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Steel Fiber Performance in Reinforced Concrete Deep Beams with Mid-Span Web Opening

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ABSTRACT

Opening on reinforced concrete beams is sometimes crucial to allow for the pipelines of electrical circuits. These openings will affect the strength and ductility of the beams. This paper presents the effect of adding steel fiber to cater the loss due to the mid-span web opening in reinforced concrete deep beams. Two amount of fibers volume fractions was considered (1% and 2%) with two different opening shapes (square and rectangular). One beam without opening was casted as a control beam. On the other hand, three beams with square opening and three beams with rectangular opening were also casted. Each beam catered for each amount of steel fiber content of 0%, 1% and 2%. The beams were tested under four-point bending test to failure. It was observed that the size or shape of the opening greatly decreased the beams' ability to support loads. Additionally, the strength and ductility of the reinforced concrete deep beams with mid-span web opening were enhanced by the inclusion of steel fiber, which made them similar to the control beam (without opening).

1. Introduction

Reinforced concrete deep beams, characterized by a small span-to-depth ratio, exhibit complex stress states due to non-linear strain distributions across their depth, making shear forces crucial for determining ultimate strength. Special considerations in their design and analysis include appropriate shear reinforcement, detailed anchorage zones, and careful attention to bearing areas due to high localized stresses [1-3]. Despite critical design considerations, incorporating openings in reinforced concrete deep beams to accommodate utility ducts is sometimes unavoidable.

The use of utility ducts for essential services such as power supply, water supply, air-conditioning, and sewerage has become increasingly prevalent in building development and construction projects. These ducts often require openings in reinforced concrete beams to allow for their passage. While routing the ducts through transverse openings in beams offers advantages like improved economic design, enhanced aesthetics, and more systematic layout for pipes and ducts, it also introduces

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discontinuities in the normal flow of stresses. These discontinuities can lead to various challenges, including high stress concentration, early cracking in the opening region, reduced overall beam stiffness, excessive cracking, excessive deflection, and a decrease in beam strength [3,4]. The reduction in beam stiffness may result in excessive deflection under service loads, causing a significant redistribution of internal forces and moments within the beam, which can adversely affect the structural performance of the member. Ultimately, any opening in a beam will inevitably weaken its resistance capacity and compromise its structural performance to some extent. Therefore, careful consideration and analysis are necessary when introducing openings in beams to ensure the structural integrity and serviceability of the beam are maintained within acceptable limits.

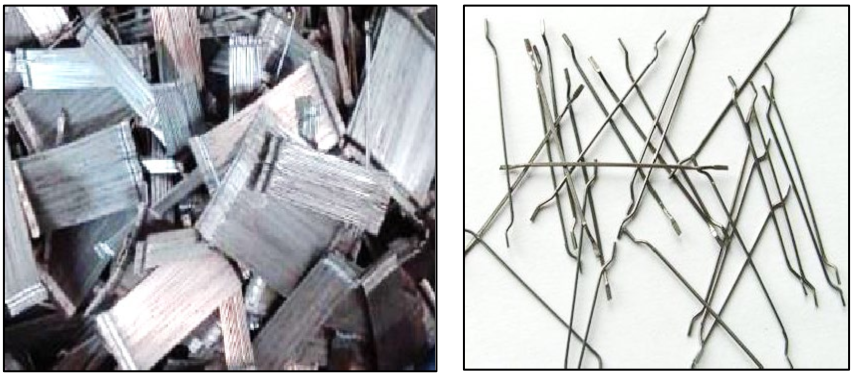
While the presence of openings in reinforced concrete beams can adversely impact their structural performance, the extent of this effect varies depending on the location and size of the openings. In cases where the reduction in strength is significant, strengthening measures become necessary. Researchers have studied and implemented various approaches to address this issue, including the external wrapping of fiber-reinforced polymer (FRP) composite sheets or plates around the opening [5,6], the installation of diagonal reinforcement around the opening [7], the increasing number of stirrups near the opening [8], the incorporation of stirrups at the top and bottom of the opening [9], and the addition of longitudinal stirrups in the posts between adjacent openings [10]. The selection of the appropriate strengthening method depends on factors such as the size and location of the openings, the anticipated loading conditions, and the desired level of structural performance, requiring careful analysis and design considerations.

