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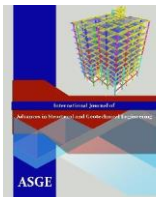

Behavior of RC Beams with Circular Openings reinforced with Strain-Hardening Cementitious Composites (SHCC)

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Abstract

In this paper, the effect of using Strain-Hardening Cementitious Composites (SHCC) to improve the shear behavior of reinforced concrete (RC) beams with web openings was experimentally investigated. A four-point bending test was performed on seven specimens. One of them, control beam BC, had no web opening, but the other six specimens were tested with web opening. The studied parameters were the effect of employing either plain or reinforced prefabricated SHCC and the influence of prefabricated SHCC configurations around web openings. On the basis of cracking patterns, load-deflection behavior, ductility, and initial stiffness, the shear behavior was evaluated. According to experimental findings, the presence of a web circular opening in the shear zone decreased the shear strength by about 46%. Nevertheless, the use of prefabricated SHCC shapes enhanced the shear strength of the tested specimens by up to 60% relative to the control specimen (BC-C). As soon as reinforcements were added to prefabricated SHCC, it was abundantly clear that the ultimate load and cracking behavior of RC beams with openings had improved.

1. Introduction

In practice, transverse openings in reinforced concrete beams are usually needed to pass pipes and ducts for services including water supply, electricity, gas, telephone, and computer networks, as shown in Fig. 1. Typically, these pipes and ducts are concealed beneath the soffit of the beam. Consequently, a false ceiling is required for aesthetic purposes, thereby reducing the net floor height. Therefore, the utilization of web openings makes it possible for the designer to reduce the building height, particularly in high-rise buildings; this results in a more cost-effective design [1-3]. The provided openings may be circular, oval, rectangular, diamond, trapezoidal, or elliptical in shape. In practice, however, circular and rectangular openings are the most prevalent [4]. Previous studies have used the terms "large" and "small" openings without creating a clear distinction for their classification. According to Mansur et al. [5] and Hasnat and Akhtarzaman [6], all circular and almost square openings were categorized as small. A small opening, according to Somes and Corley [7], is a circular opening having a diameter less than 0.25 times the total depth of the beam. The design approach for a beam with an opening can be chosen depending on the size of the opening. The design of a beam with small openings is identical to that of a solid beam. The presence of large web openings, on the other hand, will transform the simple beam behavior into vierendeel action. These openings disturb the loading trajectories, which may lead to a shortfall in the structural performance of the beam due to the weak points surrounding the openings [8]. Therefore, additional reinforcement around the opening should be provided [9,10]. As a result of the member's small size in the upper and lower chords, it is not possible to provide sufficient steel reinforcement to restrict crack growth and prevent premature shear failure of the beam. Strain-Hardening Cementitious Composites, also known as SHCC, are a new generation of fiber-reinforced cementitious composites [11,12]. The SHCC material exhibits a pseudo strain-hardening tendency characterized by the formation of multiple small cracks under tensile loading [13,14].

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Fig. 1: Web opening in RC beams.

It has been suggested that the SHCC's multiple cracking characteristics enhance the material's durability and impermeability [15,16]. In repair applications, SHCC showed a high tensile strain capacity, which is essential for a durable material that can withstand premature failures [17,18]. In recent years, numerous studies have examined the structural performance of SHCC-RC composite components. They figured out how to combine SHCC with a variety of elements to enhance their strength and ductility [19–27]. The structural application of SHCC pre-cast forms is still a major issue, despite the fact that several studies have been undertaken on SHCC materials and members. On the basis of SHCC's exceptional mechanical properties, this study aims to suggest a new strengthening strategy for RC beams with web opening. During fabrication, the SHCC can be utilized in a variety of precast forms that are positioned at critical shear spans. In this paper, the effects of using SHCC either plain or reinforced, as well as strengthening configuration have been studied. A total of seven RC beams with simple supports were prepared and tested. The cracking and ultimate loads, deflection, and crack width of the tested reinforced beams were recorded as test outcomes.

