Resilient Structures and Sustainable Construction
Edited by Pellicer, E., Adam, J. M., Yepes, V., Singh, A., and Yazdani, S.
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ISBN: 978-0-9960437-4-8

STRENGTHENING OF RC BEAMS SUBJECTED TO CYCLIC LOAD USING ULTRA HIGH-PERFORMANCE STRAIN HARDENING CEMENTITIOUS COMPOSITES

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Ultra High-Performance Strain Hardening Cementitious Composites (UHP-SHCC) is a composite material comprising a cement-based matrix and short fibers with outstanding mechanical and protective performance having advantages as large strain capacity as well as high compressive and tensile strength, which is useful for strengthening or repair concrete members. In the present study, five specimens were tested experimentally, one as a control and four strengthened with 40 mm thickness of UHP-SHCC layer attached from tension side with variable reinforcement ratios embedded in strengthening layer. Cyclic loading was applied to all specimens. The test results showed the importance of reinforcing the UHP-SHCC to eliminate the observed early strain localization and to gain adequate dissipated energy under cyclic loading. It is also proved that using an unreinforced UHP-SHCC layer for strengthening may lead to a brittle failure especially in case of cyclic load.

Keywords: Dissipated energy, Reinforced concrete, Structural engineering.

1 INTRODUCTION

The interest of strengthening and repairing of reinforced concrete structures has increased in the last few years because of poor performance under service loading in the form of excessive deflections and cracking, construction faults, design faults, excessive deterioration and the changing in use of structure. Many methods developed for purposes of strengthening and repairing under cyclic loads. As example, (Vaz *et al*. 2014), tested six specimens to study the behavior under cyclic loading of reinforced concrete beams strengthened in bending by the addition of concrete and steel on their tension side using expansion bolts as shear connectors. The comparisons of test results showed that, when the the residual deformation is deducted, beams subjected to cyclic loading did not differ much from those obtained for beams that were only subjected to static loads in the earlier works. 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. Our research is to complete the previous search with studying the behavior of beams strengthened with SHCC materials under cyclic loading. 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, Kunieda *et al*. 2010). UHP-SHCC has relatively higher hardening strain compared with ordinary UHPFRC, and relatively higher stress than ordinary SHCC. In addition, UHP-SHCC considered a perfect protective material against corrosion (Amino *et al.* 2015).

2 EXPERIMENTAL PROGRAM

2.1 Material Properties

The concrete mix used for all tested slabs was designed to give an average concrete cube strength of 29 N/mm^2 at age of 28 days. High tensile deformed steel bars with 400 MPa yield stress and 683 MPa ultimate stress were used as main reinforcement, while the secondary reinforcement (transversal) was normal mild steel with 250 MPa yield stress and 360 MPa ultimate stress. For UHP-SHCC concrete the 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 substituted with a silica fume (density: 2.2 g/cm^3). Quartz sand (less than 0.2 mm in diameter, density: 2.68 g/cm^3) was used as the fine aggregate. High strength polypropylene fiber with 6mm nominal length was chosen for UHP-SHCC and the fiber volume in the mix was 1.5%. Super plasticizer was used to enhance the workability of the matrix. The tensile behaviour of the used UHP-SHCC was characterized by testing of six dumbbell-shaped specimens (tested cross-section: 10×30mm) in uniaxial tensile test. Compressive test were performed on six cylindrical specimens having the size of 100 × 200 mm. The average tensile strength, compressive strength, ultimate tensile strain (strain at ultimate load), and ultimate compression strain of the UHP-SHCC at the age of 28 days were determined to be 6.5 MPa and 78.8 MPa; 1.4% and 0.46% respectively.

2.2 Specimen's Details

The experimental program included the testing of five R.C. beams, one as control and four RC beams strengthen with different configurations of UHP-SHCC layer before testing. All the beams had the same dimensions of 120 mm width, 200 mm height, and 1,800 mm length. Two 10 mm diameter rebar were used as tension reinforcement for all the beams with an effective depth 180 mm. Stirrups of 8 mm diameter were used in the shear span at the interval of 70 mm. The beam tesion side was washed out to obtain a rough surface. Following the wash-out process the specimens were covered with wet towels for additional 26 days. After 28 days, UHP-SHCC strengthening layer was added with 40 mm thickness in the beams' tension side. One beam was strengthened using unreinforced UHP-SHCC layer, and three beams were strengthened with steel reinforced UHPSHCC layer with diffrent reinforcement ratio.The concrete dimensions and reinforcement details of the tested specimen were shown in Figure 1.

