Emara *et al. Int J Concr Struct Mater* (2025) 19:73
https://doi.org/10.1186/s40069-025-00799-9

International Journal of Concrete Structures and Materials

RESEARCH

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Experimental Investigation of Both SCC and Rubberized Concrete Beams with Vertical Openings

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Abstract

Reinforced concrete (RC) beams with vertical openings are becoming more frequent in new construction to transport numerous services, particularly in structures with restricted height and size. A significant lack of studies was observed to investigate the influence of a vertical opening in the shear zone on the RC beams' behavior and performance. This research investigated experimentally the performance of RC beams with vertical openings at the shear zone, whether these beams were cast with self-compacting concrete (SCC) or rubberized concrete (RUC). In addition, the purpose of this work is to compare the influence of steel fiber (SF) on the performance of vertically perforated SCC beams with its influence on the performance of vertically perforated RUC beams. The impact of the number of vertical openings and the SF ratio used in beam specimens on the beam behavior, including compressive and tensile strengths, crack patterns and modes of failure, maximum deflection, stiffness, loading capacity, and ductility, was evaluated in the current paper. The experimental findings demonstrated that the existence of vertical openings at the shear zone of SCC and RUC beams resulted in a decrease in stiffness with ratios ranging from 10.43 to 66.98%, maximum loading capacity with ratios ranging from 10.66 to 37.73%, and ductility index with ratios ranging from 2.14 to 21.53% compared to the solid beams. It also has a tangible impact on raising the maximum mid-span deflection at the ultimate load, ranging from 2.03 to 81.64%. Moreover, when the number of vertical openings increased, the cracks increased at the shear span in which the openings were located. In general, adding SF to the SCC mixture showed a more significant effect on enhancing the tensile and compressive strengths, stiffness, and ultimate load compared to that in the case of the RUC. For example, the stiffness and ultimate load of the solid SCC beam with a SF ratio of 1% increased by 164.58% and 70.19%, respectively, compared to the solid SCC beam without SF, while those of the solid RUC beam with the same ratio of SF increased by 69.91% and 61.85%, respectively.

Keywords Vertical opening, Self-compacting concrete (SCC), Rubberized concrete (RUC), Steel fiber (SF)

1 Introduction

Web openings in the reinforced concrete (RC) beams serve practical purposes by allowing pipes and ducts to pass through, enabling essential services such as sewage, water, HVAC, communication, and electricity in concrete buildings. Several researchers have studied the influence of transverse web opening on the behavior of RC beams (Al-Rousan, 2017; Al-Sheikh, 2014; Amiri & ALibygie, 2004; Kartal & Kısıklı, 2024; Mansur, 1983; Nie et al., 2018; Osman et al., 2017a), especially the opening size that was examined to determine its impact on the beam

Journal information: ISSN 1976-0485/eISSN 2234-1315.

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strength (Almusallam et al., 2018; Ame et al., 2020; Hassan et al., 2018; Shoeib et al., 2017; Shubbar, 2017). Openings disrupt stress flow, causing early cracking and stress concentration; therefore, their edges should be reinforced to prevent premature failure (Fawzy et al., 2024; Jabbar et al., 2021; Kim et al., 2022; Mansour, 2021).

Aykac et al. (2013) indicated that when the openings number in RC beams increases, the eventuality of the Vierendeel mechanism is higher. Hawileh et al. (2012) presented a numerical analysis to study the effect of using CFRP as a strengthening mechanism for web openings in RC deep beams. The analysis showed that the ultimate load of the control beam was 74% lower than that of strengthened RC beams. Osman et al. (2017b) experimentally examined the rehabilitation mechanism represented using a sheet of aramid FRP to strengthen a circular opening in the RC beam. It was found that the FRP presented significant influences on beam rehabilitation as well as the modes of failure, where the improvement was observed between 21.8% and 66.4% for the rehabilitated beam. Pimanmas (2010) tested the dependence on FRP bars of two different arrangements in reinforcing the concrete beams with web openings. The results demonstrated that FRP bars located along the beam depth significantly improved ductility and load capacity, whereas those near the opening had minimal effect.

Self-compacting concrete, or for short SCC, represents substantial progress in the field of concrete technology in recent decades (Adjrad et al., 2016; Bhagwat et al., 2023; Katebi, et al., 2025; Tichko et al., 2015). SCC can flow and fill confined spaces under its own weight without the need for vibration or complex formwork, unlike traditional concrete (Bhirud et al., 2025; Okamura, 1997; Shi et al., 2015; Tichko et al., 2015). SCC offers high productivity, reduced labor, faster construction, improved structural uniformity, and better working conditions by eliminating the need for compaction (Kamal et al., 2018). As a result of its wide applications, SCC was employed in several nations, such as Canada, Japan, and the USA, for its ability in the field of construction (Kamal et al., 2014; Oliveira et al., 2015).

According to prior investigations(Dadsetan & Bai, 2017; Jalal et al., 2015), on industrial wastes, using fine components such as ground granulated blast-furnace slag, silica fume, and fly ash is fundamental to the creation of SCC. This complies with European Guidelines (EFCAA) (Concrete, 2005). Vandewalle et al. (2008) studied the distance impact of the SCC flow on fiber distribution in beam specimens. The results demonstrated that SCC flow enhanced fiber distribution, but fiber alignment was incompatible as the flow distance increased (Sarmiento et al., 2016; Vandewalle et al., 2008). Stähli et al. (2008) tested the flow velocity influence of SCC on the dispersion of fibers in a sample with a narrow U cross section. It was found that the uppermost velocity of SCC flow results in a superior fiber alignment.

The traditional concrete fails quickly after cracking due to its brittleness, while added steel fibers (SF) act as crack inhibitors by distributing randomly within the mix (Beaudoin, 1990; Yun et al., 2007). Furthermore, SF improves the mechanical characteristics of concrete, stiffness, shear strength, and durability and contributes to transforming concrete's brittle nature into a ductile one (Feng et al., 2024; Goel & Singh, 2014; Islam & Alam, 2013; Tadepalli et al., 2015). These distinctive effects are attributable to the capability of fibers which behaves like crack bridging to move tensile stress through crack superficies, in addition to their high shear strength through created cracks (Lakshmi et al., 2024). Thus, adding SF to the SCC blend provides higher effectiveness in the fresh condition as well as the hardened condition compared to the conventional vibrated concrete (Grünewald & Walraven, 2001). In addition, SF-SCC shows enhanced efficiency to disperse energy and ductile tensile behavior in comparison with the brittle performance of traditional concrete (Ghavidel et al., 2015).

On the other hand, the disposal of waste tires has become a major environmental issue due to the global rise in vehicle production (Kashani et al., 2017; Mohseni et al., 2023; Rashad, 2016; Richardson et al., 2016; Strukar et al., 2019; Wulandari & Tjandra, 2017; Youssf et al., 2017a). Using a sustainable alternative in construction offers an effective way to conserve natural aggregates and support environmental protection (Arun Kumar et al., 2024; Arunkumar et al., 2023; Hamsashree,, et al., 2024; Lakshmi, et al., 2024; Pandit & Nagesh, 2024; Pandit & Venkataramana, 2025; Sheelavantar et al., 2024, 2025). Employing rubber tires waste in concrete mixes as a relative substitution for the mineral aggregates can enhance the properties of the structural element. Furthermore, rubberized concrete (RUC) demonstrated agreeable workability over conventional concrete (Duarte et al., 2016; Evangelista & Brito, 2010; Fadiel et al., 2023; Hall & Najim, 2014; Khusru et al., 2020; Xie et al., 2019). However, the higher proportion of rubber causes a decrease in the elastic modulus of RUC in addition to its tensile and compressive strengths (Fattuhi & Clark, 1996; Hernandez-Olivares et al., 2002; Khatib & Bayomy, 1999; Liu et al., 2016). Eldin and Senouci (1993) examined the effect of crumb and shipped rubber particles on concrete properties. Replacing all fine aggregates with crumb rubber (CR) reduced compressive strength by 65%, while full replacement of coarse aggregates with shipped rubber led to an 85% decrease. RUC also exhibited more ductile failure than traditional concrete. Nevertheless, Toutanji

(1996) studied the performance of RUC when the substitution ratio of coarse aggregate was between 0 and 100%. The results demonstrated that the RUC has toughness higher than that of the traditional concrete up to 50% substitution, but the toughness remained the same when the substitution ratio of coarse aggregate exceeded 50%. Adding SF to RUC helps recover lost mechanical properties, especially tensile strength, and enhances load capacity, ductility, impact resistance, toughness, and crack control (Karimi & Nematzadeh, 2020; Nematzadeh et al., 2020; Xie et al., 2019). In this regard, supplementary cementitious materials having silica can also be used in the RUC mix to improve the mechanical characteristics of RUC (Jokar et al., 2019; Lakhiar et al., 2022; Youssf et al., 2017b).