2. Experimental work

Test matrix

Seven RC beams make up the test matrix. For comparisons, one solid beam "BC" with no opening was utilized as a reference, and the remaining six beams have a 160 mm diameter web opening. The test specimens were divided into three groups. Group (I) was built without any strengthening. The beams in the second group, on the other hand, were strengthened in the shear span with web opening by using prefabricated SHCC material (with a thickness of 20 mm around the web opening). Prior to the concrete pour, the prefabricated SHCC material was placed, and one of the beams in this group had been reinforced with 4 D 6 mm inside the prefabricated SHCC. Specimen BU1-C-R-E is the same as specimen BU1-C-R, but after the concrete was poured, SHCC prefabricated material was installed. Whereas, Prefabricated SHCC material was used to reinforce the group (III) in various configurations (square and diamond). Table.1 presents the description of the test specimens.

Dimensions and reinforcement

The concrete dimensions and reinforcement details of the tested beams are shown in Fig. 2. All of the beams were the same section size, with a depth of 400 mm, a width of 150 mm, and a total length of 3000 mm with a net span of 2800 mm between supports. All beams had a circular hole in the middle of the left shear span, with the exception of the control beam (BC). The web opening location was chosen to completely interrupt the natural load path, which is defined as the line between the support point and the load. Identical amounts of longitudinal steel rebars and shear stirrups were used to reinforce all beams. All beams are reinforced with 4 D 18 mm longitudinal tension steel bars and 2 D16 mm compression reinforcement bars. A large number of steel stirrups were used in the right shear span (D 8 @ 90) to localize the shear failure in the left shear span. In the left shear span of the beams, stirrups D 8 @ 175 mm were employed.

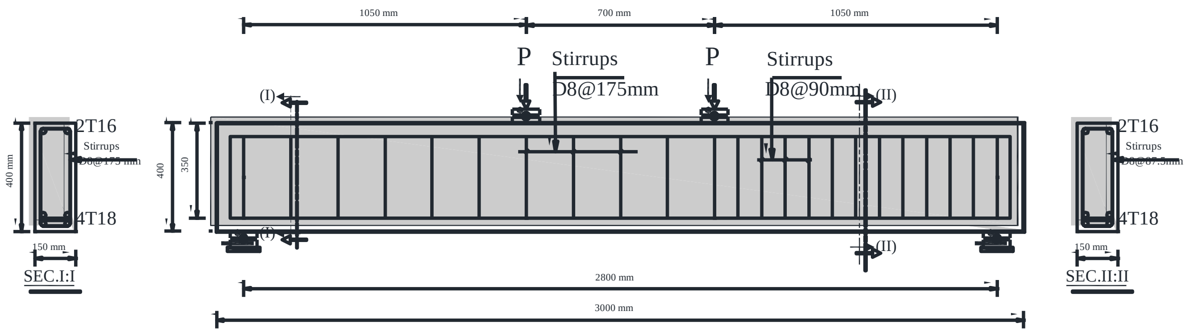
Material properties

Concrete strength has a big impact on test findings, especially when determining the shear capacity of RC beams. As a result, the same ready-mix concrete patch was used to cast all beams to ensure that the concrete quality was consistent. To reduce variation in concrete strength, all beams were cured under the same conditions. At the time of the test, the average compressive strength of concrete was 30 MPa. The splitting tensile test for three cylinders of 300 mm height and 150 mm diameter was used to measure the tensile strength of the employed concrete. Tensile strength was found to be 2.49 MPa on average. The average compressive strength of the SHCC material was 67.1 MPa, and the tensile strength was found to be 7.25 MPa on average. The mix proportions of the concrete and the SHCC material used are summarized in Table 2.