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. The instrumentation used to monitor the behavior of the beams during testing is shown in Figure 1. The applied cyclic loading protocol divided into four stages. Then if failure does not occur during these stages, the system applies monotonic loading under load-control at a rate of 0.10 kN/s until failure. The description of cyclic loading stages as follows, the system applies 100 cycles of load/unload between specified values of the load range (10%-30%, 10%-50%, 10%-70%, and 10%-90%) of the expected failure load evaluated theoretically according to ACI 318M-14 (American Concrete Institute 2014), considering applying static load.

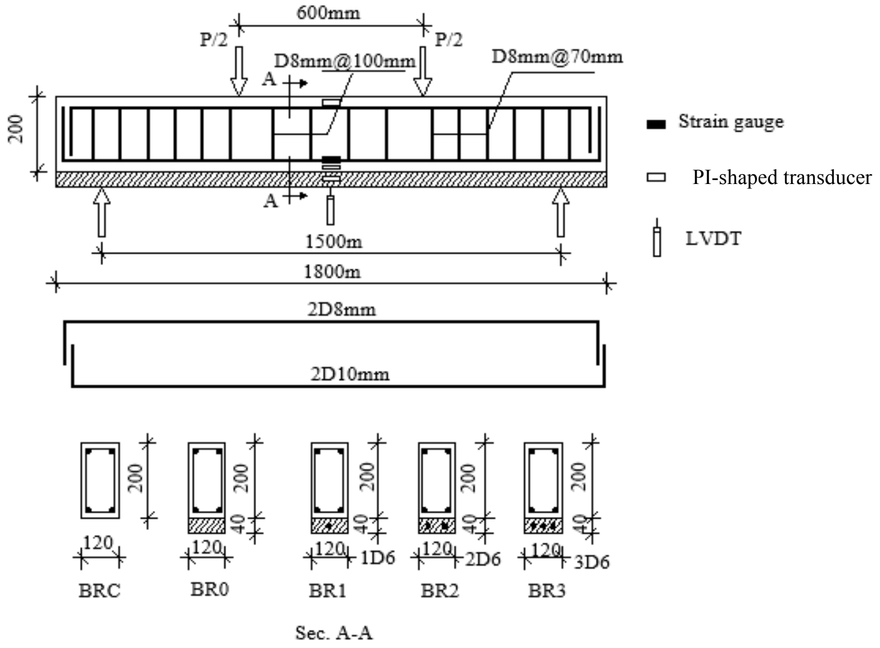

Figure 1. Test setup and specimens details.

