Resilient Structures and Sustainable Construction
Edited by Pellicer, E., Adam, J. M., Yepes, V., Singh, A., and Yazdani, S.

ISBN: 978-0-9960437-4-8

DUCTILITY ENHANCEMENT OF RC BEAMS STRENGTHENED WITH STRAIN HARDENING CEMENTITIOUS COMPOSITES

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Ultra High-Performance Strain Hardening Cementitious Composites (UHP-SHCC) is a newly developed construction material, has large advantages on large strain capacity as well as high compressive and tensile strength, which is useful for strengthening or repair concrete members. An important obstacle needs to be studied, is the strain localization occurs in the UHP-SHCC strengthening layer around the substrate concrete cracks, which severely limits the ductility of the strengthened beam. In the present study, five specimens were tested experimentally, one as a control and four strengthened with variable reinforcement ratios embedded in the strengthening layer. The recorded tests showed that it is sufficient to use 1.2% additional reinforcement ratio embedded in the strengthening layer for beams strengthened with UHP-SHCC to eliminate the observed early strain localization and to gain adequate ductility. Another important conclusion is the strengthening of RC structures using an unreinforced UHP-SHCC layer may lead to a brittle failure.

Keywords: Strengthening, Structural engineering, Toughness, Unreinforced-composites.

1 INTRODUCTION

Strengthening the structural members of old buildings using advanced materials are a contemporary research in the field of repairs and rehabilitation. Many researchers used new materials in order to overcome the various shortages of material developed for repairing or retrofitting. In order to improve the performance of ordinary cementitious materials, a new type of material, called as Ultra High Performance Strain Hardening Cementitious Composites (UHP-SHCC), is developed by (Kamal *et al*. 2008), with special objective of high tensile and compressive strength, large strain capacity, high workability, easy processing using conventional equipment, and lower fiber volume fraction (Kunieda *et al*. 2012). In addition, UHP-SHCC considered a perfect protective material against corrosion (Amino *et al*. 2015), (Kunieda 2014). On the other hand, one of the primary obstacles preventing the widespread use of UHP-SHCC is the early strain localization occurred in the strengthening layer, therefore (Hussein *et al*. 2012) presented the ductility behavior in tests on reinforced concrete beams that were strengthened in flexure with lightly steel-reinforced SHCC layer (0.3% and 0.6% steel reinforcement ratio). It has been found that the combination of the SHCC and a small amount of steel reinforcement helps develop higher strain in the SHCC strengthening layer at ultimate load and eliminates the observed early strain localization. This study concerned on determining the sufficient amount of reinforcement ratio used in UHP-SHCC layer to get the most possible benefit from using this material as a strengthening layer.

2 EXPERIMENTAL PROGRAM

2.1 Material Properties

The mix proportions of the UHP-SHCC used as a strengthening material in this study are described in (Hussein *et al*. 2012); Water to binder ratio (W/B) was 0.20. Low heat Portland cement (density: 3.14 g/cm^3) was used, and 15% of the design cement content was replaced by silica fume. Quartz sand with diameter less than 0.5 mm was used as a fine aggregate. High strength polypropylene (PP) fiber was chosen for UHP-SHCC and its volume in mix was 2%. The diameter and length of the PP fibers were 0.012 mm and 6 mm, respectively. The tensile behavior of the used UHP-SHCC was characterized by testing of three large size specimens with different embedded reinforcement ratio (tested cross-section: 50 × 200 mm) in uniaxial tensile test. The averaged tensile strength and ultimate tensile strain (strain at ultimate load) of the reinforced UHP-SHCC without the contribution of embedded reinforcement at the age of 28 days were determined to be 6.5 MPa and 1.4% respectively. To characterize the compressive properties of the used UHP-SHCC, six cube specimens having a size of 50 mm were tested at the age of 28 days and the averaged compressive strength was determined to be 78.8 MPa. The used ordinary concrete was made from a mix of ordinary Portland cement, natural sand, and gravel. The averaged compressive strength of the used substrate concrete was determined to be 29 MPa based on the compressive test results of six cube specimens having a size of 150 mm. In order to determine the mechanical properties of the used reinforcement, tensile tests were performed on three specimens of each different type of reinforcement. For the used reinforcement, the mean value of tensile yield strength, ultimate strength and Young’s modulus were 400 MPa, 683 MPa, and 200 GPa respectively.

