Structures 25 (2020) 603–612

Contents lists available at ScienceDirect

Structures

journal homepage: www.elsevier.com/locate/structures

Restoration of the shear capacity for RC beams with web openings using precast SHCC plates

Ali Hassan*, Ahmed M. Atta, Tarek F. El-Shafiey

Structural Engineering Dept., Faculty of Engineering, Tanta University, Tanta, Egypt

ARTICLE INFO

Keywords:
Shear
Concrete beams
Strengthening
Failure
Opening
Stain Hardening Cementitious Composites (SHCC)

ABSTRACT

Providing web opening in the shear-span zone of RC beams results in significant reduction in the shear capacity of such beams. Thus, an efficient restoration technique has to be found out and implemented in order to compensate the developed reduction. The main target of the current paper is to introduce and validate an innovative restoration technique for the new construction making use of the Strain-Hardening Cementitious Composites (SHCC) material. Accordingly, precast thin SHCC plates having the required opening were cast and cured for about 3 weeks to eliminate the volumetric change issues, and then placed inside the formwork at both sides before casting the RC beams included web openings. The chosen thickness of the SHCC plates was 20 mm in order to be easily accommodated in the concrete cover. For the considered openings, the opening depth was kept constant to be 0.30 of the beam effective depth, while the opening length was varied considering three values; 150, 300, and 450 mm. Besides, small amount of internal reinforcement in the form of steel wire mesh was provided inside some SHCC plates in order to enhance their shear strength and ductility. Experimental results showed that the provided SHCC layers enabled the strengthened beams to exhibit distinguished performance in terms of ultimate capacity, ductility and decreased shear crack width. In addition, the gain in shear capacity due to the SHCC plates is decreased with the increase of the opening width. Finally, comparisons between the obtained experimental results and the predicted shear capacities stipulated by the ACI 318-19 and JSCE codes were performed. The comparisons revealed that the estimated shear capacities are in satisfactory agreement with the experimental results, however, these estimations tend to be overestimated with the increase of the opening length.

1. Introduction

In the construction field, web openings in RC beams are usually required for the passage of utility pipes and ducts. These ducts are necessary to accommodate essential services such as electricity, water supply, telephone, gas, and computer network. These pipes and ducts are usually positioned underneath the soffit of the beam. For aesthetic reasons, these pipes and ducts require a false ceiling, which decreases the net height of floor. Therefore the use of web openings enable the designer to shorten the building height, especially with regard to high rise building, which can lead to a cost-effective design.

The openings may be circular, rectangular, triangular, trapezoidal, diamond, and even irregular in shape. Nevertheless, the most applicable openings are circular and rectangular [1]. Previous researchers have used the terms “large” and “small” openings for their classification without clear distinction. According to Corley and Somes [2], the circular opening may be classified as large when the opening diameter exceeds 0.25 times of the web depth. On the other hand, Mansur [3] suggested a criterion to classify the size of rectangular openings. Mansur [3] classified the web opening as small if the opening length is less than the larger of the bottom and top chords' depth. According to the opening size, the design approach of a beam with opening can be determined. The design of a beam with small openings may follow the usual design of the solid beam. While, the existence of large web openings will transform the simple beam behaviour into a vierendeel action.

The existence of openings in high shear zone produces a disturbance in the normal flow of stresses, thus stress concentration around the opening region and early cracks are expected [4]. Therefore, special reinforcement around the opening should be provided [5,6]. However, the small dimensions of upper and lower chords members do not permit providing a sufficient quantity of steel reinforcement to limit the cracks propagation and prevent potential premature shear failure of the beam.

SHCC is a new generation of fiber-reinforced cementitious

* Corresponding author at: Structural Engineering Dept., Faculty of Engineering, Tanta University, Tanta 31511, Egypt.
E-mail address: Ali_hassan@f-eng.tanta.edu.eg (A. Hassan).

https://doi.org/10.1016/j.istruc.2020.03.046
Received 12 December 2019; Received in revised form 26 January 2020; Accepted 23 March 2020
Available online 29 March 2020
2352-0124/ © 2020 Institution of Structural Engineers. Published by Elsevier Ltd. All rights reserved.

composites that consists of sand, cement, fly ash, silica fume, and short fibers [7–12]. The SHCC material exhibits a pseudo strain hardening behavior characterized by the formation of multiple fine cracks under tensile loading [13,14]. Characteristics of the multiple cracking of the SHCC could enhance both durability and impermeability properties of this material [15–22]. When the SHCC material was used in repair applications, it showed a considerable high tensile strain capacity, which is a main important criterion of a durable material in order to resist premature failures [23–26].

In the last years, the structural performance of SHCC-RC composite members has been investigated by many researchers. They revealed the effective use of the SHCC with different elements to increase their strength and ductility [27–29]. In the recent years, the use of permanent pre-cast SHCC plates is introduced. Xiangguo et al. [30] examined the effect of pre-cast U-shaped high-performance fiber reinforced cementitious composites section on the shear capacity of the composite beams. Also, Massicotte et al. [31] reported that thin pre-cast fiber reinforced cementitious composites have been applied to the rehabilitation of existing infrastructures. Although various researches on SHCC materials and members have been carried-out, the structural application of SHCC pre-cast plates is still a critical issue.

Based on SHCC with its outstanding mechanical characteristics, the present work aims to develop and asses a new strengthening technique for RC beams with web opening. The SHCC could be utilized in the form of thin pre-cast plate which is placed in the critical shear span during fabrication. In this research, the SHCC reinforcement as well as the opening length have been studied. A total of ten simply supported RC beams were fabricated and tested. The test results of the strengthened beams in form of cracking and ultimate loads, deflection and crack width were recorded and compared with similar beams without strengthening.

2. Experimental work program

2.1. Test specimens

Fig. 1 presents the concrete dimensions and reinforcement details of the tested beams. All beams had the same section dimensions of 350 mm depth, 150 mm width and a total length of 2400 mm. All beams were tested under four point loading scheme and the shear span length was 900 mm (three times the beam effective depth), which is the recommended value for assuring a negligible arch effect [32]. Except the control beam, all beams had a rectangular opening in the middle of the left shear span. The web opening location was selected to fully interrupt the natural load path which is defined as the line connecting the support point and load, as shown in Fig. 1. All beams were reinforced by the same amount of longitudinal steel rebars and shear stirrups. The reinforcement arrangement for all beams consists of 4 D 18 mm bars (1.12% reinforcement ratio) as longitudinal tension steel and 2 D18 mm bars as compression reinforcement. To localize the shear failure in the left shear span, a relatively high amount of steel stirrups were applied in the right shear span. As shown in Fig. 1, stirrups D 8 @ 75 mm were used in the beams' right shear span. Whereas, the left-side shear span was kept without web reinforcement.

2.2. Test matrix

The characteristics of the tested beams are summarized in Table 1. The test matrix consists of ten reduced scale RC beams. One solid beam "BC", without opening, was used as a reference for the sake of comparisons. The remaining nine beams with web opening were categorized into three groups. In each group, three different opening lengths were used 150, 300, and 450 mm. Whereas, the opening depth was kept constant at a value of 100 mm which represents 33% of the beam effective depth. The three beams of group (I) were constructed without strengthening. On the other hand, the beams of the second group were strengthened in the shear span with web opening using two pre-cast SHCC plates (one plate per side). Beside the steel reinforcing cage, the pre-cast plates were positioned prior to the concrete casting. The SHCC plates had a similar dimensions of 900 mm length, 350 mm height, and 20 mm thickness. Also, the used pre-cast plate had an opening with dimensions similar to that of the strengthened beam. It is worth mentioning that, after applying the pre-cast SHCC plates, the beam width is still equal to 150 mm (similar to the unstrengthened beams). The last group consists of three beams that were strengthened in the shear span with web opening by two pre-cast SHCC plates, these plates were reinforced by one layer of a galvanized steel wire mesh. The used steel wire mesh reinforcement was 0.72 mm wire diameter, tensile yield strength 250 MPa, and 6.35 mm center to center grid spacing. The control beam without opening was given the designation "BC". Whereas, the remaining beams with web openings were given the designation "B". The number following this designation indicates the opening length. These numbers are followed by designations "S" (strengthened) and R (Reinforced SHCC plate).