As mentioned above, numerous studies have explored how transverse web openings affect RC beam shear and flexural behavior, as well as methods for strengthening them (Abdalla et al., 2003; Aykac et al., 2013; De'nan et al., 2017; Naik et al., 1986; Özkılıç et al., 2023; Tseng et al., 2017). On the other hand, a significant lack of studies was observed to investigate the influence of a vertical opening in the shear zone on the RC beams'behavior and performance. Aziz and Ajeel (2010) tested RC T-beams to examine their shear behavior due to the presence of vertical openings at various positions in the flanges. The results indicated that these openings decrease beams'cracking load and shear strength. Al-Jazaeri and Dawood (2014) used CFRP sheets to strengthen RC T-beams with openings, resulting in reduced deflection, smaller cracks, and increased load capacity.

This paper aims to fill the deficiency in the recommendations about the RC beams having vertical openings that pass through the whole depth of the RC beams. Because of the paucity of research in this study, the current paper is extremely important. In addition, this paper presents a new experimental investigation involving the study of the effect of concrete mix type on the performance of RC beams having a vertical opening at the shear zone by comparing the influence of using SCC with RUC. The current study also examined how SF ratio and the number of vertical openings affect the behavior of SCC and RUC beams, including compressive and tensile strengths, cracking, failure modes, deflection, stiffness, loading capacity, and ductility to provide recommendations for RC beams with vertical openings in the shear zone.

2 Experimental Program

2.1 Details of Beam Specimens and Test Program

To study the effect of both SCC containing SF and RUC with SF on the behavior of RC beams having vertical openings with a diameter of 80 mm in the shear zone at both ends of the beam, a total of nine SCC beams in addition to nine RUC beams were formed without and with vertical openings and tested under four-point bending arrangement. The tested SCC beams were divided into three groups depending on the SF ratio. Each group comprised three beam specimens; the first was without an opening as a reference beam specimen, and the second and third beams have one and two vertical openings, respectively, in the shear zone at both ends of the beam, as shown in Fig. 1. The first group was without SF content, while the total volume fraction of SF was 0.75% in the second group and 1% in the third one. The tested RUC beams were also classified into three groups with the same description as the SCC beams groups. All the tested beams have similar dimensions with a length of 1460 mm, a width of 150 mm, and 215 mm height. To create the vertical openings in the beams, white cylinders of foam with 80 mm diameter and 250 mm height were used; Fig. 2a, b. To properly fix foam cylinders to create a vertical opening in the concrete beam while maintaining correct alignment with the shear span and ensuring the shear span-to-depth ratio (a/d) is consistent, the following steps were followed: 1. determine the opening location: (A) the shear span (a) was determined, which is the distance between the nearest support and the loading point in the four-point bending test. (B) The position within the shear span was selected based on the required shear span-to-depth ratio (a/d). (C) The exact location of the vertical opening was determined on the beam formwork. 2. Prepare and secure the foam cylinder: (A) material selection: a high-density foam cylinder was used to withstand the concrete placement without deformation. (B) Attachment method: the foam cylinder was secured to the bottom formwork using construction adhesive to prevent movement during the concrete pouring. 3. Pouring and removing the foam cylinder: (A) the concrete was carefully poured

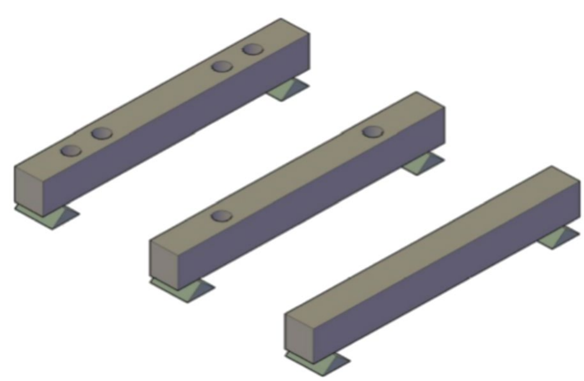


Fig. 1 Three forms of beam specimens in each group in the current study

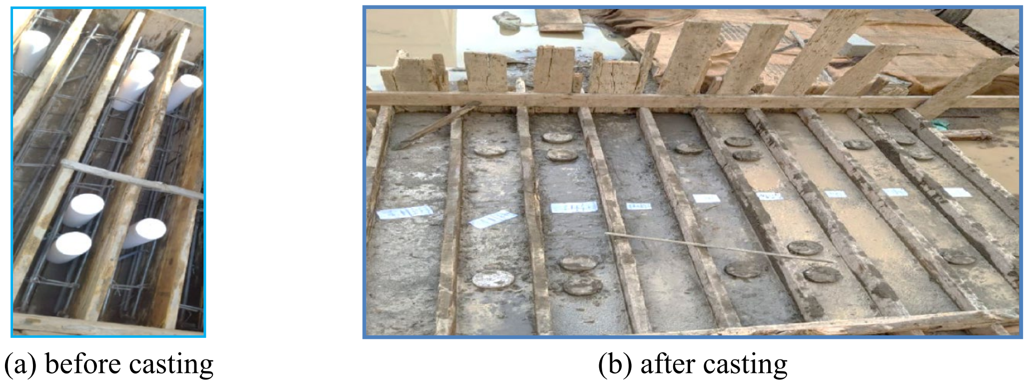


Fig. 2 Creation of openings in the beam specimens using white cylinders of foam

while ensuring no displacement of the foam. (B) After curing, the foam cylinder was removed by pulling it out manually.

The location of the one opening and two openings in addition to the beam dimensions were indicated in detail in Figs. 3 and 4. All the beam specimens were reinforced using four steel bars with a diameter of 12 mm (4Ø12 mm) at the bottom, and two steel bars with a diameter of 8 mm (2Ø8 mm) at the top, and the transverse reinforcement of stirrups was Ø6@200 mm; see Fig. 5.

The details of the tested beam specimens are listed in Table 1. The beam description in this research was proposed as follows: the beginning letter S or R refers to the type of concrete mix; S for SCC and R for RUC, respectively. The following number represents the percentages of SF (0%, 0.75%, and 1%). The next two letters (VO) indicate that the beam was with a vertical opening in the shear zone. Finally, the last number on the label refers to the number of openings. For explanation; beam specimen SO.75 VO2 was created of SCC, including SF with a total volume of 0.75%, and the beam has two vertical openings in the shear zone at both ends of the beam. For more clarification; beam specimen R0 CONTROL was created of RUC without SF (0%), and the beam was without any vertical opening at the shear zone as a control beam.

2.2 Material Properties

Normal Portland cement (NPC) was used in the production of SCC and RUC in the present study. The initial and final setting time, specific gravity, and specific surface area of NPC were 1.9 h and 5.1 h, 3.15, and 340 m^2/kg, respectively. The dolomite was selected as a coarse aggregate with water absorption of 0.69%, a maximum size of 10 mm, specific gravity of 2.64, and a sulfate content of 0.059%. A fine aggregate was used in the form of natural sand; the specific gravity, sulfate content, and water absorption of the sand particles are 2.61, 0.12%, and 0.74%, respectively. Hooked end SF in Fig. 6 with a diameter of 0.5 mm and length of 30 mm was added to both mixes of SCC and RUC in the current study. Although SF

