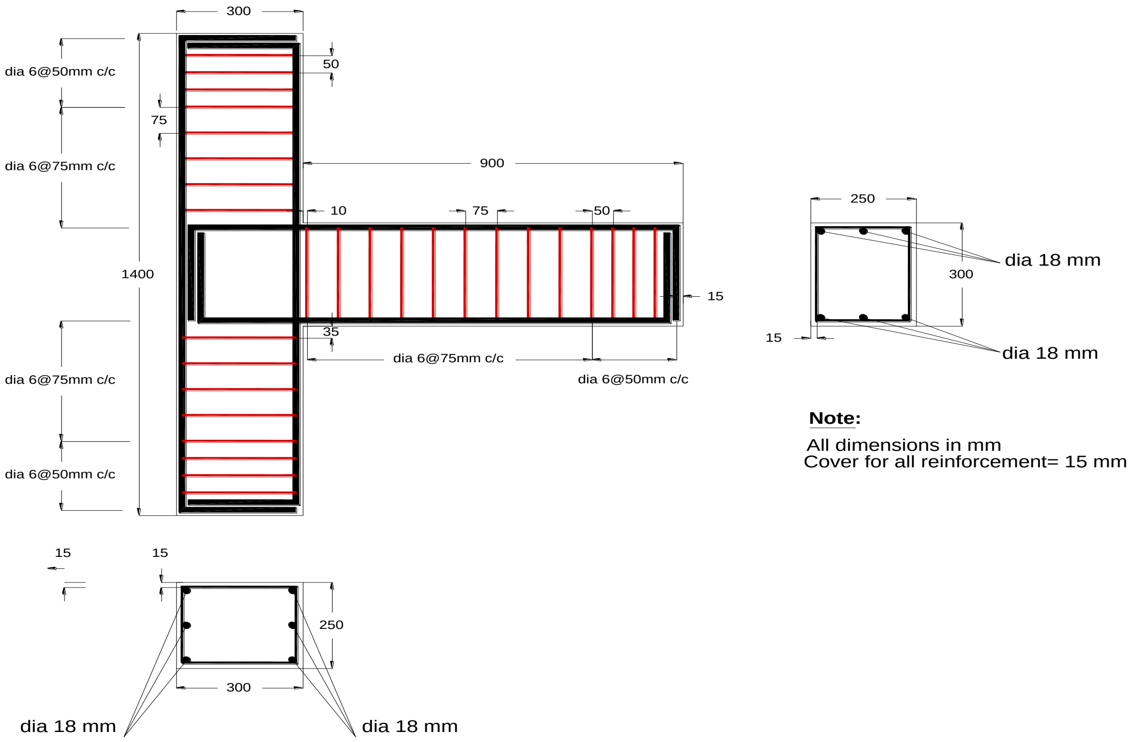

Fig. 1 Geometric and reinforcement details for BCJ-18 MM

Self-reacting steel frame was used in testing the specimens of beam-column joint, with additional supports to hold the specimen at the top and bottom of column and the tip of beam. The load was applied using two hydraulic jacks. One hydraulic jack with capacity of 30 tons was used for applying constant axial load to the column while the other hydraulic jack with capacity of 10 tons was used in applying cyclic loading to the tip of the beam.

Three load cells were used to measure the load during the test. Two load cells with capacity of 100 ton were installed at top and bottom of the beam while the other one with capacity of 20 ton was installed at the top of the column. Four LVDTs were used in the test. Two LVDT's were installed at the top and bottom of the column to monitor the movements, two LVDT's were installed at the intersection area to measure the diagonal crack openings. The beam deflection was monitored by string type LVDT. Concrete and reinforcement steel strain gauges were installed in order to monitor the concrete and steel reinforcement strain.