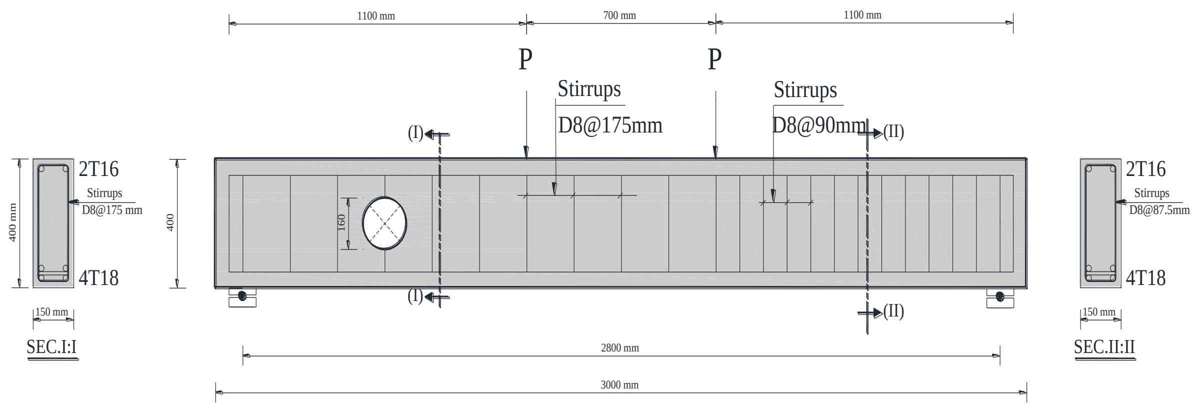
Tensile tests were performed on three specimens to determine the mechanical properties of the used steel reinforcement rebars of 18 mm, 16 mm, and 8 mm diameter. The yield and ultimate tensile strengths of the high tensile steel D 18 mm were 410 MPa and 631 MPa, respectively, and Young's modulus was 205 GPa. For D 16 mm, the obtained mean values of yield and ultimate tensile strengths were 420 MPa and 605 MPa, respectively, and Young’s modulus was 203 GPa. While, for the mild steel reinforcement D 8 mm, the obtained mean values of yield and ultimate tensile strengths were 240 MPa and 362 MPa, respectively, and Young’s modulus was 200 GPa.

Table 1: Description of the test specimens.

Group	Specimen	SHCC characteristics		Description of tested specimens	Objectives
		Thickness (mm)	Internal RFT		
1	BC	———	———	Control beam without opening	Reference group
	BC-C	———	———	Control beam with circular opening	
2	BU1-C-0	20	———	Beam with circular opening surrounded by prefabricated plain SHCC of 20 mm thickness	Studying the effect of using prefabricated SHCC either plain or reinforced
	BU1-C-R	20	2 D 6	Beam with circular opening surrounded by prefabricated reinforced SHCC of 20 mm thickness	
	BU1-C-R-E	20	2 D 6	Beam with circular opening surrounded by prefabricated reinforced SHCC of 20 mm thickness attached to the specimen by epoxy resin	
3	BU2-C-R	20	2 D 6	Beam with circular opening surrounded by prefabricated reinforced square-shaped SHCC of 20 mm thickness	Studying the effect of the configurations of prefabricated SHCC
	BU3-C-R	20	2 D 6	Beam with circular opening surrounded by prefabricated reinforced diamond-shaped SHCC of 20 mm thickness	



(a) Specimen BC.



(b) Other specimens except for specimen BC

Fig. 2: Dimensions and reinforcement details.

Manufacturing of the SHCC-strengthened beams

The manufacturing processes of the beams strengthened with prefabricated SHCC material are shown in Fig. 3. SHCC was cast in molds made of a PVC pipe with a diameter of 160 mm inside a wooden cylinder or box of 20 mm thickness. The SHCC material self-consolidates, and neither internal nor external vibrations were used in the casting process. To establish a consistent fiber distribution, prefabricated SHCC were cast using the same process. The prefabricated SHCC were de-molded after 24 hours and cured for two weeks under wet circumstances. The SHCC and the beam's reinforcing cage were built and set in the wooden forms by the end of the two weeks. The surface of the prefabricated SHCC has been roughened to improve the bond between it and the concrete core. The concrete beams were cast using ready-mix concrete. Wet sackcloth was used to cure the upper surface of all beams for two weeks, after which they were permitted to air dry until the testing day. For specimen BU1-C-R-E, it is worth mentioning that SHCC materials were glued to the concrete substrate by epoxy resin after casting the beam.

Test setup and instruments

The specimens were tested under a 4-point loading system as shown in Fig. 4. The clear span between the supports was 3000 mm, and the distance between the loads was 700 mm. A manual hydraulic jack loaded the beam by applying downward force, which was measured by a load cell attached to the jack. A linear voltage displacement transducer (LVDT) with a gauge length of 100 mm was employed to measure the deflection under the mid span point. For all specimens, the crack widths at different loading levels were measured using a microscope with an accuracy of 0.05 mm. An electrical resistance strain gauge was fixed at the bottom soffit of the flexural reinforcement at midspan and at the stirrup in the shear span to measure the developed strains. Pi-gauges of 100 mm gauge length were utilized to measure the generated deformations on the concrete surface at the compression side of the midspan section. After each loading step, the vertical deflection and resulting normal stresses in the longitudinal steel bars were recorded and stored using an automatic data logger device (TDS-150).