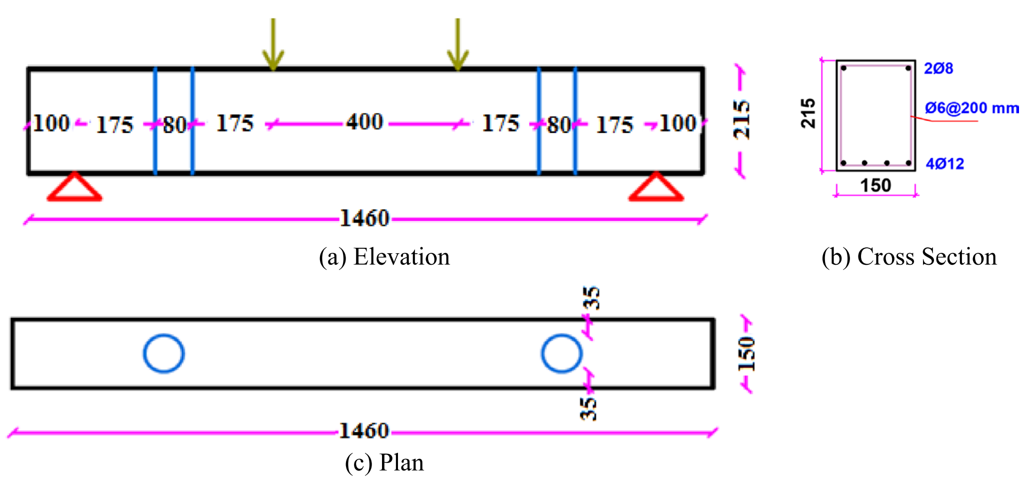


Fig. 3 Dimensions of beam specimens and the location of the one opening in detail. (Dim in mm)

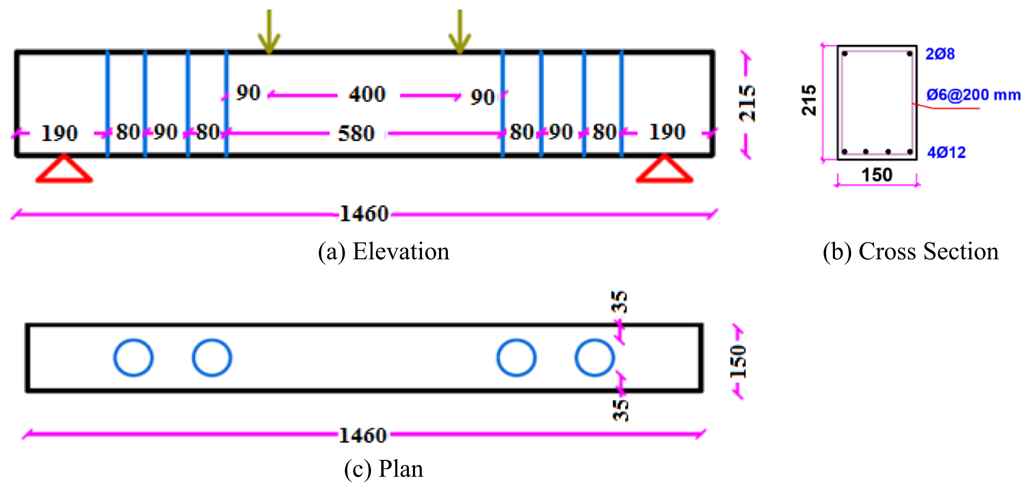


Fig. 4 Dimensions of beam specimens and the location of the two openings in detail. (Dim in mm)

Fig. 5 Reinforcement details of the tested beams

has an essential role in achieving ductile failure of concrete and enhancing its mechanical characteristics, there is a genuine possibility of fibers balling up when the concrete blend is mixed. Consequently, one of the research objectives is to produce a homogenous mixing between the ingredients of the concrete; Fig. 7. Employing SF has additional restrictions, such as the large weight and corrosion. The SF's characteristics are listed in Table 2.

Silica fume with a specific gravity of 2.14 was added to the SCC mixes to increase its durability and strength. It

Table 1 Details of the tested beam specimens

Group number	Beam label	Matrix type	Volume fraction of SF (%)	Number of openings at the shear zone	fcu (MPa)	A_O/A_{Sec}	A_O/A_{Reinf}
1	S0 CONTROL	SCC	0	–	26	–	–
	S0 VO1	SCC	0	One	26	0.312	18.19
	S0 VO2	SCC	0	Two	26	0.624	36.38
2	S0.75 CONTROL	SCC	0.75	–	34.67	–	–
	S0.75 VO1	SCC	0.75	One	34.67	0.312	18.19
	SO.75 VO2	SCC	0.75	Two	34.67	0.624	36.38
3	S1 CONTROL	SCC	1	–	40.17	–	–
	S1 VO1	SCC	1	One	40.17	0.312	18.19
	S1 VO2	SCC	1	Two	40.17	0.624	36.38
4	R0 CONTROL	RUC	0	–	18	–	–
	R0 VO1	RUC	0	One	18	0.312	18.19
	R0 VO2	RUC	0	Two	18	0.624	36.38
5	R0.75 CONTROL	RUC	0.75	–	20.52	–	–
	R0.75 VO1	RUC	0.75	One	20.52	0.312	18.19
	RO.75 VO2	RUC	0.75	Two	20.52	0.624	36.38
6	R1 CONTROL	RUC	1	–	24.21	–	–
	R1 VO1	RUC	1	One	24.21	0.312	18.19
	R1 VO2	RUC	1	Two	24.21	0.624	36.38

"A_O" stands for the area of the openings, "A_{Sec}" denotes the cross-sectional area of the beam, and "A_{Reinf}" refers to the steel reinforcement area

current study.

Fig. 6 Hooked end SF used in the current study

Fig. 7 Homogenous mixing between the ingredients of the concrete

Table 2 Physical and mechanical characteristics of SF

Length (mm)	Diameter (mm)	Tensile strength (MPa)	Density (kg/m^3)	Elastic modulus (GPa)	Aspect ratio
30	0.5	1680	7850	200	60

can also reduce the permeability and segregation of the concrete (Dalvand & Ahmadi, 2021; Okoye et al., 2017; Singh et al., 2024). CR was obtained using mechanical milling of rubber tire waste (see Fig. 8) and was used in the current work as an essential ingredient in the RUC mixes as a recycled substance to improve certain properties of the structural elements in addition to its environmental benefits. CR with a partial replacement proportion of 10% from fine aggregate was employed in the RUC mixes with a maximum size of 0.6 mm.

To create appropriate workability and significant-flowability concrete, Sika ViscoCrete® −3425 with 1.17 specific gravity and 1.05 relative density was added to the SCC and RUC mixes as a superplasticizer (SP). The SP enhanced the concrete's strength. This SP complies with types A and F (ASTM, 2005) and is chloride-free. Table 3 presents the ingredients of SCC and RUC used in the test matrix created for the present investigation. The produced SCC matrix and RUC matrix were poured into the prepared formworks seen in Fig. 9. The direct tensile test was performed on the main and transverse reinforcing steel bars to obtain their mechanical properties (ASTM, 2001). Table 4 illustrates the elastic modulus and the yield and ultimate strengths of reinforcing steel bars used in the tested beam specimens.

Fig. 8 Particles of crumb rubber used in RUC mixes

Thirty-six standard cubes (150 mm × 150 mm × 150 mm) were prepared to perform the compression test after 7 days and 28 days of the processes of casting and curing; six cubes for each SCC mix and the same for each RUC mix. The final average compressive strength by the end of 28 days registered about 26 MPa, 34.67 MPa, and 40.17 MPa for SCC mixtures containing SF ratios of 0%, 0.75%, and 1%, respectively, and about 16 MPa, 18.52 MPa, and 23.21 MPa for RUC mixtures containing SF ratios of 0%, 0.75%, and 1%, respectively. On the other hand, eighteen cylinders with a length of 200 mm and diameter of 100 mm were employed to carry out the Brazilian tensile test on both SCC and RUC (three cylinders for each mix of SCC and the same for each mix of RUC) after 28 days of the processes of casting and curing. The tensile strengths calculated by the test were about 3.18 MPa, 5.67 MPa, and 6.05 MPa for SCC mixtures containing SF ratios of 0%, 0.75%, and 1%, respectively, and about 2.39 MPa, 3.26 MPa, and 4.69 MPa for RUC mixtures containing SF ratios of 0%, 0.75%, and 1%, respectively.

2.3 Test Setup

A testing machine with 2500 kN peak capacity was utilized to perform the test on all beam specimens under the effect of a four-point bending arrangement. The load was gradually applied at a rate of 6.5 kN/min. A linear variable displacement transducer (LVDT) has been set up

Table 3 Mixture ingredients of both SCC and RUC

Mix type	Cement (kg/m^3)	Sand (kg/m^3)	Dolomite (kg/m^3)	Silica fume (kg/m^3)	Water (Lit/m^3)	HRWR[a] (Lit/m^3) (2% of the Cementitious materials)	Rubber (kg/m^3)	SF volume fraction, (%)
SCC	382.50	833	833	67.50	202.50	9	–	0, 0.75, and 1
RUC	382.50	749.7	833	–	202.50	7.65	83.3	0, 0.75, and 1

[a] High range water reducer


(a) Formworks before placing the reinforcing cage

(b) Formworks after placing the reinforcing cage and during the casting

Fig. 9 Prepared formworks for beam casting

to measure the deflection at the mid-span of the tested beams, whereas a certified load cell was adopted to register the loads, as shown in Fig. 10. All required data were recorded automatically during the test via a data logger.