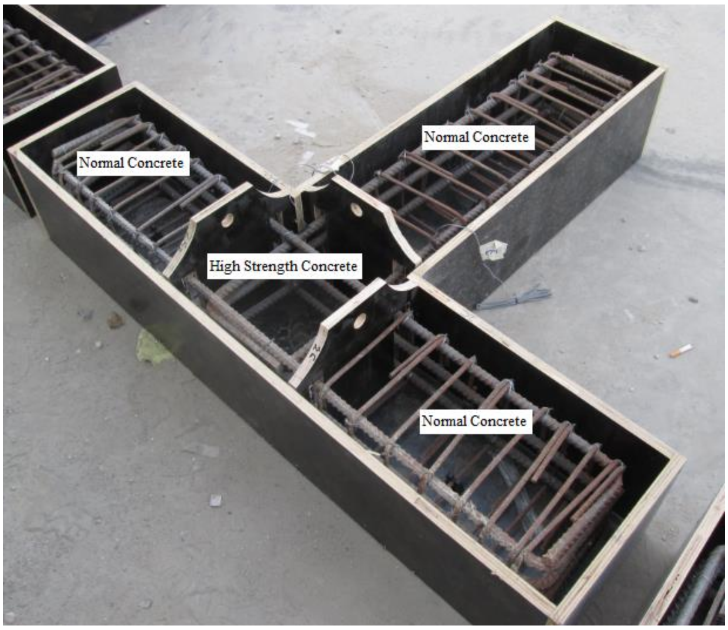

Fig. 2 High strength concrete joint

Normal concrete, which was used in the specimens, had a compressive strength of 30MPa with 110mm slump, and 25mm maximum size aggregate. The tensile strength of the normal concrete was 2.2 MPa with a modulus of elasticity of 26000 MPa. The compressive strength of UHPC was 108 MPa with a tensile strength of 31MPa. The yield strength and ultimate strength of the reinforcement steel is shown in Table 3.

Table 3 Strength of steel bars.

Reinforcement	Area (mm²)	Yield strength (MPa)	Ultimate strength (MPa)
Ø 18	254.34	593	660
Ø 8	50.24	480	575

3 RESULTS AND DISCUSSION

The load vs. displacement curve for NC-BCJ-18MM specimen shows that the maximum load was 97.2 kN at displacement of 17.5 mm (Fig. 3). At a load of 37.1 kN and a displacement of 3.5 mm, the first flexural crack was formed in the specimen near the beam-column interface. At a load of 50 kN and a displacement of 5.5mm, the first diagonal crack was formed in the joint region. It is noted that as the load increased, the diagonal cracks extended and became wider. The specimen failed due to shear failure of the joint (Fig. 4). This is confirmed by the softening displayed by the member following the peak load attained. Further, the flexural capacity of the beam was computed as 137 kN, which is significantly greater than the peak load that was attained during the experiment i.e. 97.2 kN. The steel reinforcement strains measured were also less than the yield strain.

The load vs. displacement curve for UHPC-BCJ-18MM specimen shows that the maximum load was 160 kN at a displacement of 39 mm. The first crack in the specimen was flexural crack in the beam at a load of 41 kN and a displacement of 2.8 mm, while the first diagonal crack occurred at a load of 146 kN and a displacement of 19 mm. It is observed that as the load increased, the width of the flexural cracks increased and extended through the beam while the shear crack was very fine. The specimen failure was a flexural failure (Fig. 5), which is confirmed by the fact that the flexural strength of the beam was computed as 137 kN. Also, gauges installed on the 18 mm bars showed that the strain had exceeded the yield strain of the reinforcement. The load carrying capacity for the strengthened specimen was enhanced by 65% and the failure mode changed from joint shear failure to the preferred ductile flexural failure caused by yielding of the beam reinforcement.

The cyclic loading test of control specimen (NC-BCJ-18MM) shows that the maximum load in the push and pull cycles was 99 kN and 100.3 kN, respectively (Fig. 4). At load of 45 kN, the first flexural crack was formed near the beam column interface. The diagonal crack in the joint region formed at a load of 60 kN in the push cycle. The diagonal cracks extended toward the center of the joint as the load and displacement increased. In the last two cycles, the beam-column interface was crushed and spalled off on the both sides of the joint. The specimen failed due to the joint damage in the joint. The cyclic behavior of UHPC-BCJ-18MM confirmed the non-softening, flexure failure mode of the UHPC joint modified beam.