3. Experiment results

Crack pattern and ultimate loads

The tested specimens' final crack pattern is shown in Fig. 5. After the solid specimen (BC) developed flexural cracks, an inclined shear crack propagated in one or both shear spans. Shortly after the flexural crack formed, a small diagonal crack appeared suddenly, slightly at mid-height and at approximately the middle of the shear span. By increasing the load, the inclined shear crack progressed towards the specimen's supports and loading points and extended directly to the top surface of the specimen with a little change in load. A very thin concrete segment was left above the inclined shear crack without any evidence of crushing. This failure mode is conventionally called diagonal tension failure, and when the opening was introduced in the web of the beams, a diagonal crack formed near the edge of the opening and extended to the point of the applied load and to the support, bringing about a diagonal tension failure. Evidently, the use of polypropylene fibers in plain and reinforced SHCC tubes has a significant impact on the crack pattern due to the fibers' bridging action. In addition, the use of steel bars in the prefabricated SHCC tubes of specimen BU1-C-R enhanced the mode of failure in comparison to specimen BU1-C-0.

On the other hand, provided SHCC technique played a significant rule in increasing the first cracking and ultimate loads as listed in Table 3. The first crack for the strengthened specimens BU1-C-0, BU1-C-R, BU1-C-R-E, BU2-C-R, and BU3-C-R increased by 35.7%, 46.4%, 42.9%, 51.8%, and 55.4%, respectively, compared with the control specimen (BC-C). The ultimate load for specimens BU1-C-0, BU1-C-R, BU1-C-R-E, BU2-C-R, and BU3-C-R is equal to 175.6 kN, 195.4 kN, 192.4 kN, 205.2 kN, and 210.6 kN, respectively, which is 33.8%, 48.9%, 56.4%, 60.5%, and 46.6% greater than the control beam (BC-C).

Cracking behavior

Fig. 6 shows the development of the diagonal crack widths of the tested specimens against the load. The examination of strengthened specimens with plain and reinforced prefabricated SHCC tubes before failure shows that adding steel reinforcement significantly improves the SHCC cracking behavior. It can be deduced that the use of internal reinforcement inside prefabricated SHCC tubes will result in an increase in the number of cracks that form in the SHCC tubes when compared to the number of cracks that develop in plain SHCC tubes.

Load-deflection response

During the test, load and midspan deflection data were collected at each load step for each beam and displayed as load vs. midspan deflection curves in Fig. 7. Up to the cracking load, the relationship is approximately linear. Deflection tends to increase rapidly after cracking and vary from linearity as the load increases till failure. In contrast, as compared to specimens without strengthening, the SHCC strengthening technique had a substantial effect on reducing midspan deflection. As per the stiffness of the tested specimens, using SHCC tubes generally enhanced the stiffness as compared to the control specimen (BC-C). The stiffness of specimens BU1-C-0, BU1-C-R, BU1-C-R-E, BU2-C-R and BU3-C-R, increased by 21.9%, 50.6%, 45.7%, 60.4%, and 79.3%, respectively, relative to the control specimen (BC-C). It was obvious that using reinforced SHCC tubes has a pronounced effect on the stiffness values.

Table 2: Mix proportions per meter cubic of RC and SHCC materials (kg).

Concrete mix	W/B*	Cement	Sand	Coarse pink limestone	Water	Silica fume	Super-plasticizer	PP Fiber (12 mm)
RC	0.50	350	637	1295	175	---	---	---
SHCC	0.27	1090	654	---	327	109	24	12

* W/B is the water/ binder ratio, B = cement + silica fume

Fig. 3: Fabrication of the prefabricated SHCC.