2.3. Material properties

Concrete strength can significantly affects the test results especially in estimating the shear capacity of RC beams. Therefore, to assure that the concrete characteristics were almost identical in all beams, the same ready-mix concrete patch was used for casting all beams. Also, all beams were cured under the same conditions to minimize the variation in concrete strength. The average compressive strength of concrete at the test date was 35.2 MPa. The tensile strength of the used concrete was determined based on the splitting tensile test for three cylinders 300 mm height and 150 mm diameter. The average value of tensile strength was 3.49 MPa.

In order to obtain the mechanical properties of the used steel reinforcement rebars 18 mm and 6 mm diameter; tensile tests were individually carried out on three specimens. For the high tensile steel D 18 mm, the obtained mean value of yield and ultimate tensile strengths were 410 MPa and 631 MPa, respectively, and Young's modulus was 205 GPa. For the mild steel reinforcement D 6 mm, the obtained mean value of yield and ultimate tensile strengths were 254 MPa and 370 MPa, respectively, and Young's modulus was 205 GPa.

Table 2 summarizes the mix proportions of the used SHCC material. The water/binder ratio was 0.20. Ordinary Portland cement was used, and fifteen percent of the design cement content was replaced by silica fume. Fine Quartz sand with diameter less than 0.5 mm was used. High strength polypropylene fiber (PP) was selectively chosen for the SHCC and its volume fraction in mix was 2.0%. The length and diameter of the PP fibers were 12 mm and 0.025 mm, respectively. The SHCC material mix was prepared in a Hobart horizontal mixer with 20 L capacity. The sand, cement and silica fume were mixed for approximately two minutes to homogenize the dry ingredients, after that water mixed with a super-plasticizers were added and mixed for additional two minutes until a homogeneous SHCC mix was obtained. Finally, the PP fibers were added to the mix. After adding the PP fibers, the mixer was run at medium speed for two minutes and high speed for four minutes. The tensile characteristics of the used SHCC was determined by testing of six uniaxial tensile test specimens. The tensile test specimen cross-section was 50 × 200 mm and 900 mm length. Fig. 2 shows the test setup and instrumentations of the carried-out uni-axial tensile test. To evaluate the effect of the steel wire mesh reinforcement on the tensile behaviour of the SHCC material, three of the tensile test specimens were provided with a single layer of wire mesh at the middle of the SHCC layer. The tensile stress–strain relationship for a test specimen obtained from the uni-axial tensile test is shown in Fig. 3. As shown in Fig. 3, the first cracking strength of the SHCC specimen was almost similar in both of reinforced and unreinforced specimen and about 3.01 MPa. While, the average ultimate tensile strengths were 7.05 MPa and 7.64 MPa for the unreinforced and reinforced specimens, respectively. The

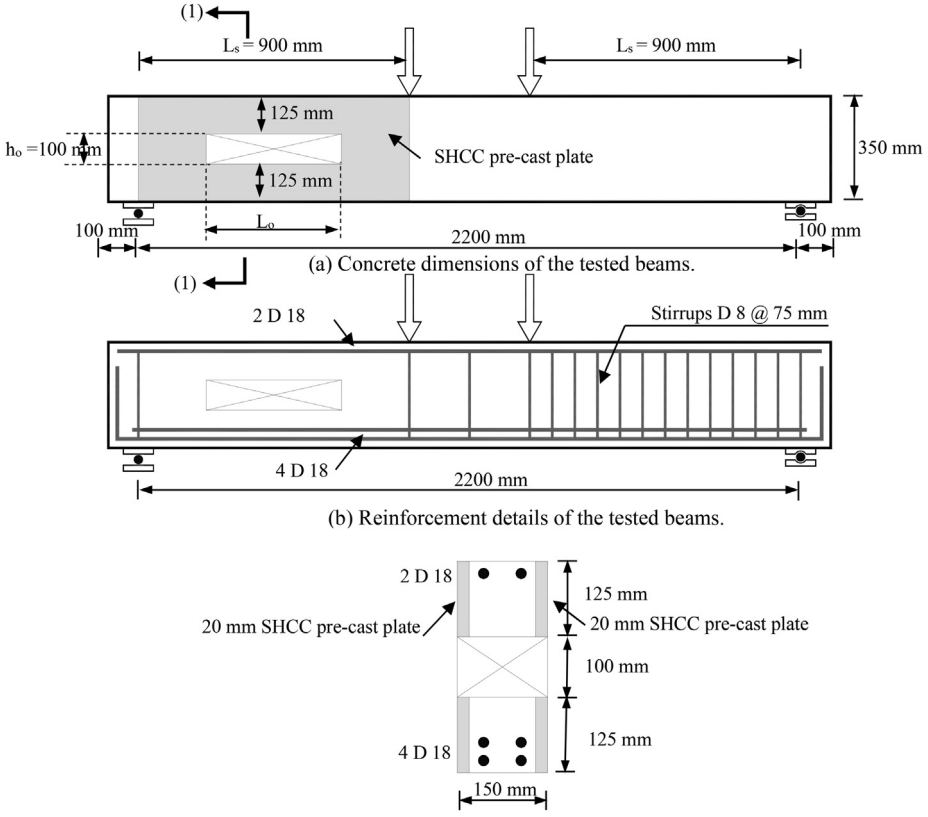


Fig. 1. Details of the tested beams.

corresponding ultimate tensile strains for the unreinforced and reinforced SHCC plates were 5051, and 7400 micro-strain, respectively. In order to obtain the compressive strength of the used SHCC, three cylinders having a size of 50 × 100 mm were tested. The average compressive strength of the SHCC material was 65.5 MPa. Fig. 4 shows a sample of the compressive stress–strain relationship of the SHCC material measured from the uni-axial compressive tests based on average sense.

2.4. Manufacturing of the SHCC strengthened beams

Fig. 5-a to -d show the fabrication stages of the beams strengthened using pre-cast SHCC plates. All beams were cast in two stages. In the first stage, the SHCC plates were cast in to wooden molds as shown in Fig. 5-a. For the SHCC plates provided with steel wire mesh, the SHCC mix was cast into the molds up to 10 mm thickness, and then the steel wire mesh was positioned on top of the 10 mm layer thick. Beyond which, the remaining SHCC is then cast into the mold so that the total thickness of the pre-cast SHCC plates became 20 mm. The SHCC material has self-consolidating characteristics; no internal or external vibrations were applied during the casting. The SHCC was poured from one end of the formwork and was allowed to flow to the other end. The same casting method was used for all plates to maintain a similar fiber distribution. It is worth mentioning that, during the fabrication of the SHCC plates, the upper surface of plates was kept rough without any smoothen. The pre-cast SHCC plates were de-molded after 24 h then cured under wet conditions for two weeks, see Fig. 5-b. By the end of the two weeks, the SHCC plates and the beam's reinforcing cage were assembled together and placed in the wooden forms to be ready for the second casting stage, as shown in Fig. 5-c and -d. To increase the bond

Table 1
Experimental test matrix.