2.2 Specimen's Details

The experimental program contains five specimens, one control and four strengthened specimens with variable reinforcement ratios embedded in the strengthening layer which attached to the soffit part of the beam. All the beams had dimensions of 120 mm width, 200 mm height, and 1,800 mm length. The beams were demoulded at the age of 2 days, and their bottom surface (tension reinforcement side) was washed out using a retarder to obtain a rough surface. Following the wash-out process the specimens were covered with wet towels for additional 26 days. At the age of 28 days, UHP-SHCC strengthening layer was cast with 40 mm thickness in the beams’ tension side (rebar side). For the UHP-SHCC-strengthened beams, one beam was strengthened using unreinforced UHP-SHCC layer, whereas three beams were strengthened with steel reinforced UHP-SHCC layer with variable reinforcement ratio as shown in Figure 1. Additional reinforcement similar to main reinforcement used in the beam.

2.3 Test Setup and Instrumentations

All the beams were loaded in four-point bending. The load was applied using a hydraulic actuator through a spreader steel beam to the specimen. Each specimen spanned 1,500 mm and was loaded symmetrically about its centerline at two points 600 mm apart. A load cell was attached to the loading actuator to record the applied load. One Pi-shaped displacement transducers was bonded to the top concrete surface of each specimen at mid-span, to record the compression strain in the extreme concrete fibers. One strain gauge was bonded to each rebar in the tension side at its mid-span. During the test, UHP-SHCC strengthening layer's strains were recorded by Pi-shaped displacement transducers with a gauge length of 100 mm applied on layer's bottom side as shown in Figure 1, whereas an additional Pi-shaped displacement transducers were used to record the substrate concrete strains at concrete-UHP-SHCC layer interface as shown in Figure 1. Displacement at mid-span was measured using Linear Variable Differential Transformer (LVDT). An automatic data acquisition system was used to monitor loading, displacements and strains. The instrumentation used to monitor the behavior of the beams during testing is shown in Figure 1.

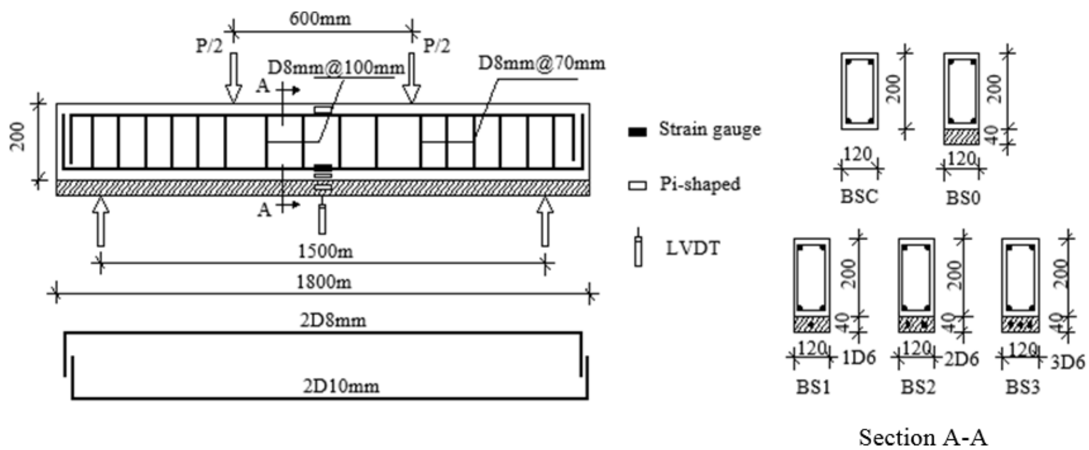

Figure 1. Test setup and specimens details.

3 TEST RESULTS AND DISCUSSION

3.1 Loads, Crack Patterns, and Failure Modes

The control specimen beam (BSC), was failed as expected in flexure, failed at load 53.4 kN. For all strengthened beams, the beams continued to support the applied load until failure., at ultimate loads 77, 84, 94, and 103.7 kN for strengthened beams BS0, BS1, BS2, and BS3, respectively. At failure, the strengthening layer was ruptured near the mid span or loading points, after yielding of the reinforcing steel bars and before concrete crushing in the compression zone.

When reinforcement used in UHP-SHCC layer there seems to be a delay in the formation of wide cracks in the UHP-SHCC layer, which allows the beam to achieve considerably higher deflection and ultimate loads compared to beam BS0. The ultimate loads, the cracking loads, and the yielding loads are shown in Table 1. Experimental results reported in Table 1 indicate an increase of varying degrees in the cracking load for all of the strengthened beams over that of the control beam. This is to be expected, partially because of the stiffening of the beams due to the application of the strengthening layer.