3 Results and Discussion

3.1 Concrete Properties

It was found that the compressive strength of the standard cubes of both SCC and RUC has been improved by raising the SF content in the mixture up to 1%, as shown in Fig. 11, and this is consistent with (Kamal et al., 2014; Lv et al., 2024). This may be attributed to the fibers'uneven distribution to prevent cracks from

Table 4 Properties of reinforcing steel bars

Diameter (mm)	Elastic modulus Es (GPa)	Yield strength fy (MPa)	Ultimate strength fu (MPa)
12	203	498	670
8	203	362	487
6	200	252	374

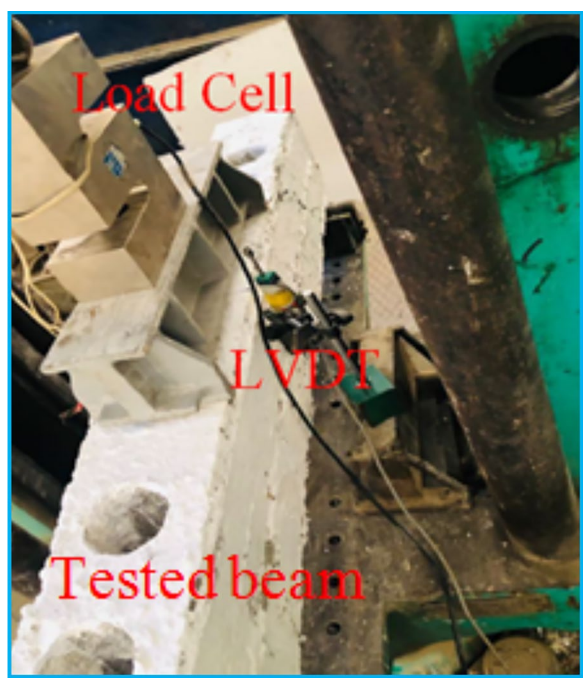


Fig. 10 Test setup

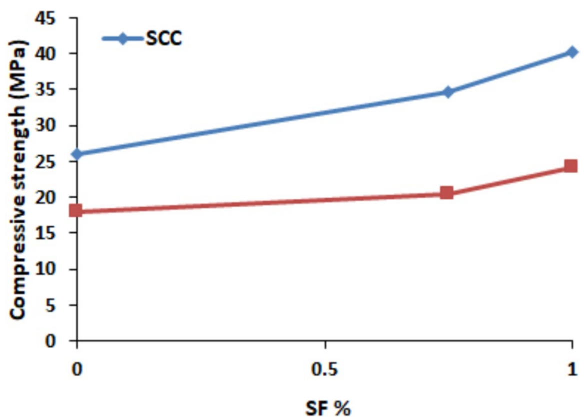


Fig. 11 Effect of using SF on compressive strength of SCC and RUC

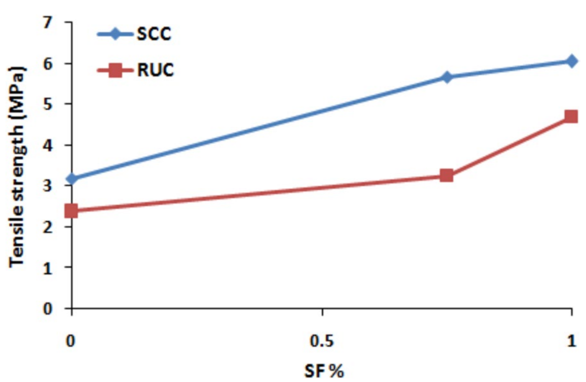


Fig. 12 Effect of using SF on tensile strength of SCC and RUC

spreading, hence enhancing the compressive strength. On the other hand, the tensile strength of SCC and RUC significantly increased when the concentration of fibers increased up to 1%, as shown in Fig. 12, and this is consistent with (Alrawashdeh & Eren, 2022; Alsaif et al., 2022) In general, adding SF to the SCC mixture showed a greater effect on enhancing the tensile and compressive strengths compared to that in the case of the RUC; see Figs. 11 and 12. This is due to the comparatively weak strength and stiffness of CR in the RUC mixture (Yu & Zhu, 2016).

3.2 Crack Patterns and Modes of Failure

For all beam specimens tested in the current study, the cracks'progress and modes of failure were noticed, and it was found that the initial crack was formed along the bottom face of the concrete surrounding the opening for each beam specimen having vertical openings. This initial crack originated in the reference beams, which were without openings, after reaching a level of cracking load more than that in the beams with openings. As the applied loading is increased, the cracks spread more widely at the shear zone, which includes the vertical openings, than that at the other regions without opening in the tested beams. After that, the cracks multiplied towards the position of loading points, as indicated in Figs. 13 and 14.

At the ultimate load, the shear failure pattern was observed obviously through the opening for each beam specimen having a vertical opening at the shear zone; Figs. 13 and 14. The shear cracks formed around the opening, which is located in the high-shear region due to stress concentration, and thus, the diagonal tension failure occurred when the shear stress exceeded the concrete's tensile strength. This agrees with the specifications outlined in ACI-318-19(22) (2022) and BS 8110 standard (Standard, 1986).

The maximum shear loading capacity of the reference beam specimens without openings was more than that of the other beam specimens with vertical openings. This outcome is consistent with (Aziz & Ajeel, 2010). It was noticed also that when the number of vertical openings increased, the cracks increased at the shear span in which the openings were located and decreased at the remaining unopened regions along the beam. In general, the RUC beams showed cracks width relatively more than that of SCC beams, and severe concrete collapse occurred in RUC beams because of their lower compressive strength. Furthermore, increasing the fiber content in both SCC and RUC beam specimens demonstrated a relatively lower deterioration degree at the end of the test compared to the beams without fibers, see Figs. 13 and 14. This result agrees with some investigations (Alsaif et al., 2022; Buratti et al., 2010).

3.3 Load–Deflection Relationship and Ultimate Capacity

The relation between the load acting on the tested beam specimens and the corresponding deflection at mid-span is presented in Figs. 15–24. The most important experimental outcomes were summarized for each tested beam in Table 5, including ultimate load, yield mid-span deflection, ultimate mid-span deflection, stiffness, ductility index, and energy absorption capacity. The load–deflection curves revealed that the deflection value increases linearly with the rise in the loading value up to the maximum load. When the maximum load was exceeded, the carrying capacity of the tested beams dropped with a relatively rapid rise in the deflection value as a result of the beams'crushing beginning. In general, it was observed that the ultimate deflection value of each beam having vertical openings is often larger than that obtained from its reference beam without opening under identical loading conditions, see Figs. 15 and 16.