Group	beam designation	Opening dimensions		(L_s) (mm)	L_o/L_s (%)	Strengthening regime	Studied parameter
		(h_o) (mm)	(L_o) (mm)				
Control	BC	Without opening		900	——	——	Reference beam
Group (I)	B_{150}	100	150	900	16.67	Without strengthening	Effect of opening length
	B_{300}	100	300	900	33.33		
	B_{450}	100	450	900	50		
Group (II)	$B_{150,S}$	100	150	900	16.67	Unreinforced SHCC plate	Effect of using SHCC pre-cast plates
	$B_{300,S}$	100	300	900	33.33		
	$B_{450,S}$	100	450	900	50		
Group (III)	$B_{150,S,R}$	100	150	900	16.67	Reinforced SHCC plate	Effect of using reinforcement inside the SHCC plates
	$B_{300,S,R}$	100	300	900	33.33		
	$B_{450,S,R}$	100	450	900	50		

h_o = opening height; L_o = opening length; L_s = shear span length.

Table 2
Mix proportions of the used SHCC material (kg/m^3) for cubic meter.

Water-to-binder ratio	Water	Super plasticizers	Fibers (volumetric ratio)	Silica fume	Sand	Cement
0.20	312.1	31.6	16.20 (2.0%)	237	157.9	1342

between the pre-cast plates with the concrete core, the rough surface of the SHCC plate was positioned opposite to the reinforcing cage. In the second stage, the concrete core was cast using a ready-mix concrete. The upper surface of all beams were cured by wet sackcloth for two weeks, and then allowed air-drying until the testing day.

2.5. Test setup and instrumentations

Fig. 6 shows the executed test setup in order to perform the four point loading scheme. The beam ends were simply-supported over a roller support at one end and a hinged support at the other end. The effective beam span was 2200 mm, keeping an overhanging length of 100 mm at each end, and the shear span length was 900 mm. A load cell of 400-kN capacity was used to measure the acting loads on the tested beams. A laser level was used to ensure the coincidence of the axes of tested beam and the load cell before testing. Also, to monitor the developed vertical deflection along the beam length, a series of 100 mm linear variable displacement transducers (LVDTs) were placed under the two loading points, mid span, opening corners, and the middle of the opening. An electrical strain gauge with 10-mm gauge length was mounted on the longitudinal tension reinforcement at mid-span. Moreover, two Pi gauges 100 mm gauge length (0.005 mm accuracy) were placed at the opening corner in order to measure the developed crack width in case of one crack passing through the measuring length. While, in the case of more than one crack passing through the measuring length, an optical microscope (0.01 mm accuracy) was used to measure the width of the major crack. After each load increment, the vertical deflection, strain and Pi gauges readings, and the major crack width were recorded. The same loading rate for all beams was applied about 0.04 kN/s. An automatic data logger unit was used in order to record data during the test for load cell, steel strains, LVDTs, and measuring gauges.

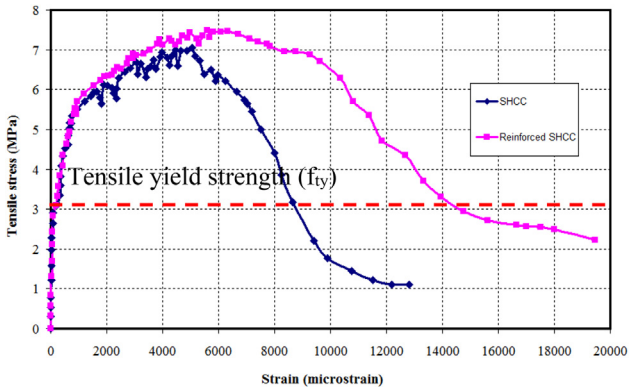


Fig. 3. Stress-strain of SHCC specimen under uniaxial tensile test.

3. Experimental results

3.1. Ultimate loads and modes of failure

The main experimental test results are given in Table 3. The table gives the shear cracking load ($P_{cr,sh}$), the ultimate shear load (P_{ult}) and its corresponding deflection (Δ_{ult}). The reductions in the ultimate shear capacity due to the inclusion of openings exhibited by the unstrengthened beams with respect to the reference solid beam BC are also reported. The gain in the shear capacity due to the proposed strengthening technique relative to those without strengthening are also summarized in Table 3.

Fig. 7 shows the final crack pattern of the tested beams. As shown in this Figure, all beams exhibited shear failure in two distinctly different modes. The measured strain in the longitudinal steel reinforcement in all tested beams indicated that the bottom tensile steel reinforcement did not reach the yield strain until failure took-place. Details of the

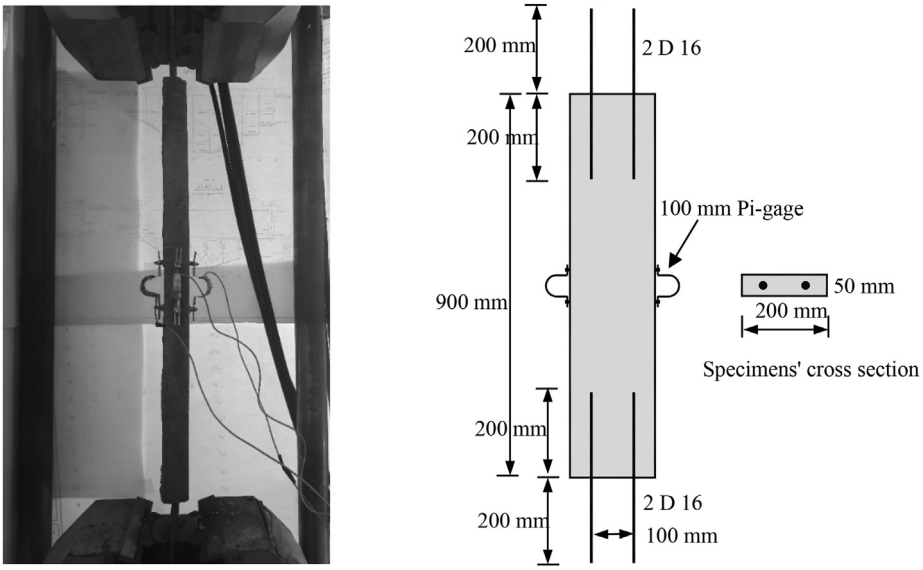


Fig. 2. Test setup of uniaxial tensile test of SHCC specimen.

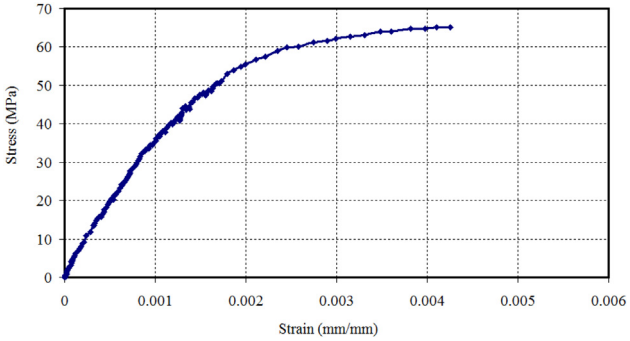


Fig. 4. Stress-strain of SHCC specimen under uniaxial compressive test.

cracking patterns and failure modes of the tested beams are subsequently reported.