3.2 Load Versus Deflection Response at Midspan

Figure 3 shows the measured load deflection response for all beams. The control beam (BSC) showed the usual elastic and inelastic parts of its deflection behavior and failed, as expected, due to yielding of the tensile steel reinforcement prior to crushing of the concrete at significantly high final deflections than the UHPSHCC strengthened beams. The characteristics of the load-deflection behavior of beam BS0 may be summarized as follows. Initially, the behavior is linear up to the cracking load, with cracks appearing near the beam's mid-span the curve begins to deviate from the linear path. After the strengthened beam reaches its ultimate load, the load drops rapidly from the peak to a significantly lower load level round the control beam (BSC) capacity due to the localized failure of the strengthening layer which produced by the high strain concentration points in UHP-SHCC layer developed by the cracks in the concrete substrate, as stated previously, then the beam's behavior was controlled by the original steel reinforcement.

Beams BS1, BS2 and BS3, provided with 0.6%, 1.2%, and 1.8% reinforcement ratio, respectively, demonstrated the same load-deflection response, as beam BS0, up to ultimate load. However, after the beams reached their ultimate load (Figure 3), they were able to sustain inelastic deformation prior to collapse, without significant loss in resistance. This might be attributed to a greater resistance to local failure of steel-reinforced UHP-SHCC. Additionally, the sustained inelastic deformation was increased by increasing reinforcement ratio. After the strengthened beams reached their ultimate load, and contrary to the observed behavior of BS0, the curve demonstrated a softening tail, and the load drops gradually from the peak to a constant load level for each beam. Thereafter, the beam's behavior was controlled by the steel reinforcement.

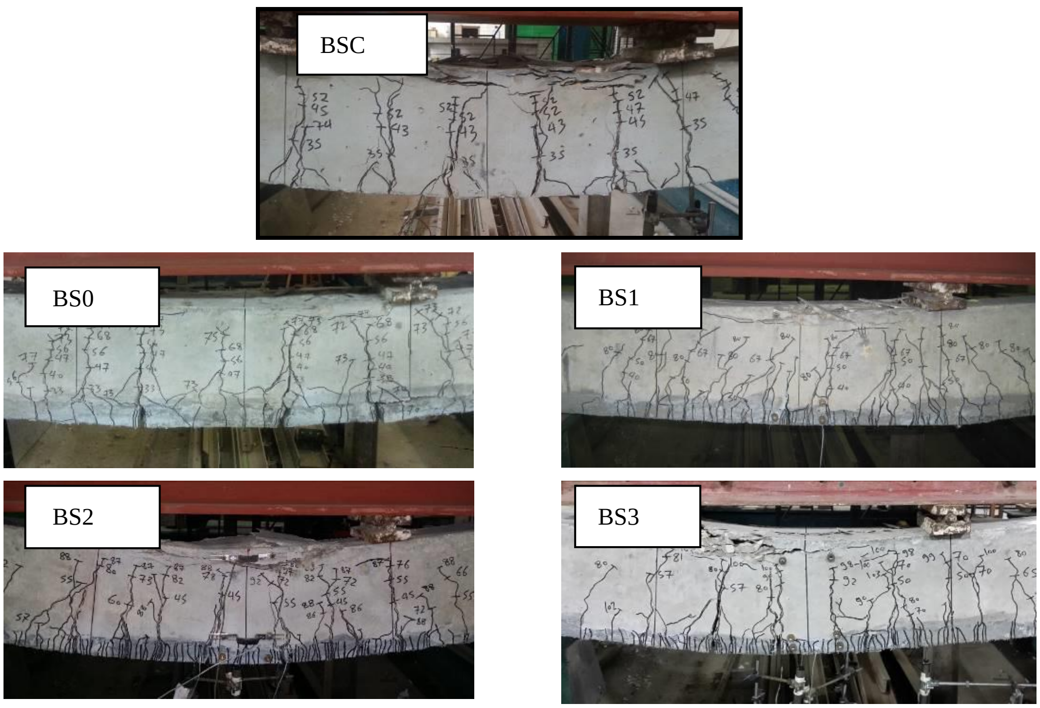

Figure 2. Cracks pattern and failure mode of tested beams.

3.4 Ductility Analysis

Ductility is an important property for safe design of strengthening of any structural element. As UHP-SHCC strengthening is a relative recent strengthening strategy, understanding the effect of this technique on the ductility of a RC member is crucial. Therefore, the ductility index (μØ), which expressed as the ratio between the curvature at the ultimate condition (Øu) and curvature at the yield load (Øy), will be the indicator of ductility for all tested beams.