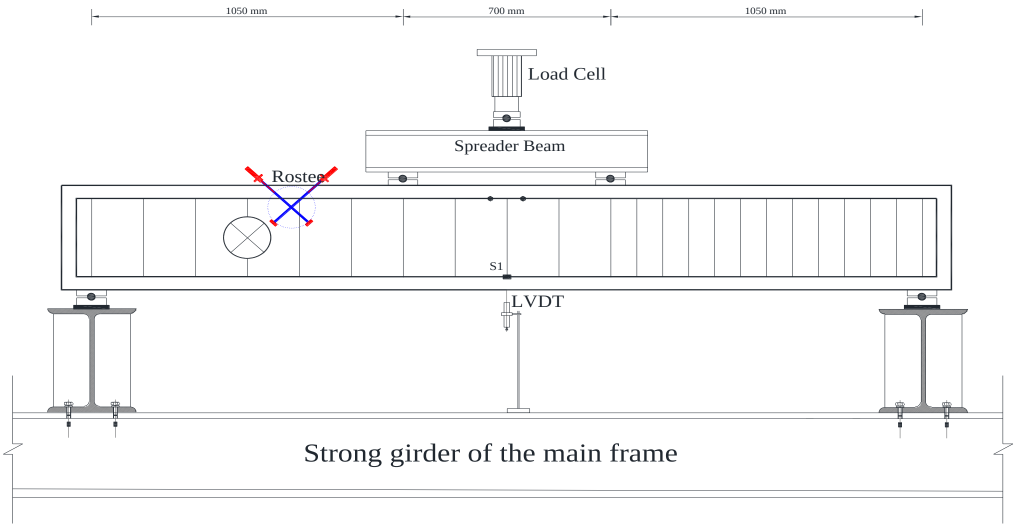


Fig. 4: Test setup and instrumentations.

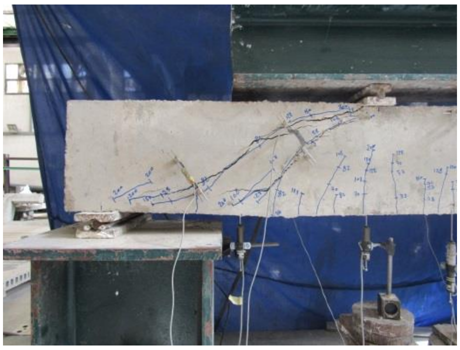
Ductility

A material is said to have good ductility if it can continue to sustain loads even after being deformed inelastically beyond the point at which it initially yields. The ductile failure mode is desirable for RC members because it gives warning of an impending failure without reducing the members' load-carrying capacity. This makes the ductile failure mode the preferred failure mode for RC members. On the other hand, RC members that experience a brittle mode of failure will present limited warning signs of distress before they fail. This is because brittle failures are more likely to be sudden and catastrophic. In the current study, a displacement-based ductility index was selectively chosen for ductility calculations. The displacement ductility index (μ_Δ) is defined by equation $\mu_\Delta = \Delta_u / \Delta_y$, where Δ_u is the midspan deflection at ultimate load and Δ_y is the midspan deflection at yielding load based on the load-deflection relationship. As shown in Table 3, the specimens that were strengthened with SHCC exhibited superior ductility than the un-strengthened specimen BC-C.

4. Conclusions

Based on the experimental investigation, the following conclusion can be drawn:

1. The use of a 20 mm SHCC tube enabled specimen BU1-C-20-0 with a circular opening in the shear span to achieve an ultimate load of 175 kN, 34% higher than the control specimen BC-C.
2. When internal steel was added to the prefabricated SHCC tubes, the ultimate load for specimen BU1-C-R was about 11% higher than for specimen BU1-C-0.
3. Specimen BU3-C-R (diamond SHCC shape) had the higher ultimate load compared to specimens BU1-C-R (circular SHCC shape) and BU2-C-R (square SHCC shape). It is clear that the ultimate load was significantly increased with the increase in the volume of SHCC, especially when the SHCC is perpendicular to the expected crack line. The ultimate load was increased by about 8% and 5%, respectively.



(a) Specimen BC.

(b) Specimen BC-C.

(c) Specimen BU1-C-0.

(d) Specimen BU1-C-R.

(e) Specimen BU1-C-R-E.

(f) Specimen BU2-C-R.