For further assessment of the effect of the web opening on the shear capacity of unstrengthened concrete beams, the reference solid beam BC was tested. For beam BC, reaching about 64 kN, the first flexural crack took-place within the loading zone where the maximum flexural moment is located. On the other hand, the first visible shear crack was noticed in the weak side when the load reached about 80 kN. The shear crack extended from the loading point to the support, as load increased, the crack widened with appearance of another minor cracks appeared. Finally, when the load reached about 180 kN the beam suddenly failed in shear.

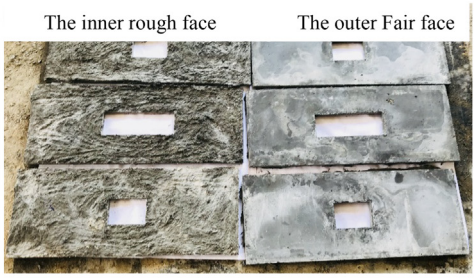
Fig. 8 presents a relation between the ultimate loads (P_u) and the opening width-to-shear span length ratio (L_o/L_s). As shown in Fig. 8, it is clear that the inclusion of a web opening in the unstrengthened concrete beams resulted in a drastic loss in the beam ultimate capacity. The deterioration in the shear capacity was influenced by the opening width-to-shear span length ratio (L_o/L_s). For beams B_{150} and B_{300}, with L_o/L_s values of 16.6% and 33.3%, respectively, the first shear crack was noticed at about 70 and 45 kN, respectively, at the opening corner near to the support due to stress concentration. While the load increasing, another shear crack was noticed in the opposite corner of the opening, the developed cracks progressed very rapidly, upon initiation, until they reached the loading and support points, generating a sudden failure. Post failure inspection of the beams showed, a similar failure mode, which is typical of the failure observed in the solid beam as shown in Fig. 7. The maximum achieved ultimate loads were 115 and 90 kN for beam B_{150} and B_{300}, respectively. Conversely, as shown in Fig. 7, beam B_{450} with L_o/L_s = 50%, failed by the formation of two parallel diagonal cracks, crack per each chord member bridging the two solid segments of the beam, which is called frame-type failure. In this beam, the shear cracks initiated at 35 kN, earlier compared to B_{150} and B_{300} and the maximum achieved load was 80 kN. The test observations indicate that as L_o/L_s ratio increases the failure mode of the tested beams tends to change from a shear failure at the opening corners to a shear failure in the chords below and above the opening with a large decrease in the achieved load carrying capacity.

All beams of group (II) failed in a similar mode, the beams failed in shear at the opening corners due to stress concentration. Although the failure was brittle, it was less sudden than that in the case of the similar unstrengthened beams with web opening. The failure was governed by rupture of the SHCC plates with no signs of debonding or delamination between SHCC plates and concrete interface as shown in Fig. 9. This observation illustrates that the proposed strengthening system can mitigate the shear failure in the cords below and above the opening which is commonly observed in the concrete beams with large opening size, B_{450}.

The ultimate load and the gain in the ultimate load of the strengthened beams compared to the unstrengthened beams are listed in Table 3. As shown in Table 3 it is clear that, using SHCC pre-cast plates, with its superior tensile characteristics, significantly enhanced the load carrying capacity of the strengthened beams. Strengthening of $B_{150,S}$ using unreinforced SHCC plates enabled the beam to achieve an ultimate load of about 196 kN (1.09 times the ultimate capacity of the



(a) Placing of steel wire mesh during casing process of SHCC plate.



(b) Photo of the pre-cast SHCC plates after its hardening.



(c) Assembly of beam reinforcing cage with two pre-cast SHCC plates.



(d) Photo of tested beams prior casting of concrete.

Fig. 5. Fabrication process of test specimens.

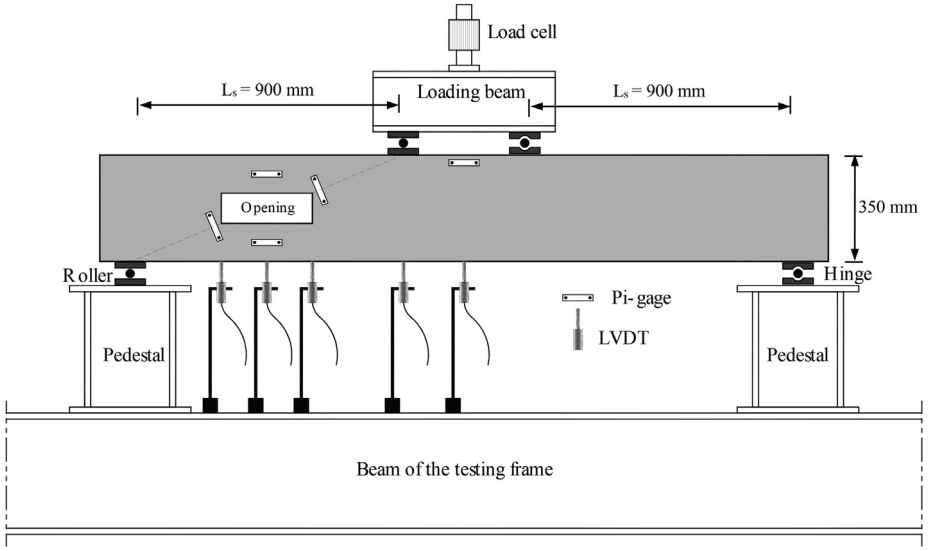


Fig. 6. Test setup and instrumentations.

Table 3
Experimental test results.

Group	Specimen designation	$P_{cr,sh}$ (kN)	P_{ult} (kN)	Δ_{ult} (mm)	W_{cr} (mm)	Reduction in shear capacity due to opening (%)	Strength gain (%)	E (kN.mm)
Control	BC	80	180	9.91	3.01	–	–	1027
Group (I)	B_{150}	70	115	6.75	3.86	36.11	–	457
	B_{300}	45	90	6.41	3.12	50.00	–	350
	B_{450}	35	80	6.59	3.03	55.55	–	311
Group (II)	$B_{150,S}$	81	196	10.97	3.10	–	70.4	1263
	$B_{300,S}$	50	149	9.84	2.85	–	65.5	866
	$B_{450,S}$	40	120	9.80	2.84	–	50.0	743
Group (III)	$B_{150,S,R}$	80	214	11.51	2.65	–	86.1	1497
	$B_{300,S,R}$	51	164	10.38	2.10	–	82.2	953
	$B_{450,S,R}$	39	132	10.40	2.20	–	65.0	817

$P_{cr,sh}$ = shear crack load; p_{ult} = ultimate load; Δ_{ult} = deflection corresponding to maximum peak load; W_{cr} = major shear crack width at ultimate; E = absorbed energy

solid beam BC and 1.70 times the ultimate capacity of the similar un-strengthened beam). Which demonstrates a prosperous technique for strengthening of shear critical concrete beams. However, as shown in Fig. 7, the gain in the beam capacity is directly affected by the opening width. Increasing the opening width decreased the gain in the shear capacity obtained by SHCC pre-cast plates. This is attributed to the reduction in the inclination of the load path which produces a high concentration of tensile stresses at the corners. This observations is consistent with the previous studies on shear behaviour of concrete beams with openings [33,34].

For group (III), adding a steel wire mesh did not affect the cracking pattern as well as the mode of failure manifested by the beams of group (II), as shown in Fig. 7. Based on the test results summarized in Table 3, it can be noticed that the ultimate load was slightly increased after addition of steel wire mesh into the pre-cast SHCC plates. The increase in ultimate capacity ranged between 9 and 10% in comparison with the similar beams strengthened with unreinforced SHCC plate. This is to be expected, the wire mesh reinforcement increases the tension stiffening of the SHCC plates which in turn enables the beam to carry higher loads.