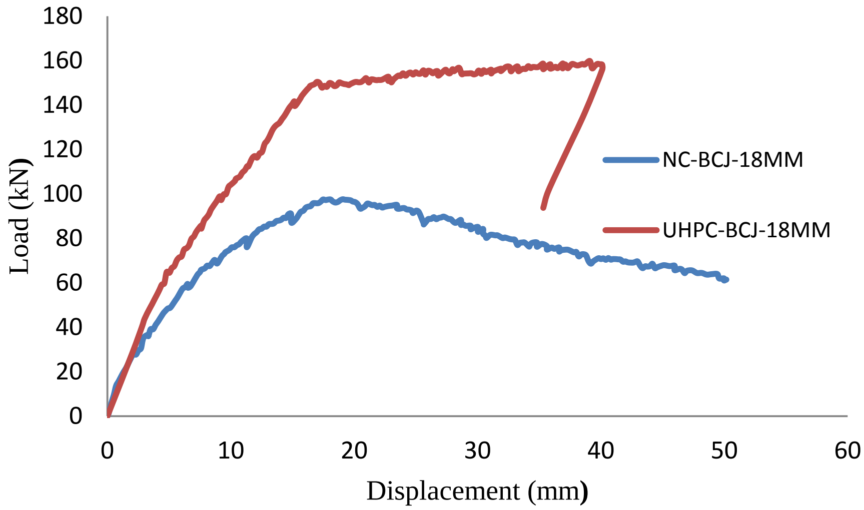

Fig. 3 Load vs. displacement for specimen UHPC-BCJ-18MM &NC-BCJ-18MM

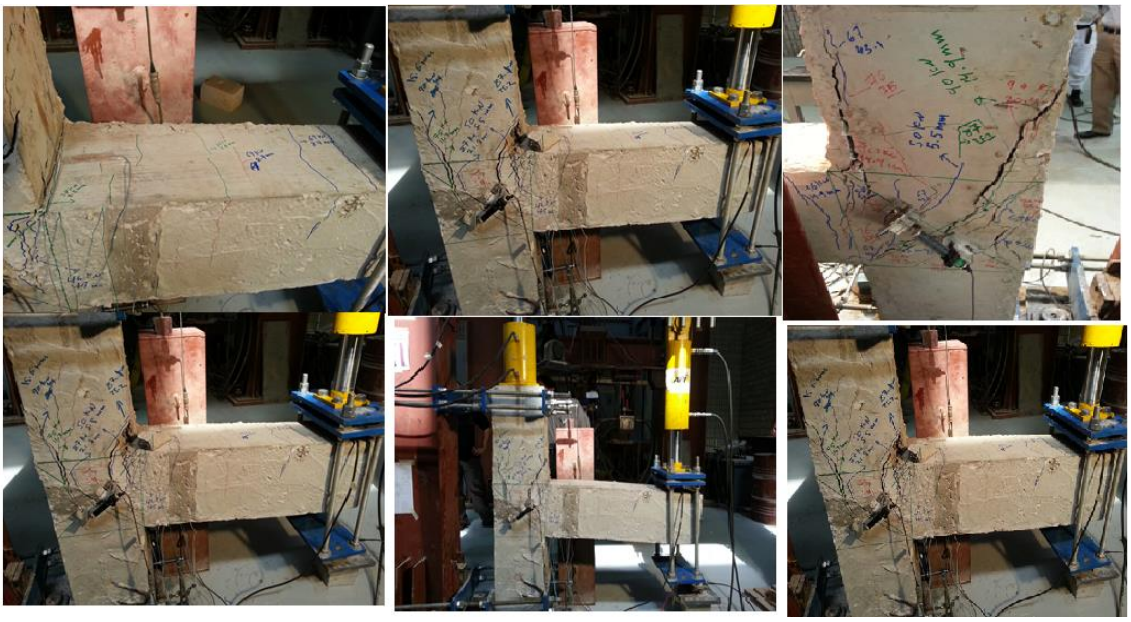

Fig. 4: Crack pattern for specimen NC-BCJ-18MM

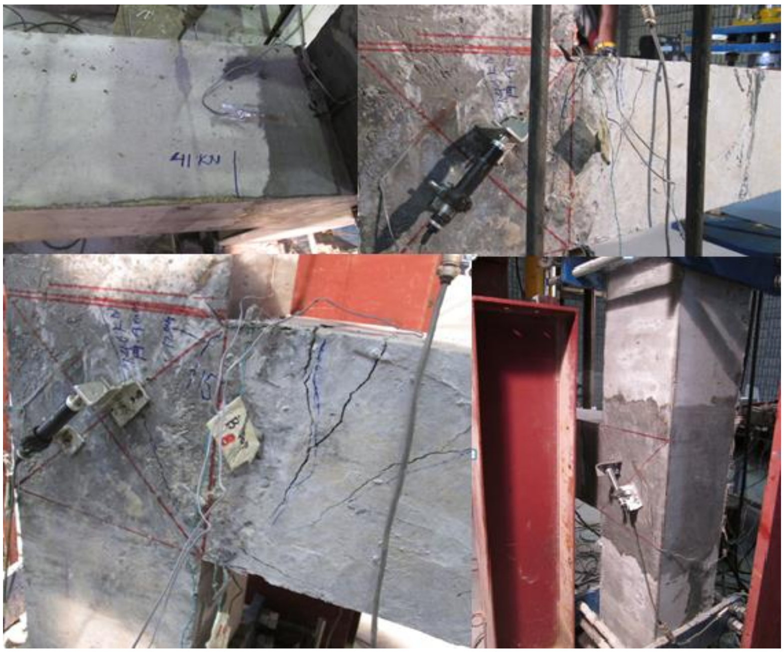

Fig. 5: Crack pattern for specimen UHPC- BCJ-18MM

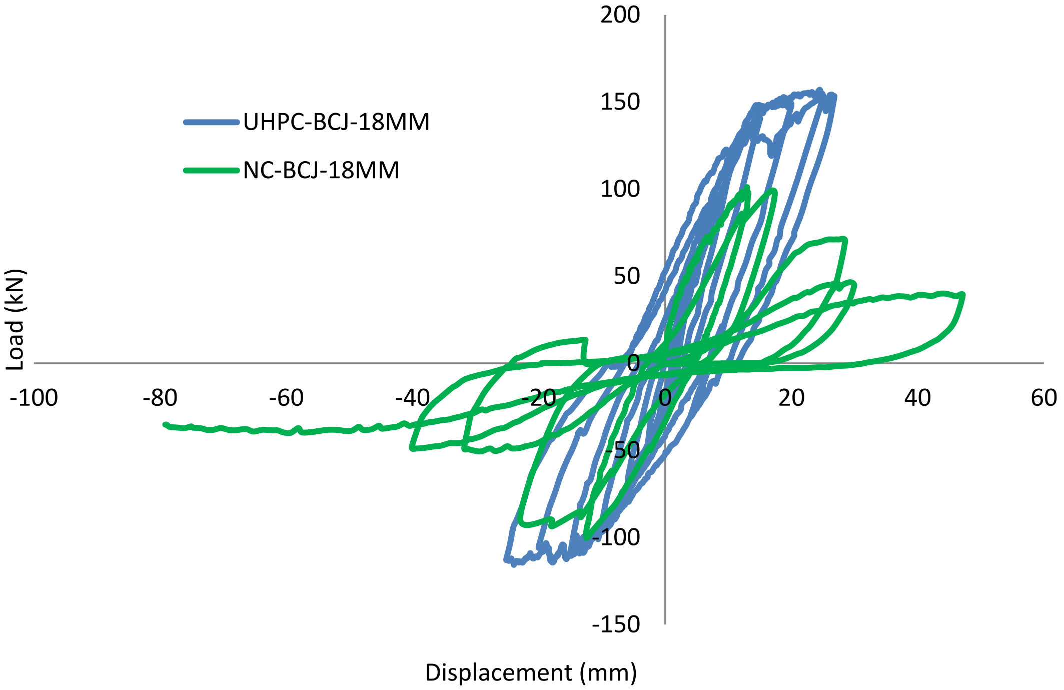

Fig. 6: Load vs displacement graph for specimen UHPC-BCJ-18MM &NC-BCJ-18MM

4 CONCLUSIONS

This paper has shown that for reinforced concrete structures where beam and joint dimensions are fixed due to architectural constraints, and the beam reinforcement requirements are such that the likelihood of joint failure precedes the yielding of beam reinforcement, a creative solution can be provided by the use of high shear strength UHPC in the joint region only, which will satisfy the seismic design philosophy of strong column/weak beam. The idea of using of UHPC in beam-column may allow for the elimination of transverse reinforcement in the joint leading to excellent damage tolerance.

The use of an ultra-high performance concrete (UHPC) joint has been shown to change the mode of failure of exterior beam-column joint from diagonal shear failure in the joint of a normal concrete beam-column construction to a flexural failure at the beam column interface of the UHPC modified beam. This is due to the presence of the steel fibre which improved the shear and tensile strength of the concrete, and hence the shear carrying capacity of the joint. The enhancement of shear strength of the joint due to the presence of UHPC in the present work has been noted to be greater than the use of CFRP in the same joint as reported in an earlier KFUPM study presented by Halahla (2014).

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