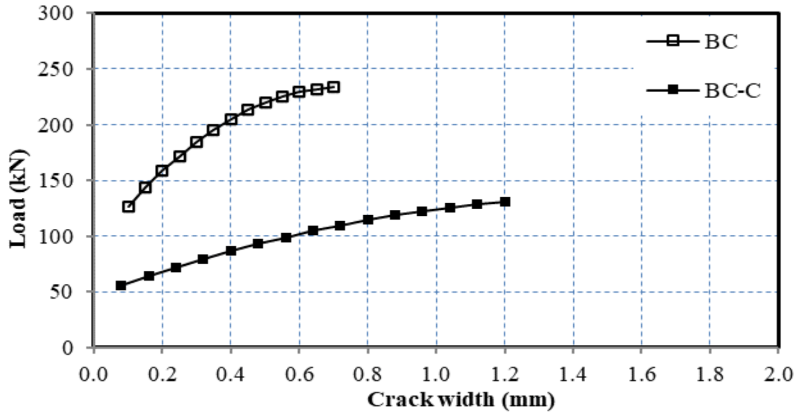
(g) Specimen BU3-C-R.

Fig. 5: Final crack pattern of the tested specimens.

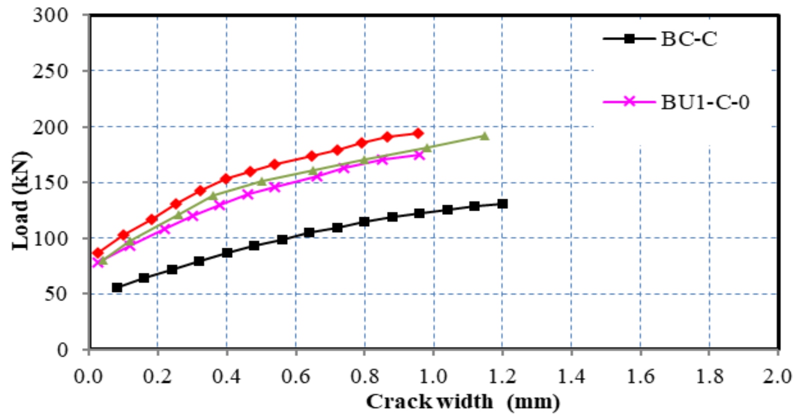
Table 3: Test results.

Specimen	Loads (kN)			Deflection (mm)		Stiffness kN/mm	Displacement-based ductility			
	Cracking	Ultimate	Gain % respect to BC-C	At cracking	At ultimate		Δ_y (mm)	Δ_{max} (mm)	μ_Δ	W.R.T BC-C
BC	126	243	-----	2.45	11.22	30.7	6.47	12.24	1.89	__
BC-C	56	131.2	-----	1.57	9.79	16.4	6.78	9.99	1.47	1.00
BU1-C-0	76	175.6	33.8%	1.77	10.21	20	7.44	12.07	1.62	1.1
BU1-C-R	82	195.4	48.9%	1.72	9.55	24.7	6.72	12.53	1.86	1.27
BU1-C-R-E	80	192.4	46.6%	1.85	10.01	23.9	6.85	11.59	1.7	1.16
BU2-C-R	85	205.2	56.4%	2.56	10.26	26.3	6.61	13.63	2.06	1.4
BU3-C-R	87	210.6	60.5%	2.46	10.79	29.4	6.08	15	2.47	1.68

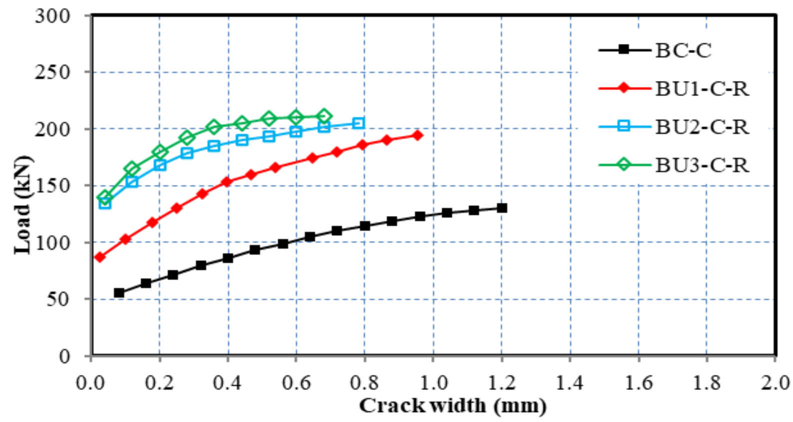
Analytical study



(a) Group 1.