3.2. Load deflection response

The load-deflection curve of the tested beams of group (I) is shown in Fig. 10. The response of the reference solid beam BC was included for the purpose of comparison. As shown in Fig. 10, up to about 60% of the ultimate load, shear cracking load of group (I), there was no significant difference in deflection response between the reference solid beam BC and the beams of group (I). After the shear crack took-place, the effect of the opening inclusion was clear in the form of higher deflection at the same load level. Approximately 30%, 55% and 65% reductions in the beam stiffness were recorded for the unstrengthened beams BC_{150}, BC_{300} and BC_{450}, respectively, relative to the reference solid beam BC. Also, after reaching the ultimate load, the unstrengthened beams failed suddenly and the load dropped instantly to the release load.

The load-deflection curves of group (II) as well as group (I) is shown in Fig. 11. As shown in Fig. 11, group (I) and (II) showed a similar trend till shear cracking, beyond which the residual stiffness (stiffness after cracking) of group (II) was greater than that of group (I). This may be attributed to the fibers bridging effect. Fibers in SHCC mix restrains the crack opening by intact fibers in the crack surface, as shown in Fig. 12. This phenomenon “fiber bridging” controlled the stiffness degradation of SHCC strengthened beams. Furthermore, after the SHCC strengthened beams reached their ultimate capacity, the high post-cracking tensile deformability and resistance of the SHCC avoid the occurrence of sudden failure, thus the beams demonstrated the softening tail. This means that the failure of the strengthened beams was more ductile than that of the unstrengthened beams. Although the use of pre-cast SHCC plates significantly increased the shear capacity of group (II) compared to group (I), the strengthening technique is not capable of restoring the shear strength and stiffness of the solid beam BC except for beam $BC_{150,S}$. This indicates that for beams with a small opening width, the

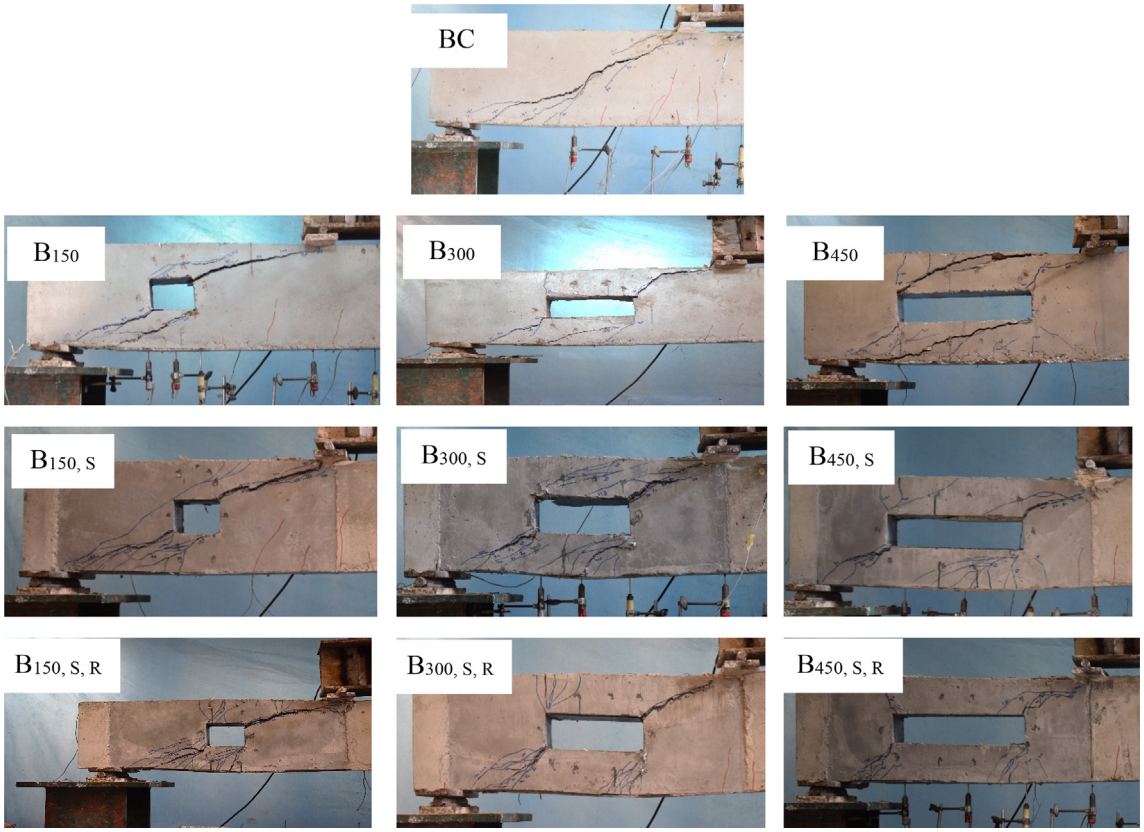


Fig. 7. Final crack pattern of the tested beams.

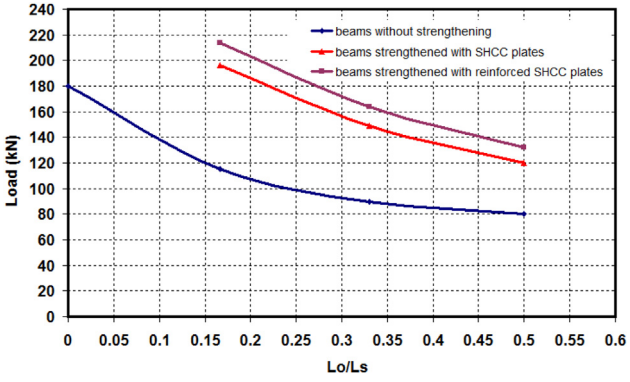


Fig. 8. The relation between ultimate load and L_o/L_s ratio.

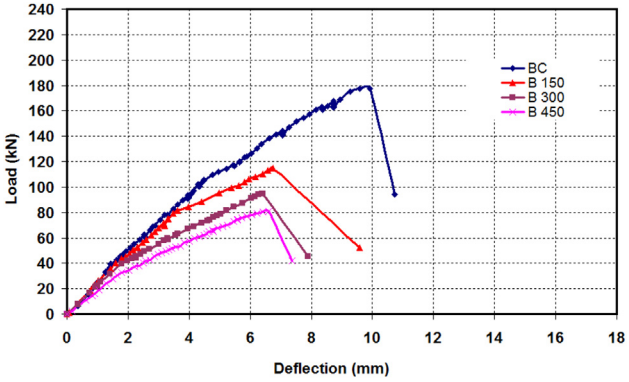


Fig. 10. Load-deflection curves for beams of group (I).

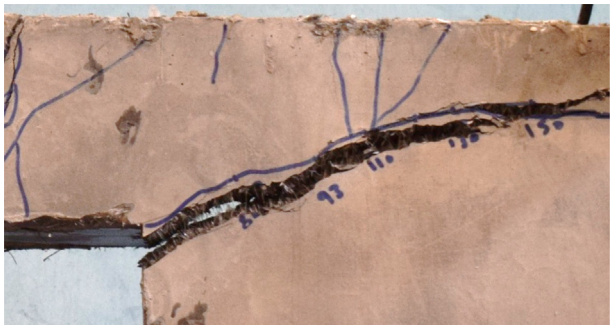


Fig. 9. Plate rupture and fibers pull out through the crack surface.