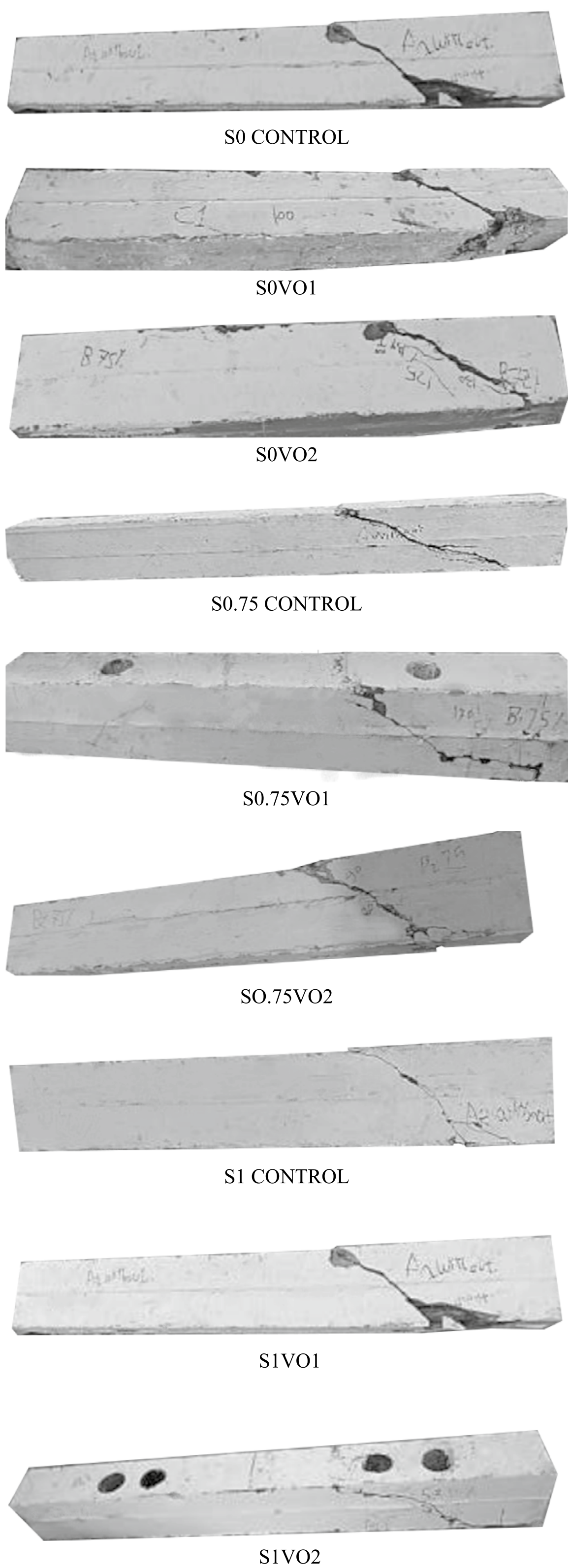


Fig. 13 Failure modes and crack patterns of all tested SCC beams

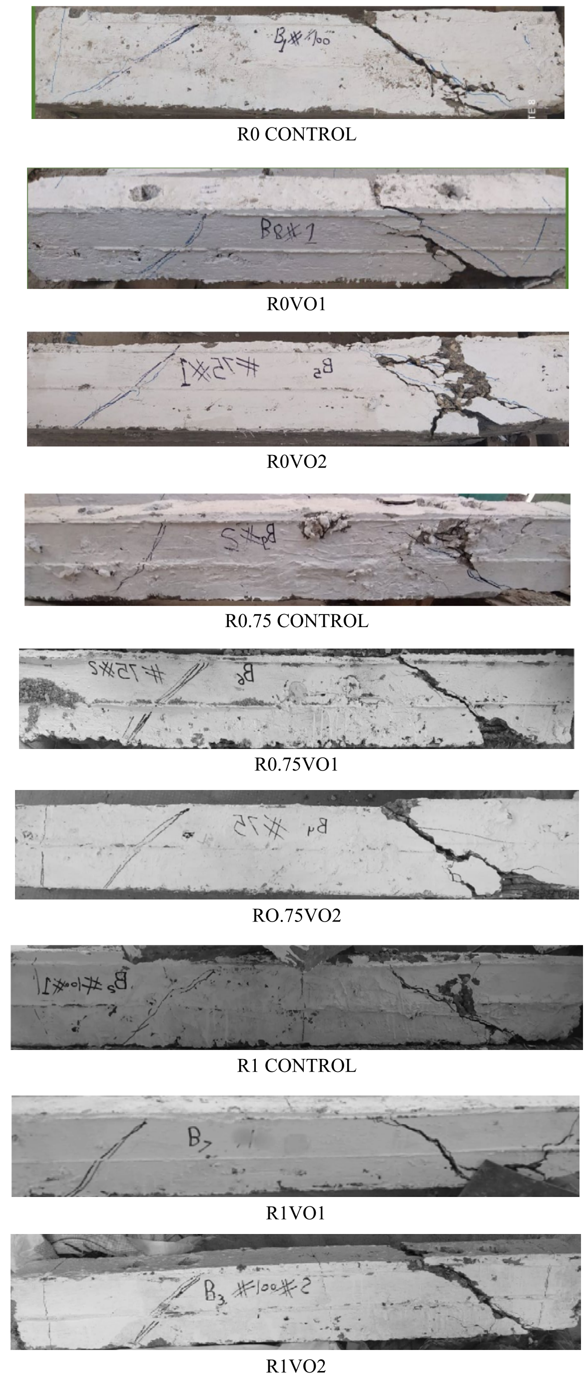


Fig. 14 Failure modes and crack patterns of all tested RUC beams

Table 5 and Figs. 17 and 18 demonstrate that when the compressive strength value of the matrix was raised, the ultimate mid-span deflection value decreased, while the beam stiffness and loading capacity improved. This was especially obvious as the fiber content in the mixes of SCC or RUC beams increased. These findings agree well

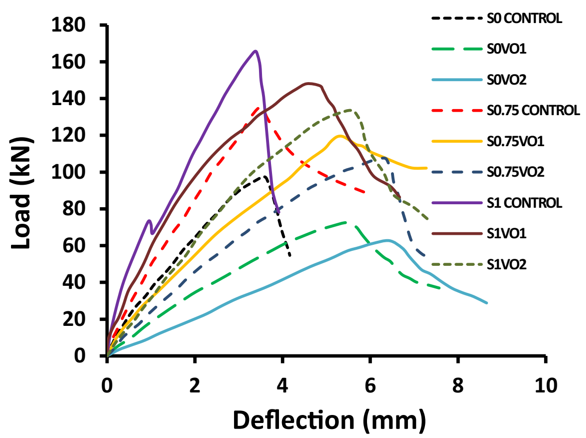


Fig. 15 Load–mid-span deflection of all tested SCC beam specimens

with earlier studies (Adam et al., 2016; Albidah & Alsaif, 2024).

For example, the stiffness and the ultimate load increased by 164.58% and 70.19%, respectively, in the beam S1 CONTROL that contains a SF ratio of 1%, compared to the beam S0 CONTROL without SF; Fig. 17, while the stiffness and the ultimate load increased by 69.91% and 61.85%, respectively, in the beam R1 CONTROL that contains a SF ratio of 1%, compared to the beam R0 CONTROL without SF; Fig. 18.

For the first group of SCC beam specimens without fiber content (group No. 1), the ultimate load of its reference beam without openings (S0 CONTROL) was 97.39 kN. The existence of one opening and two openings at the shear zone reduced the ultimate load by 25.63% and 35.63%, respectively; specimens (S0 VO1 and S0 VO2), as shown in Fig. 19. This might be attributed to the fact that increasing the number of vertical openings in the shear zone reduces the beam stiffness (Sayed, 2019). Where the stiffness of the reference beam S0 CONTROL was 33.65 kN/mm and decreased by 41.81% and 66.98% for specimens S0 VO1 and S0 VO2, respectively; Table 5. For the second group of SCC beam specimens that contain a total volume fraction of SF of o.75% (group No. 2), the ultimate load of its reference beam without openings (S0.75 CONTROL) was 134.84 kN. It was also noted that the presence of one opening and two openings at the shear zone led to a decrease in the ultimate load by 11.39% and 20.22%, respectively; specimens (S0.75 VO1 and S0.75 VO2), as indicated in Fig. 20. The stiffness of the reference beam S0.75 CONTROL was 51.79 kN/mm and decreased by 34.76% and 39.68% for specimens S0.75 VO1 and S0.75 VO2, respectively; see Table 5. Likewise, the SCC beam specimens in the third group (group No. 3) with a total volume fraction of SF of 1% confirmed that the existence of openings at the shear zone reduced