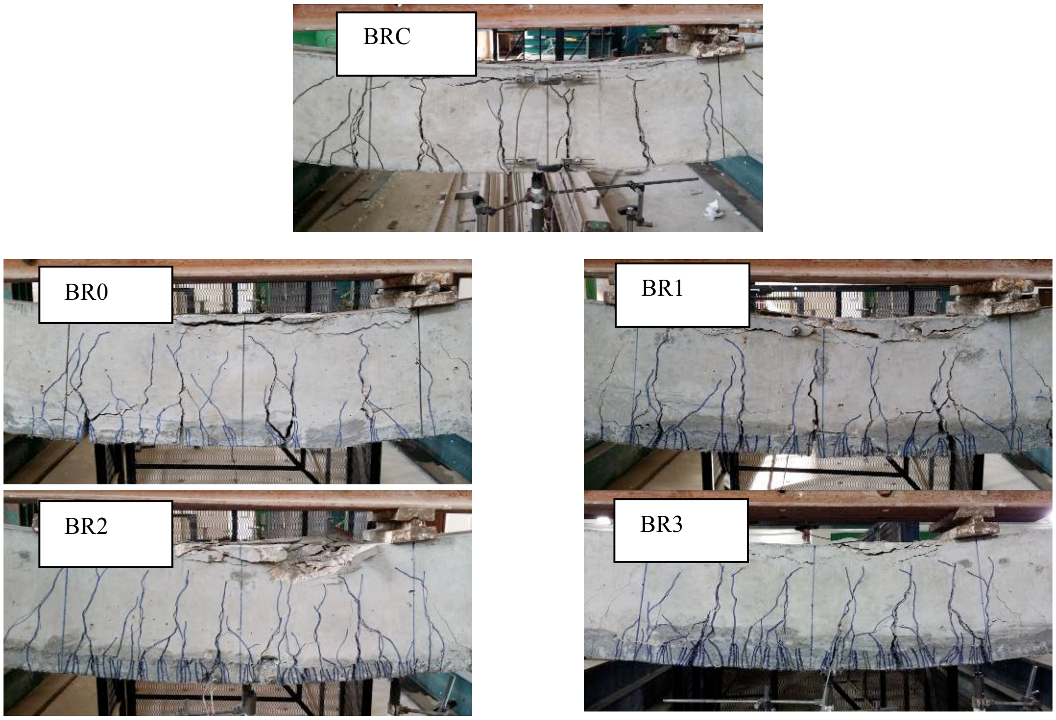

Figure 2. Cracks pattern and failure mode of tested beams.

3 TEST RESULTS AND DISCUSSION

3.1 Loads, Crack Patterns, and Failure Modes

The control beam (BRC), failed as expected in flexure. The failure was ductile with wide flexure cracks within the middle third and shear flexure cracks through the inner and outer third span of the beam, as shown in Figure 2, the beam failed at 49.7 kN. For all strengthened beams flexure cracks started to appear in substrate concrete at the tension side. With the increase in loading, cracks started to appear in the strengthening layer during the third stage of loading for beams BR0 and BR1 and during the second stage of loading for beams BR2 and BR3 then propagated upward in substrate concrete. The beams continued to support the applied load until failure was occurred, at ultimate loads 71, 79, 91 and 100 kN for strengthened beams BR0, BR1, BR2 and BR3, respectively, when 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, according to strain monitoring realized during the test.

Cracks pattern for the strengthened beams are shown in Figure 2. It was possible to verify on the experimental results that the development of a crack in the concrete substrate might produce high strain concentration points in the UHP-SHCC strengthening layer, inducing the tensile failure of the strengthening layer. When reinforcement were used in UHP-SHCC 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 BR0.

3.2 Load Deflection Hysteresis Loops

An important figure that must be generated to evaluate the structural performance under repeated loading is the load-deflection hysteresis loops. Structure elements are expected to enter in elasto-plastic range during repeated loading and the hysteresis loops can provide good understanding for the analysis of elasto-plastic response. The Load-deflection hysteresis response indicates the energy dissipation capacity of the structure by considering the area enclosed by the hysteresis loops. Figure 3 shows the envelop curves of load deflection hysteresis loops which shows easily the ultimate loads and corresponding deflection for all tested specimens. From the last mentioned figure, it can be noticed the great increase in the initial stiffness for the strengthened specimens compared to the control one, this is to be expected, partially because of the stiffening of the beams due to the application of the strengthening layer. In addition, increasing the ultimate deflection for specimens strengthened using reinforced UHP-SHCC may indicate the important role of the additional reinforcement in the delay of the strain concentration and localized failure occurred in the strengthening layer.

3.3 Dissipated Energy

For structures, surviving a seismic event depends mainly on their capacity for energy dissipation. Greater the energy dissipated, better the specimen performance. Energy dissipation is also a relevant parameter in order to analyze the performance of reinforced concrete member subjected to repeated loading. The injected energy into the structure has two forms: dissipated energy (ABCDA); and recoverable energy (ADCEA) as shown in Figure 4 of a typical loading cycle. Total energy absorbed by the system is the sum of dissipated energy and recoverable energy. The dissipated energy is the area enclosed by the hysteresis loop as shown in Figure 4.The energy dissipated during each loading cycle was calculated using the trapezoidal rule to determine the area within the load-deflection hysteresis loop. The value of dissipated energy in all cycles at same loading stage was determined. The values of dissipated energy (ABCDA) of each type of beam are shown graphically in Figure 5. In Figure 5, it can be observed that, during first three loading stages, for all beams the dissipated energy increased by increasing reinforcement ratio used in the strengthening layer, however still smaller than the control beam, that enhancement in energy dissipated occurred in strengthened beams was due to fibers inside the matrix of UHP-SHCC layer and the additional steel bars used in this layer, which act as energy dissipaters, but still smaller than the control beam which was able to made large deflection and lead to widely cracks compared to other strengthened beams at the same load stage that helps to dissipate more energy. During the fourth stage (10-90 %), it can be observed that all strengthened beams with additional reinforcement in UHP-SHCC layer (BR3, BR2 and BR1) were able to dissipated more energy than the control beam and beam BR0, this is because that the great contribution gained from the fibers and additional reinforcement in the strengthening layer, which obtained larger strain in the UHP-SHCC layer than other strengthened beams and this large strain gained large dissipated energy.