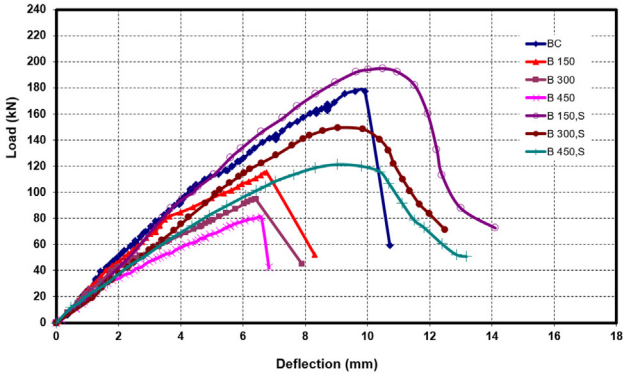


Fig. 11. Load-deflection curves for beams of groups (I) and (II).



Fig. 12. Fiber bridging phenomenon.

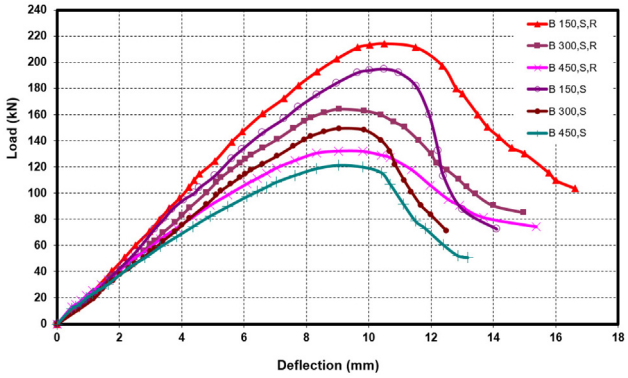


Fig. 13. Load-deflection curves of the tested beams of groups (II) and (III).

proposed shear strengthening technique is recommended to restore the shear strength and stiffness of a solid beam.

Fig. 13 shows the load-deflection curve for the tested beams of group (III) as well as the beams of group (II). Beams of group (III) were strengthened with SHCC pre-cast plate provided with a steel wire mesh reinforcement. All beams of group (II) and (III) showed approximately the same response till the shear cracking load. After the initiation of the shear crack, the effect of reinforcement was apparent, the beams showed less deflection at the same loading level. Furthermore, after the beams reached their ultimate loads, the beams of group (III) exhibited a softer post-peak response in comparison with the similar beams of group (II).

3.3. Energy absorption

According to the previous studies, different measurements were used to evaluate the ductility. In this work, ductility was evaluated in terms of energy absorption of the beam. The energy absorption (E) is the area under the load–deflection curve up to the maximum load [35]. As shown in Table 3, the energy absorption values have been significantly decreased due to the opening in the unstrengthened beams. As expected, the maximum decrease was recorded with the unstrengthened beam B_{450} (L_o/L_s = 50%). The loss in energy absorption reached about 70% compared to the solid beam BC. Whereas, the strengthened beams showed a great enhancement in energy absorption compared to the unstrengthened beams as can be seen in Table 3. It is worth mentioning that, the enhancement in energy absorption was increased by the use of reinforced SHCC plates. The maximum increase in the energy absorption was obtained by beam $B_{150,S,R}$ (1497 kN.mm), which was about 3.27 times of the unstrengthened beam B_{150}

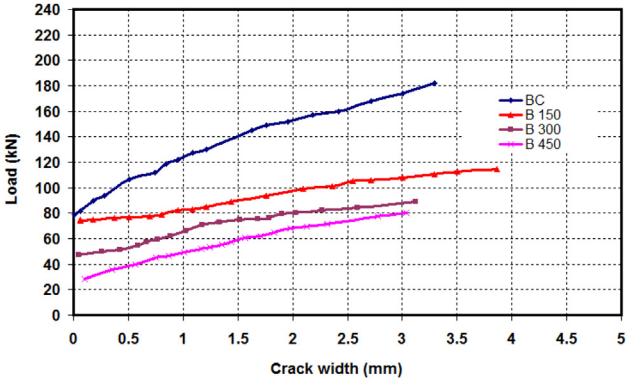


Fig. 14. Load-crack width response for beams of group (I).

(457 kN.mm) and higher than that obtained by the reference solid beam BC by about 45%. The test results reflect the effectiveness of the proposed strengthening technique for strengthening concrete beams with web opening in critical shear zones.

3.4. Cracking behaviour

Durability of reinforced concrete elements can be enhanced by controlling crack width. Also, all design codes limit the crack width in reinforced concrete elements to avoid corrosion problems. Therefore, the crack width is a very important parameter to achieve a durable structures. One of the most important findings of this investigation is the enhanced cracking behaviour of strengthened beams compared to the reference unstrengthened beams in terms of the cracks number and width. Figs. 13–15 show the load crack-width response for test beams. As depicted in Fig. 14, shear cracks appeared in the reference solid beam BC once the cracking capacity of the concrete was exceeded at load of about 80 kN. Increasing the applied load, it was observed that the main shear crack width increased and reached 3.85 mm at ultimate load level (P_u = 180 kN). Regarding to beams of group (I), the cracking behaviour seems to be affected dramatically due to the stress concentration around opening corners. B_{450} showed a decrease in shear cracking load by 56% compared to the solid beam BC, followed by beams B_{450} and B_{300}, exhibiting a decrease by about 43% and 12.5%, respectively. Also, as shown in Fig. 14, the measured crack with of these beams was much higher in all loading levels in comparison with the reference solid beam BC.

The proposed strengthening technique has noticeably enhanced the cracking behaviour. An increase in cracking load ranged between 15% and 11% was recorded in the beams of group (II) that were strengthened using unreinforced SHCC plates. Also, as shown in Fig. 15, the utilization of SHCC plates effectively controlled the crack width beyond the shear crack occurrence. This may be attributed to the crack-

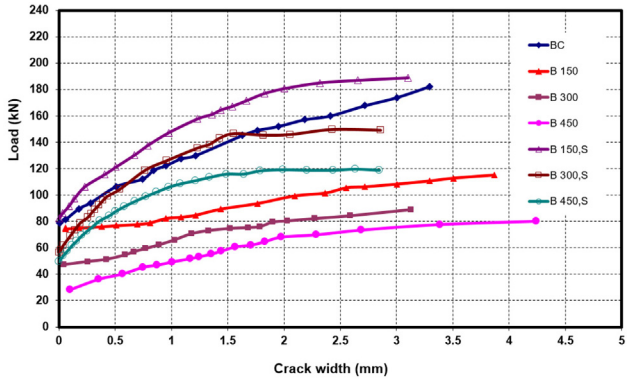


Fig. 15. Load-crack width curves for beams of groups (I) and (II).