Table 2 lists the values of the ductility index for all tested beams. According to the (CEB-FIB. 2010) recommendations, the minimum ductility index, in terms of curvature, should be approximately 1.7 and 2.6 for concrete types C35/45 or lower and concrete types higher than

C35/45, respectively. The ductility index should exceed this minimum value to prevent the occurrence of sudden failure in the strengthened flexural members. The curvature ductility indexes (μØ) of all the UHP-SHCC-strengthened beams are lower than the value obtained for the control beam, as shown in Table 2. However, the curvature ductility index (μØ) of beams BS1, BS2 and BS3, are higher than the one obtained for beam BS0, that because of the strain localization occurred in the unreinforced strengthening layer which made a rapid collapse. The results seem to indicate that the use of steel reinforcement can successfully enhance the ductility of UHP-SHCC strengthened beams. Moreover, 0.6%, 1.2% and 1.8% steel reinforcement enabled beams BS1, BS2 and BS3 to attain a curvature ductility index (μØ) of 2.09, 3.70 and 3.72 respectively, which, according to (CEB-FIB. 2010) recommendations, is adequate to guarantee satisfactory ductility.

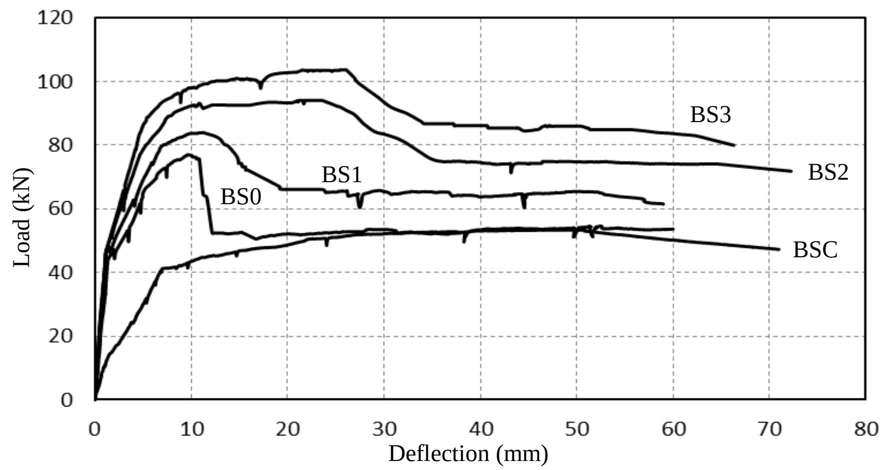

Figure 3. Envelope load-deflection relationships for tested specimens.

Table 1. Test results for all specimens.

Specimen code	Cracking		Yield		Ultimate	
	UHP-SHCC		Main Reinforcement			
	Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)
BSC	-	-	41.4	6.90	53.4	50.84
BS0	46.6	1.39	73.4	7.10	77.0	9.62
BS1	46.2	1.20	81.6	7.55	84.0	11.44
BS2	46.9	1.16	90.2	7.80	94.0	23.60
BS3	47.0	1.18	95.4	8.05	103.7	26.13

3.5 Toughness

The toughness was measured as the area under the load - deflection curve up to the peak for each beam which may be considered as a ductility indicator. As shown in Table 2, the toughness of all the UHP-SHCC strengthened beams are lower than the value obtained for the control beam. However, the toughness of beams BS1, BS2, and BS3, strengthened with steel reinforced UHP-SHCC layer, are higher than the one obtained for beam BS0, strengthened with unreinforced UHP-SHCC layer. The results seem to indicate that the use of steel reinforcement can successfully enhance the ductility of UHP-SHCC strengthened beams. Moreover, 1.8% steel reinforcement enabled beam BS3 to attain a toughness of (2283), which is closer to other one (2088) obtained by 1.2% steel reinforcement beam BS2 that emphasized the previous explanation of the insignificant enhancement occurred in the ductility behavior when using reinforcement ratio beyond 1.2% in UHP-SHCC strengthening layer.

Table 2. Ductility index and toughness for group (I).

Beam	**Yield curvature (km^{-1})**	**Ultimate curvature (km^{-1})**	**Ductility index ($\mu_{\varnothing}$)**	**Toughness (kN.mm)**
BSC	18.75	143.11	7.63	2360
BS0	19.38	23.75	1.22	745
BS1	19.13	40.00	2.09	1032
BS2	19.81	73.25	3.70	2088
BS3	19.94	74.25	3.72	2283

4 CONCLUSIONS

- Strengthening of RC structures using unreinforced UHP-SHCC layer may lead to brittle failure.
- Comparing to the specimen strengthened by unreinforced UHP-SHCC layer, distributed fine cracks were observed in the reinforced UHP-SHCC layer and the cracks were increased.
- No delamination at the interface between UHP-SHCC layer and the substrate was observed.
- The load–deflection response of the strengthened beams indicates that the use of small amount of steel reinforcement within the UHP-SHCC strengthening layer significantly enhanced their post peak behavior.
- The convergent previous results of ductility index, toughness for beams strengthened with 1.2% and 1.8% reinforcement ratio in the strengthening layer emphasized the insignificant use of reinforcement ratio higher than 1.2% in the ductility enhancement of strengthened beams.

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