Table 5 Main experimental outcomes of all tested beam specimens

Group number	Beam label	Pu (kN)	Δy (mm)	Δu (mm)	Stiffness (kN/mm)	DI	Energy absorption capacity (kN.mm)
1	S0 CONTROL	97.39	1.28	3.54	33.65	2.77	248. 80
	S0 VO1	72.43	2.03	5.41	19.58	2.67	337.72
	S0 VO2	62.69	2.52	6.43	11.11	2.55	309.52
2	S0.75 CONTROL	134.84	1.03	3.45	51.79	3.35	471.54
	S0.75 VO1	119.47	1.78	5.36	33.79	3.01	566.63
	SO.75 VO2	107.57	2.22	6.26	31.24	2.82	474.09
3	S1 CONTROL	165.75	0.96	3.38	89.03	3.52	473.31
	S1 VO1	148.08	1.55	4.85	49.32	3.13	684.28
	S1 VO2	133.50	1.96	5.58	33.38	2.85	608.99
4	R0 CONTROL	92.92	1.31	3.68	20.67	2.81	277.35
	R0 VO1	67.76	1.79	4.92	17.10	2.75	462.57
	R0 VO2	57.86	1.86	4.97	10.64	2.67	340.64
5	R0.75 CONTROL	125.47	1.02	3.52	24.26	3.45	280.78
	R0.75 VO1	94.82	1.16	3.69	21.73	3.18	505.17
	RO.75 VO2	80.82	1.82	4.94	18.40	2.71	343.19
6	R1 CONTROL	150.39	0.94	3.45	35.12	3.67	384.86
	R1 VO1	116.37	1.10	3.52	30.15	3.20	596.83
	R1 VO2	98.94	1.31	3.77	27.30	2.88	413.97

"Pu" stands for ultimate load, "Δy" denotes yield mid-span deflection, "Δu" refers to ultimate mid-span deflection, and "DI" stands for ductility index

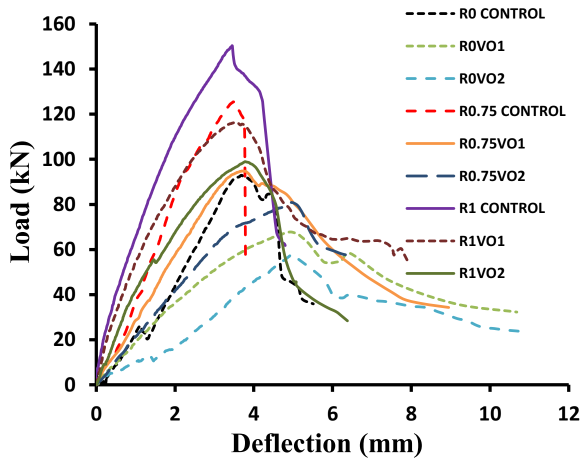


Fig. 16 Load–mid-span deflection of all tested RUC beam specimens

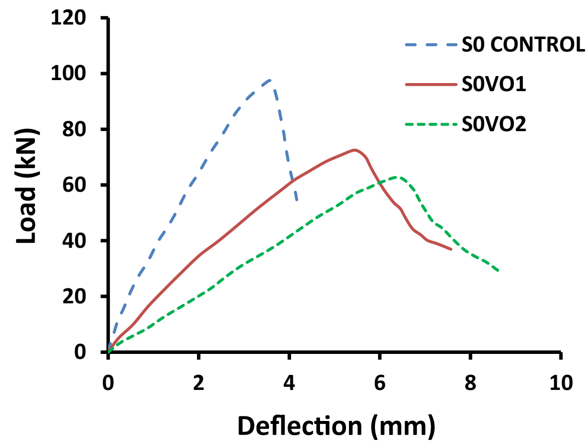


Fig. 19 Load–mid-span deflection of the tested SCC beam specimens without fiber content

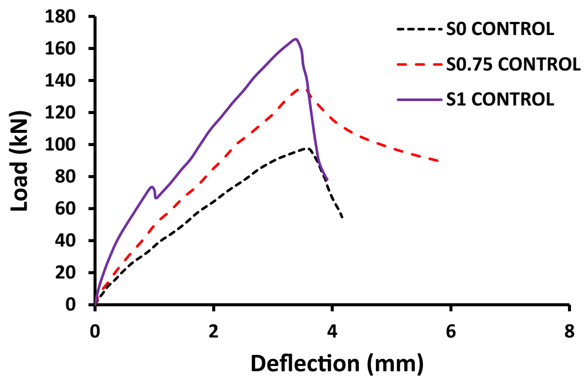


Fig. 17 Load–mid-span deflection of the tested reference SCC beam specimens

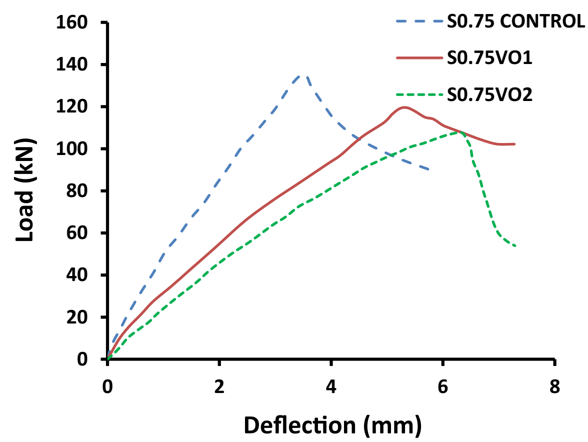


Fig. 20 Load–mid-span deflection of the tested SCC beam specimens with a total volume fraction of SF of 0.75%

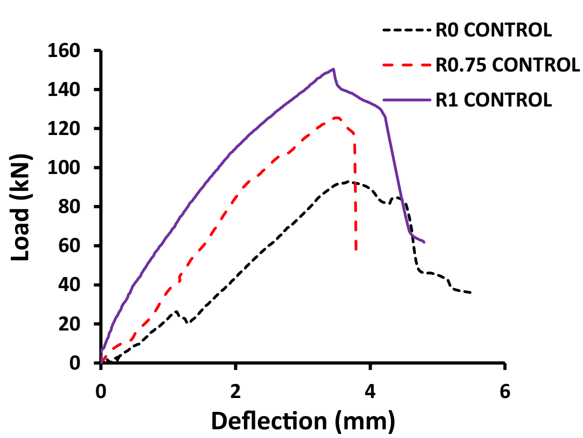


Fig. 18 Load–mid-span deflection of the tested reference RUC beam specimens

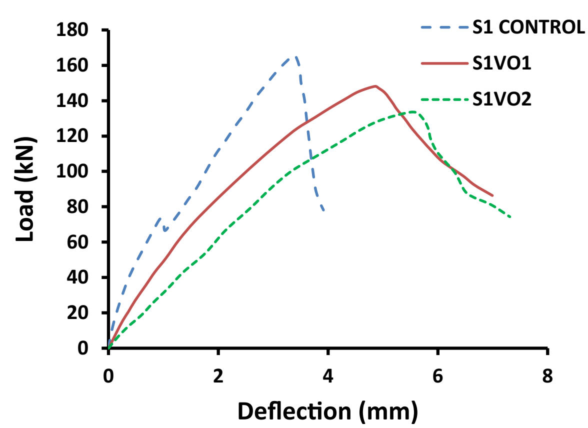


Fig. 21 Load–mid-span deflection of the tested SCC beam specimens with a total volume fraction of SF of 1%

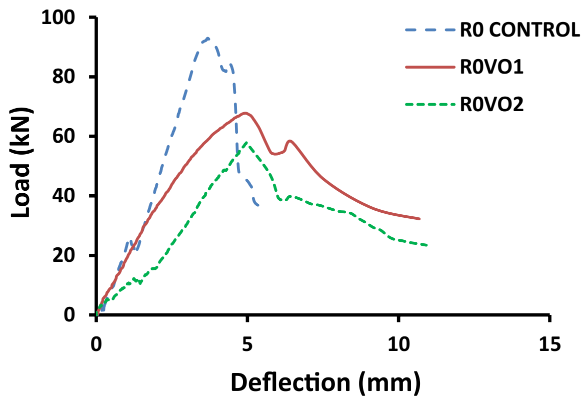


Fig. 22 Load–mid-span deflection of the tested RUC beam specimens without fiber content

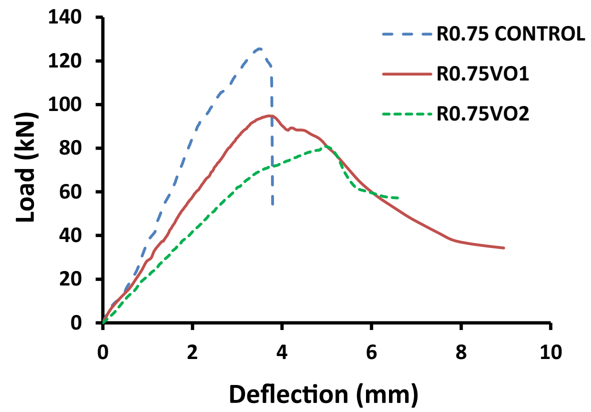


Fig. 23 Load–mid-span deflection of the tested RUC beam specimens with a total volume fraction of SF of 0.75%

both the stiffness and the loading capacity, as observed in Fig. 21.