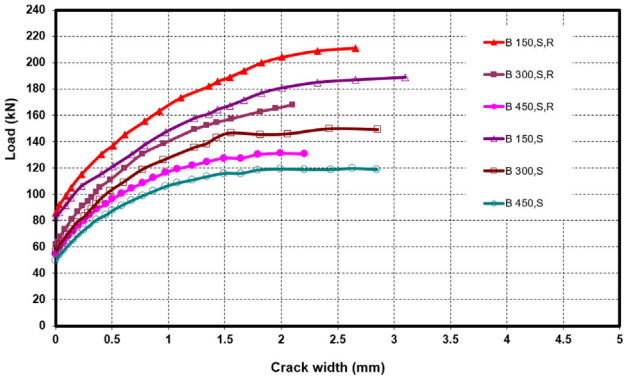


Fig. 16. Load-crack width curves for beams of groups (II) and (III).

arresting action of the fiber in SHCC plates which altered the cracking pattern compared to the unstrengthened beams. For instance, the reference unstrengthened beam B_{450} had a crack width of 3.07 mm at the ultimate load (P_u = 80 kN), meanwhile, the crack width of beam $B_{450,S}$ was just 0.364 mm (11% compared to beam B_{450}). To shed the light on the effect of the added SHCC reinforcement, Fig. 15 shows a comparison between group (II) and group (III). As shown in Fig. 16, using reinforced SHCC plates did not affect the cracking load. Whereas the effect of reinforcement was clear after the beginning of the shear cracks, using the reinforcement led to a decrease in crack width. The enhancement in cracking behaviour may be attributed to the increase in axial stiffness at cracks due to the contribution from reinforcement. Reinforcing the SHCC pre-cast plates reduces the fibers' stress after cracking, as the increase in crack width is governed by the pull-out of fibers.

4. Test results in comparison with the available codes formulations

The shear capacity of strengthened concrete beam with web opening comprises two contributions. The first contribution is the resistance out-coming from the concrete section. This resistance is mainly depend on the effective area of concrete section (*bd*), the concrete compressive strength (f_c), the ratio of longitudinal tensile steel reinforcement (ρ), and the opening depth (h_o). While the second contribution is the effect of the strengthening material. This resistance is depending on the mechanical characteristics of the used material. According to the experimental outcomes, expect beam B_{450}, all beams failed in shear with a similar mode, which is labelled beam type failure. In case of beam type failure, similar to a solid beam, ACI-318 [36] proposed the following equation to predict the shear strength of an unreinforced unstrengthened beam with web opening:

$$V_c = \frac{1}{6}\sqrt{f'_c}\, b_w (d - h_o) \tag{1}$$

where f_c' = cylinder concrete compressive strength; b_w = beam width; d = effective beam's depth; and h_o = the opening depth.

The current experimental investigation demonstrated that, the shear strength of strengthened beams influenced by the use of the SHCC pre-cast plates. Consequently, the contribution of SHCC plates to the shear capacity should be consider. Based on the Japan Society of Civil Engineers recommendations (JSCE) [37], the shear strength of the SHCC material is represented by the following equation:

$$V_{SHCC} = 0.18\sqrt{f'_c}\, t{\cdot}d + \frac{f_t}{\tan\beta} t{\cdot}Z \tag{2}$$

where f_c' = cylinder concrete compressive strength; t = thickness of the SHCC; d = effective beam depth; f_t = tensile yield strength of SHCC which is considered equal to the first cracking strength of SHCC; z is the distance measured from location of compressive stress resultant to the tensile steel, and can be considered as d/1.15; and β = inclination of shear crack to the axis of beam which is considered the slope of the line connecting the opening corner to the load.

To estimate the contribution of the SHCC plate with opening to the shear strength, the section depth (d) in Eq. (2) can be replaced by ($d - h_o$), which is consistent with the ACI-318 equation. In addition, the inclination of the shear crack "β" was considered the slope of the line connecting the opening corner and the load location.

Table 4 presents the shear capacity of concrete predicted by ACI equation (V_c), the contribution of the SHCC plates to the shear capacity predicted by JSEC equation (V_{SHCC}), and total shear capacity of the beam obtained by the summation of $V_{conc,ACI}$ and $V_{SHCC,\ JSCE}$. The $V_{exp.}/V_{anal.}$ values are listed in Table 4. As shown in Table 4, the code predictions tend to underestimate the shear capacity of the strengthened beams with web openings 150 mm. The values of $V_{exp.}/V_{anal.}$ for beams $B_{150,S}$ and $B_{150,S,R}$ are 1.03 and 1.12, respectively. While, the code predictions tend to overestimate the shear capacity of the strengthened beams with web openings 300 mm and 450 mm. The values of $V_{exp.}/V_{anal.}$ for beams $B_{300,S}$, $B_{450,S}$, $B_{300,S,R}$ and $B_{450,S,R}$ are 0.89, 0.84, 0.98 and 0.92, respectively. This may be attributed to the increase in corner stress with the increase of opening length which is not considered in both of Eqs. (1) and (2). Thus, it is recommended to adopt a higher safety margins in design of beams with web openings.

5. Conclusion

Based on the current experimental investigation, the following conclusions have been drawn:

- The existence of a web opening in reinforced concrete beams dramatically affected the ultimate shear capacity and mode of failure of the unstrengthened beams. The reduction in the shear capacity was

Table 4
Experimental versus predicted results.

Group	Beam designation	Experimental $V_{exp.}$ (kN)	Analytical			$V_{exp}/V_{anal.}$
			$V_{c,\ ACI}$ (kN)	$V_{SHCC,\ JSCE}$ (kN)	$V_{anal.}$ (kN)	
Group (I)	B_{150}	115	59.32	–	59.32	1.93
	B_{300}	90	59.32	–	59.32	1.51
Group (II)	$B_{150,S}$	196	43.50	146.07	189.57	1.03
	$B_{300,S}$	149	43.50	122.69	166.19	0.89
	$B_{450,S}$	120	43.50	99.21	142.71	0.84
Group (III)	$B_{150,S,R}$	214	43.50	146.07	189.57	1.12
	$B_{300,S,R}$	164	43.50	122.69	166.19	0.98
	$B_{450,S,R}$	132	43.50	99.21	142.71	0.92

$V_{exp.}$ = experimental failure load; $V_{c,ACI}$ = analytical shear capacity of concrete predicted by ACI equation; $V_{SHCC,\ JSCE}$ = contribution of the SHCC plates to the shear capacity predicted by JSEC equation; $V_{anal.}$ = analytical shear capacity of the beam obtained by the summation of $V_{conc,ACI}$ and $V_{SHCC,\ JSCE}$.

relative to L_o/L_s ratio. When L_o/L_s ratio was increased to 50%, the reduction in shear capacity reached about 55%. In addition, the beam mode of failure changed from shear corner failure to failure in chords.