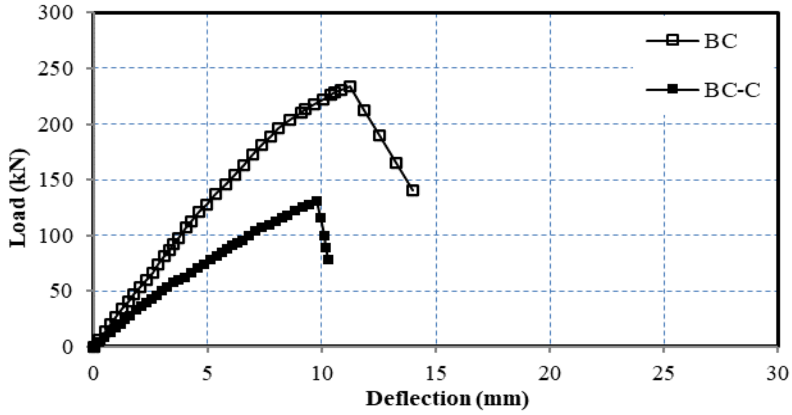


(b) Group 2.

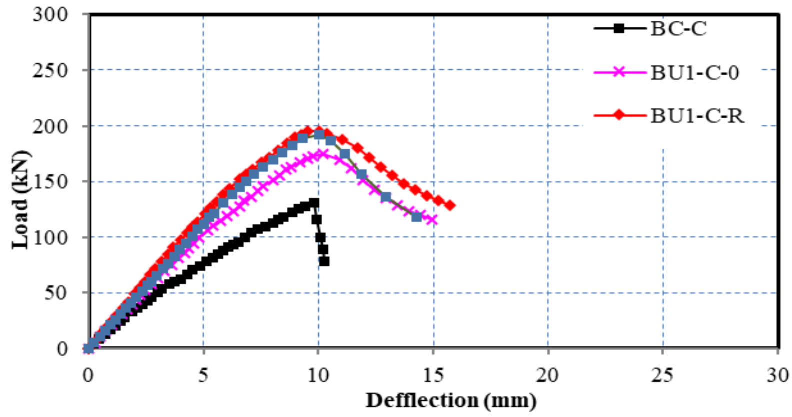


(c) Group 3.

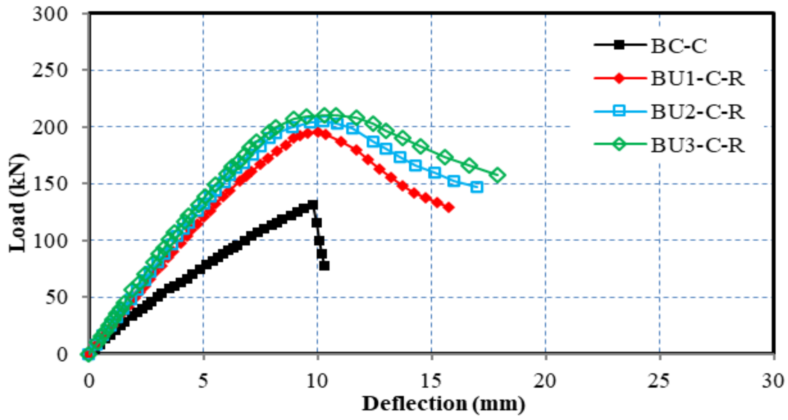
Fig. 6: Load-crack width curves for the tested specimens.



(a) Group 1.



(b) Group 2.



(c) Group 3.

Fig. 7: Load-deflection curves for the tested specimens.

4. Compared to the control specimen, the usage of SHCC tubes delays stiffness deterioration because it prevents cracks from developing in the substrate concrete.

It should be noted that, while the results of the tests on the strengthened RC beams are promising, a great deal of research and experimental and analytical verification of a wide range of parameters is still required before design guidelines can be established for the SHCC technique's application to the strengthening of RC beams with opening.

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