On the other hand, all tested RUC beam specimens showed a lower stiffness and loading capacity than the corresponding SCC beam specimens because of the low compressive strength of RUC compared to that of SCC. For further clarification, the fourth group that includes RUC beam specimens without fiber content showed that the stiffness and the ultimate load of the reference beam without openings (R0 CONTROL) were 20.67 kN/mm and 92.92 kN, respectively, showing a reduction in the stiffness and the ultimate load by about 38.57% and 4.59%, respectively, compared to the corresponding similar reference SCC beam (S0 CONTROL). In addition, the existence of one opening and two openings at the shear zone of RUC beams reduced the stiffness by 17.27% and 48.52%, respectively, and thus the ultimate load decreased by 27.08% and 37.73%, respectively; specimens (R0 VO1 and R0 VO2) compared to its reference beam (R0 CONTROL), as shown in Fig. 22. For the fifth group that includes RUC beam specimens with a total volume fraction of SF of 0.75%, the ultimate load of its reference beam (R0.75 CONTROL) was 125.47 kN. It was also observed that the ultimate load decreased by 24.43% and 35.59% when the beam was provided with one and two openings at the shear zone, respectively, as in the specimens R0.75 VO1 and R0.75 VO2; Fig. 23. The stiffness of the reference beam R0.75 CONTROL was 24.26 kN/mm and decreased by 10.43% and 24.15% for specimens R0.75 VO1 and R0.75 VO2, respectively, as indicated in Table 5. Similarly, as shown in Fig. 24, the RUC beam specimens in the sixth group with a total volume fraction of SF of 1% demonstrated that the presence of openings at the shear zone lessened both stiffness and loading capacity.

3.4 Ductility

When testing the beam specimens, the ductility may be used as an obvious measure of the extent to which they can be plastically deformed. There were two various methodologies used in this study to determine the ductility coefficient. The first methodology depends on identifying the product of dividing the ultimate mid-span deflection by the yield mid-span deflection. This methodology has been given the name"ductility index"or DI for short. In the second methodology, the area under the entire curve that represents the relationship between load and mid-span deflection was computed through the use of numerical integration to estimate the ductility of the beam specimens, as reported by Hadi (2006; 2007). This methodology is known as the energy absorption capacity or EAC for short. Table 5 and Fig. 25 display the results of DI and EAC calculations performed on all the beam specimens.

All RUC beam specimens showed relatively higher DI than that of the corresponding SCC beam specimens, while RUC beam specimens with SF demonstrated a lower EAC compared to SCC beam specimens; see Table 5. It was observed that by increasing the ratio of SF

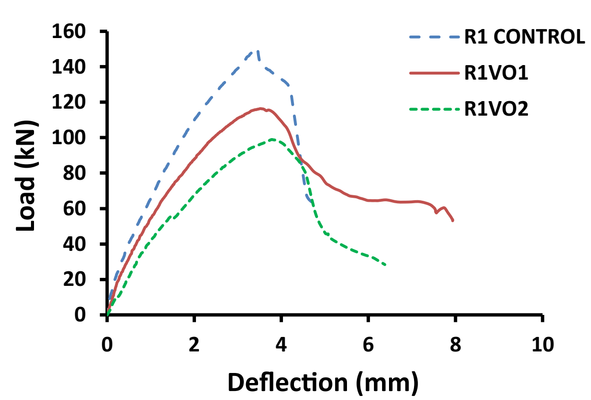
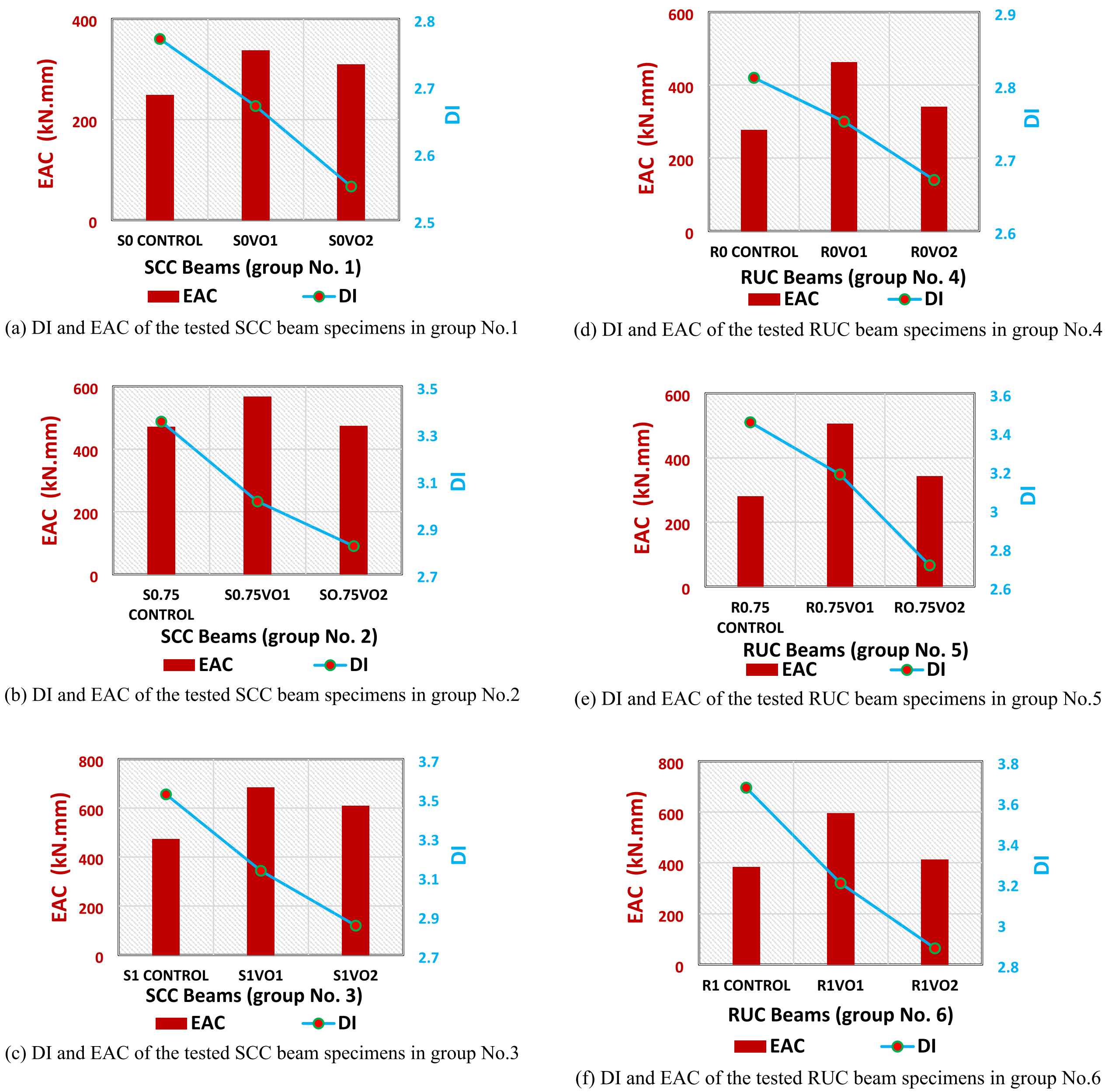


Fig. 24 Load–mid-span deflection of the tested RUC beam specimens with a total volume fraction of SF of 1%



(a) DI and EAC of the tested SCC beam specimens in group No.1

(d) DI and EAC of the tested RUC beam specimens in group No.4

(b) DI and EAC of the tested SCC beam specimens in group No.2

(e) DI and EAC of the tested RUC beam specimens in group No.5

(c) DI and EAC of the tested SCC beam specimens in group No.3

(f) DI and EAC of the tested RUC beam specimens in group No.6

Fig. 25 Representation of DI and EAC of all tested beams

up to 1% in SCC or RUC beam specimens, both DI and EAC improved; Table 5. This could be attributed to the relatively slight deterioration of the specimens containing SF compared to those without SF content. This agrees with the outcomes obtained by Emara et al. (2021) and Medina et al. (2015).