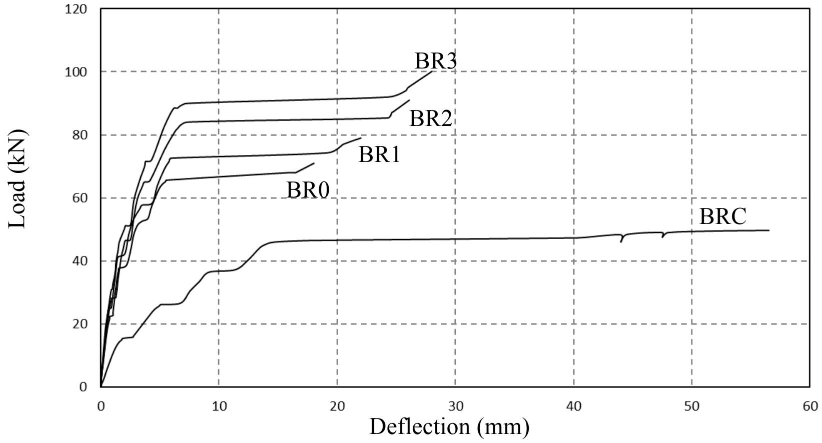

Figure 3. Envelope load-deflection relationships for tested specimens.

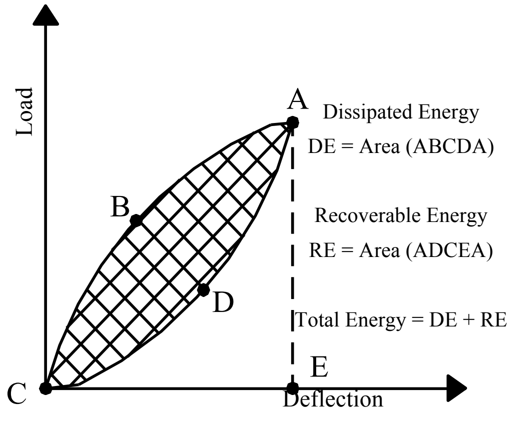

Figure 4. Typical loading cycle for a structural element.

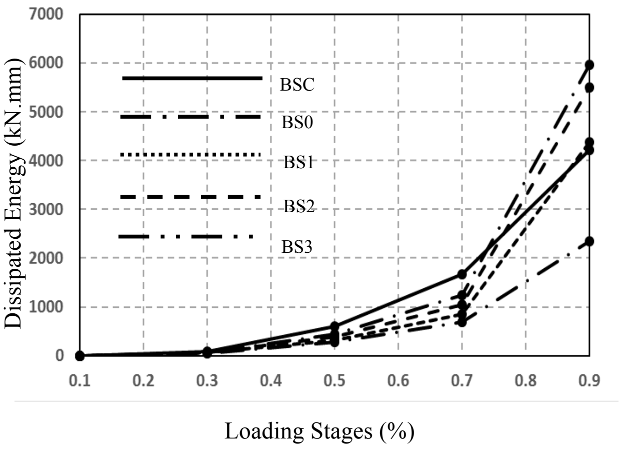

Figure 5. Dissipated energy for all tested specimens.

4 CONCLUSIONS

Based on the results obtained in this work, the following conclusions can be drawn:

- Strengthening of RC structures using an unreinforced UHP-SHCC layer may lead to a 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 number of cracks was dramatically increased.
- No delamination at the interface between UHP-SHCC layer and the substrate was observed under cyclic loading.
- The load-deflection hysteresis loops indicate the capability of the small amount of steel reinforcement to reduce the stiffness degradation of the UHP-SHCC strengthening layer under repeated loading.
- The convergent previous results of the total dissipated energy and stiffness degradation obtained by 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 the strengthened beams.

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