- The SHCC-shear strengthening technique around the opening significantly increased the shear capacity of the beams. In case of L_o/L_s = 16.67%, using unreinforced SHCC plates enabled the strengthened beam to reach an increase in shear strength gain of 70.4%, which was increased to 86.1% with adding a steel wire mesh to the SHCC plates. However, the shear strength gain was decreased with the increase of L_o/L_s ratio.
- Compared to the unstrengthened reference beams, the SHCC precast plates with a thickness of 20 mm was placed beside the beam reinforcement cage gave substantial enhancement in post-cracking stiffness. For beam with L_o/L_s = 16.67%, the developed strengthening technique was capable of restoring the shear strength and stiffness of the solid beam. This enhancement is attributed to the formation of stable minor-cracks in the SHCC plates as opposed to widened and localized cracks in the concrete beams without strengthening.
- The SHCC strengthening technique has generally improved the behaviour of the strengthened beams especially in post-peak stage. Prior the failure, the strengthening technique enabled the beams to sustain inelastic deformation, and during load release the beams demonstrated the softening tail. In addition, using reinforced SHCC plates gave a more ductile response than the unreinforced counterparts. Also, the strengthening technique improved the energy absorption of the strengthened beams relative to the benchmark beams. The maximum increase in energy absorption was recorded with the beam strengthened using reinforced SHCC plates, when L_o/L_s was 16.67%, the increase reached about 227%.
- The results of this research have confirmed that, the serviceability characteristics of SHCC strengthened beams was remarkably improved. Compared to the unstrengthened beams, a considerable decrease in the major shear crack width was recorded.
- Based on the predicted results obtained from the ACI 318–19 and JSCE recommendations. The predicted results are in satisfactory agreement with the experimental results of the tested beams with opening length 150 mm. Whereas, the code models tend to overestimate the shear capacity of the tested beams with web opening 300 mm and 450 mm.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Prentzas EG. Behavior and reinforcement of concrete beams with large rectangular apertures PhD Thesis UK: University of Sheffield; 1968 p. 230.2.
[2] Somes NF, Corley WG. Circular openings in webs of continuous beams. Shear in Reinforced Concrete. American Concrete Institute; 1974. p. 359–98.
[3] Mansur MA, Tan KH, Lee SL. Collapse loads of RC beams with large openings. ASCE J Struct Eng 1984;110(11):2602–10.
[4] Elsanadedy HM, Al-Salloum YA, Almusallam TH, Alshenawy AO, Abbas H. Experimental and numerical study on FRP-upgraded RC beams with large rectangular web openings in shear zones. Constr Build Mater 2019;194:322–43.
[5] Mansur MA. Ultimate strength design of beams with large openings. Int J Struct 1988;8(2):107–25.
[6] Architectural Institute of Japan. AIJ standard for structural calculation of reinforced concrete building; 1994. p. 207.
[7] Li VC. From micromechanics to structural engineering: the design of cementitious composites for civil engineering applications. JSCE J Struct Mech Earthq Eng 1993;10:37–48.
[8] Li M, Li VC. High-early-strength ECC for rapid durable repair: material properties. ACI Mater J 2011;108:3–12.
[9] Li VC. Tailoring ECC for special attributes: a review. Int J Concr Struct Mater 2012;6:135–44.
[10] Dhawale AW, Joshi VP. Engineered cementitious composites for structural applications. Int J Appl Innovation Eng Manage (IJAIEM) 2013;2:198–205.
[11] Fischer G, Li VC. Effect of fiber reinforcement on the response of structural members. Eng Fract Mech 2007;74:25–272.
[12] Li VC. Reflections on the research and development of engineered cementitious composites (ECC). In: Proceedings of the JCI international workshop on ductile fiber reinforced cementitious composites (DFRCC) – application and evaluation, DFRCC-2002, Takayama, Japan; October 21–22, 2002. p. 1–21.
[13] Mündecke E, Mechtcherine V. Tensile behaviour of strain-hardening cement-based composites (SHCC) with steel reinforcing bars. Cem Concr Compos 2020;105:103423.
[14] Li J, Weng J, Yang E. Stochastic model of tensile behavior of strain-hardening cementitious composites (SHCCs). Cem Concr Res 2019;124:105856.
[15] Li VC. On engineered cementitiouscomposities (ECC), a review of the material and its applications. J Adv Concr Technol 2003;1:215–30.
[16] Fukuyama H, Matsuzaki Y, Nakano K, Sato Y. Structural performance of beam elements with PVA-ECC. In: Reinhardt Naaman A, editor. Proc of high performance fiber reinforced cement composites 3 (HPFRCC 3). Chapman & Hull; 1999. p. 531–42.
[17] Li VC, Fischer G. Reinforced ECC – an evolution from materials to structures. In: Proceedings on CD, Session 5, Paper K-13, Fib 2002, Osaka, Japan; 2002.
[18] Fischer G, Li VC. Deformation behavior of fiber-reinforced polymer reinforced engineered cementitious composite (ECC) flexural members under reversed cyclic loading conditions. ACI Struct J 2003;100:25–35.
[19] Fischer G, Li VC. Intrinsic response control of moment resisting frames utilizing advanced composite materials and structural elements. ACI Struct J 2003;100:166–76.
[20] Li VC, Li M. Durability performance of ductile concrete structures. Proceedings of the 8th international conference on creep, shrinkage and durability of concrete and concrete structures, Ise-Shima, Japan. 2008. p. 761–8.
[21] Sahmaran M, Li M, Li VC. Transport properties of engineered cementitious composites under chloride exposure. ACI Mater J 2007;104:604–11.
[22] Li M, Li VC. Cracking and healing of engineered cementitious composites under chloride environment. ACI Mater J 2011;108:333–40.
[23] Afefy HM, Kassem NM, Hussien M, Taher SF. Efficient strengthening of opened-joint for reinforced concrete broken slabs. Compos Struct 2016;136:602–15.
[24] Afefy HM, Kassem NM, Hussein M. Enhancement of flexural behavior of CFRP-strengthened reinforced concrete beams using engineered cementitious composites transition layer. Struct Infrastruct Eng 2015;11(8):1042–53.
[25] Hussein M, Kassem NM, Hassan A. An Innovative Efficient Strengthening For Reinforced Low Strength Concrete Cantilever Slabs. IOSR-JMCE 2015; Volume 12, Issue 5 Ver. I, PP 01-13.
[26] Kassem M, El-Shafeiy T, Hussein M, Afefy H, Hassan A. Shear Behaviour of SHCC Dry Joints in Precast Construction International Conference on Advances in Structural and Geotechnical Engineering, ICASGE'17, Hurghada, Egypt, 27-30 March 2017.
[27] Dantino T, Sneed LH, Carloni C, Pellegrino C. Effect of the inherent eccentricity in single-lap direct-shear tests of PBO FRCM-concrete joints. Compos Struct 2016:01.076.
[28] Escrig C, Gil L, Bernat-maso E. Experimental comparison of reinforced concrete beams strengthened against bending with different types of cementitious-matrix composite materials. Constr Build Mater 2017:317–29.
[29] Raoof SM, Koutas LN, Bournas DA. Textile-reinforced mortar (TRM) versus fibre-reinforced polymers (FRP) in flexural strengthening of RC beams. Constr Build Mater 2017:279–91.
[30] Wu X, Kang THK, Lin Y, Hwang HJ. Shear Strength of Reinforced Concrete Beams with Precast High-Performance Fiber-Reinforced Cementitious Composite Permanent Form. Compos Struct 2018.
[31] Massicotte B, Dagenais MA, Lagier F. "Performance of UHPFRC Jackets for the Seismic Strengthening of Bridge Piers." Proc., the Rilem-fib-AFGC International Symposium on Ultra-High Performance Fibre-Reinforced Concrete. Marseille, France; 2013, pp. 89-99.
[32] Collins MP, Mitchell D. Prestressed concrete structures. Englewood Cliffs, NJ: Prentice-Hall; 1997.
[33] Yang K, Eun H, Chung H. The influence of web openings on the structural behavior of reinforced high-strength concrete deep beams. Eng Struct 2006;28(13):1825–34.
[34] El-Maaddawy T, El-Ariss B. Behavior of concrete beams with short shear span and web opening strengthened in shear with CFRP composites. J Compos Constr 2012;16:47–59.
[35] Ebead U. Inexpensive strengthening technique for partially loaded reinforced concrete beams: experimental study. J Mater Civ Eng 2015:;11:4015002.
[36] ACI Committee 318 (2019). Building Code Requirements for Structural Concrete (ACI 318-19) and Commentary (ACI 318R-19). American Concrete Institute, Farmington Hills, MI, 519 pp.
[37] Japan Society of Civil Engineers (JSCE). Recommendations for design and construction of high performance fiber reinforced cement composite with multiple fine cracks (HPFRCC), Concrete engineering series 82, 2008.