For more illustration, for example, the enhancement in DI of the SCC beams S0.75 CONTROL and S1 CONTROL was approximately 20.94% and 27.08%, respectively, higher than that of the control SCC beam without SF (S0 CONTROL). While the EAC of the beams S0.75 CONTROL and S1 CONTROL increased by about 89.53% and 90.24%, respectively, over that of the beam S0 CONTROL. In the same context, the increase in DI value of the RUC beams R0.75 CONTROL and R1 CONTROL was approximately 22.78% and 30.60%, respectively, more than that of the control RUC beam without SF (R0 CONTROL). Whereas the EAC of the beams R0.75 CONTROL and R1 CONTROL improved by about 1.24% and 38.76%, respectively, over that of the beam R0 CONTROL.

In general, it was found that the existence of one opening and two openings at the shear zone reduced the DI of the beam, as shown in Fig. 25a–f. This is in agreement with the previous studies (Hassan et al., 2019; Ibrahim et al., 2017). Where the first group of SCC beam specimens without SF content (group No. 1) displayed that the DI of its reference beam without openings (S0 CONTROL) was 2.77, and it decreased by 3.61% and 7.94% when the beam was provided with one and two openings at the shear zone, respectively, as in the specimens S0 VO1 and S0 VO2; Fig. 25a. For the second group of SCC beam specimens that contain a total volume fraction of SF of o.75% (group No. 2), the DI of its reference beam without openings (S0.75 CONTROL) was 3.35. It was also observed that the presence of one opening and two openings at the shear zone led to a reduction in DI value by 10.15% and 15.82%, respectively; specimens (S0.75 VO1 and S0.75 VO2), as indicated in Fig. 25b.

Likewise, the existence of one opening and two openings at the shear zone of RUC beam specimens without SF content in the fourth group presented a negative effect on the value of DI, which decreased by about 2.14% and 4.98%, respectively; specimens (R0 VO1 and R0 VO2) compared to its reference solid beam (R0 CONTROL), as shown in Fig. 25d. For the fifth group that includes RUC beam specimens with a SF ratio of 0.75%, the DI decreased by 7.83% and 21.45% when the beam was provided with one and two openings at the shear zone, respectively, as in the specimens R0.75 VO1 and R0.75 VO2, compared to its reference solid beam (R0.75 CONTROL); Fig. 25e. In addition, increasing the SF content to 1% in SCC or RUC beam specimens (group No. 3 and group No. 6) showed a higher effect on the rate of declining DI value for the beam specimens with openings compared to the solid beam; Fig. 25c, f.

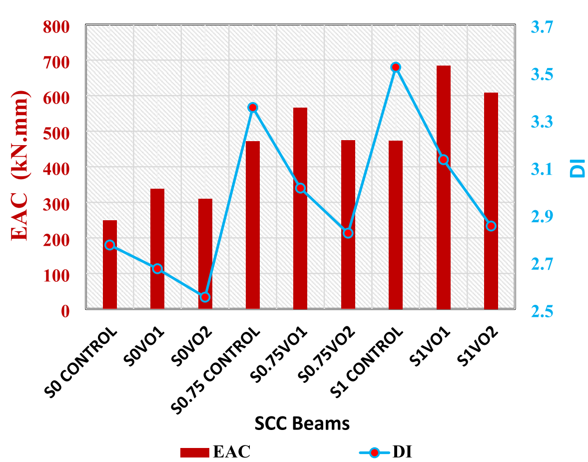


Fig. 26 Representation of DI and EAC of all tested SCC beams

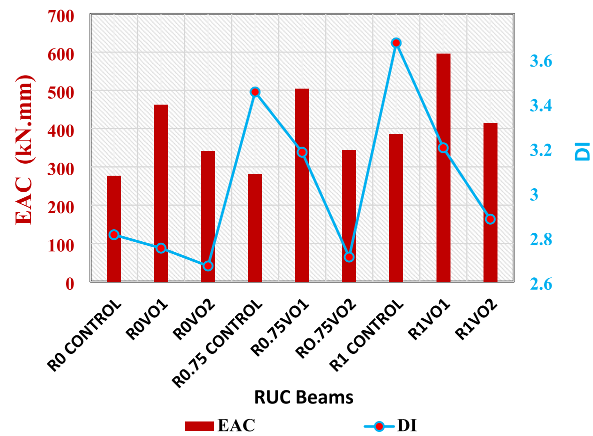


Fig. 27 Representation of DI and EAC of all tested RUC beams

Finally, it should be noted that the presence of openings in SCC or RUC beams caused an increase in EAC compared to the solid beam, as indicated in Table 5 and Figs. 26 and 27, and this may be due to the relatively large deformation capacity of the beam specimens with vertical openings; see Figs. 15–24. The RUC beam specimen R0.75 VO1 showed the highest ratio of increase in EAC value by about 79.92% compared to its reference beam specimen R0.75 CONTROL.

4 Conclusions

In this study, nine SCC beams, in addition to nine RUC beams, were tested under a four-point bending arrangement. The tested SCC or RUC beams were divided into three groups depending on the SF ratio (0%, 0.75%, 1%). Each group included a reference beam without openings and two beams with one and two vertical openings. The effects of SF ratio and number of openings on beam behavior, including compressive and tensile strengths, crack patterns, failure modes, deflection, stiffness, load capacity, and ductility were evaluated. The following significant conclusions may be presented in light of the experimental findings:

- Adding SF to the SCC matrix had a greater positive effect on the strength, stiffness, and ultimate load compared to the RUC.
- The RUC beams showed relatively larger crack widths than those of the SCC beams.
- More vertical openings led to increased cracking in the shear span.
- Higher SF content reduced deterioration and decreased mid-span deflection in both SCC and RUC beams.

- The ultimate deflection value of each beam with vertical openings is often larger than that obtained from its reference solid beam.
- Increasing vertical openings reduced beam stiffness and ultimate capacity. For example, in SCC beams without SF having one and two openings, stiffness dropped by 41.81% and 66.98%, respectively, and ultimate load decreased by 25.63% and 35.63%, respectively.
- All tested RUC beam specimens showed lower stiffness and loading capacity than the corresponding SCC beam specimens.
- All RUC beam specimens showed relatively higher DI than that of the corresponding SCC beam specimens, while RUC beam specimens with SF demonstrated a lower EAC compared to SCC beam specimens.
- In general, the existence of one or two openings at the shear zone reduced the DI of the beam.
- Increasing the SF ratio up to 1% in SCC or RUC beams enhanced both DI and EAC. For example, in solid RUC beams with 0.75% and 1% SF, DI increased by 22.78% and 30.60%, respectively, while EAC improved by 1.24% and 38.76%, respectively.

5 Scope of Future Work Related to Long-Term Effects

The long-term effects of incorporating vertical openings in SCC and RUC beams can be evaluated in terms of durability, structural performance, and material degradation over time. While the current study provides initial insights into these factors, further experimental research and numerical modeling are required to validate long-term predictions under real-life environmental and loading conditions.

To build on the current findings, the following future research directions are recommended:

- Durability and material degradation:
- Study the potential reduction in concrete strength due to environmental factors, such as moisture penetration, freeze–thaw cycles, and chloride attack.
- Study the long-term performance of rubberized concrete, considering the potential aging of rubber particles and their impact on mechanical properties.
- Structural integrity over time:
- Investigate the influence of openings on the progressive deterioration of beam stiffness, cracking behavior, and deflection under cyclic loading.
- Investigate the possible fatigue failure due to stress concentrations around openings, especially under repeated loading conditions.
- Load-bearing capacity in the long run:
- Study the effect of the presence of openings on the shear and flexural capacity after extended exposure to service loads.
- Study the role of steel fibers in mitigating long-term degradation by enhancing crack resistance and ductility.
- Conduct in-depth theoretical analysis to complement the current experimental results.

Acknowledgements
Not applicable.

Author contributions
Mohamed Emara: investigation, data curation, supervision, writing—original draft preparation, and writing—reviewing and editing. *Mostafa S. Rizk:* investigation, data curation, supervision, writing—original draft preparation, and writing—reviewing and editing. *Heba A. Mohamed:* investigation, data curation, supervision, writing—original draft preparation, and writing—reviewing and editing.

Funding
Open access funding provided by The Science, Technology & Innovation Funding Authority (STDF) in cooperation with The Egyptian Knowledge Bank (EKB).

Availability of data and materials
Data will be available upon request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
All authors have reviewed the manuscript and agreed to its submission for publication.

Competing interests
All author declare that they have no conflict of interest.

Received: 17 December 2024 Accepted: 1 May 2025
Published online: 20 August 2025

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