Fiber reinforced concrete, particularly steel fiber reinforced concrete, has been widely used in the construction industry to enhance the strength, flexural strength, ductility, crack resistance, and durability of structures [11]. It is commonly used in pavements, airport pavements, bridge deck slabs, tunnel linings, and shotcrete, and can also cater to seismic loading and impact load due to its good energy absorption properties [12,13]. Another potential application of steel fiber reinforcement is to compensate for the loss of shear resistance caused by web openings in reinforced concrete deep beams [14-16]. For instance, Vengatachalapathy and Ilangovan [17] conducted an investigation on steel fibres in the deep beam with and without opening in web subjected to two-point loading. It was observed that the addition of steel fibres increased the tensile strength of the beam concrete and enhanced the flexural rigidity of the beam. Other investigation by Punnoose and Hameed [4] studied the performance of steel fibre reinforced concrete beam with circular opening and observed that fibre content of 0.5% by volume fraction improved the strength and ductility due to the uniform distribution of steel fibre.

Limited research exists on the structural behavior of steel fiber reinforced concrete deep beams with web openings, particularly regarding the combined effects of opening parameters and fiber reinforcement. Previous studies indicate that beam performance varies significantly with opening shape, size, and location. This research investigates the structural behavior of reinforced concrete deep beam with square (150 mm x 150 mm) and rectangular (300 mm x 150 mm) openings located at the mid-span. The study aims to evaluate the effectiveness of hooked-end steel fiber reinforcement at 0-2% fiber volume fraction in mitigating the adverse effects caused by the presence of these openings. By incorporating steel fibers into the concrete matrix, the study investigates the potential of this reinforcement method to compensate for the reduction in shear resistance and overall structural performance resulting from the web openings.

2. Methodology

The primary components of the concrete were water, locally available crushed granite, river sand, and ordinary Portland cement. In compliance with ASTM C33 (2003) [18], the granite and river sand were sieved using sieve analysis to guarantee particle size homogeneity and eliminate any contaminants. The coarse aggregate (crushed granite) employed in this investigation had a maximum size of 20 mm. For this investigation, commercially available Stahlcon hooked end steel fiber measuring 60 mm in length and 0.75 mm in diameter was taken into consideration. Figure 1 shows the hooked steel fiber used in the study.



(a) (b)

Fig. 1. Sample images of hooked end steel fibre (a) Bulk (b) Separated

As inclusion of the steel fiber will affect the workability of the concrete, Sika Viscocrete-2199 super-platicizer was added to the concrete mixture to maintain the water cement ratio of the concrete. The dosage of the super-plasticizer used was 2 liters per 100kg cement. Concrete mix design was done based on British Standards (BS EN 206-1, 2000) [19] to reach a compressive strength of 25 MPa at 28th day. Table 1 shows the summary of the concrete mix design used in this study. The steel fibres were incorporated into the mixes design based on volume fraction (Vf) at maximum of 2% as recommended in [20].

Table 1
Design mix compositions of concrete mixtures

Vf (%)	Fibre (kg/m^3)	Cement (kg/m^3)	Water (kg/m^3)	Sand (kg/m^3)	Granite (kg/m^3)
0	0	346	190	1001	888
1	75	346	190	1001	888
2	150	346	190	1001	888

Six cubes for each concrete mixture by a dimension of 150 mm x 150 mm x 150 mm were prepared to determine the compressive strength of the concrete at 7th and 28th day. Three prisms for each mixture with 100 mm x 100 mm cross section and 500 mm length were casted as well. The prisms were tested under flexural strength test on the 28th day. All the specimens were cured using water curing.

For the present work, the deep beam with the dimension of 125 mm x 450 mm x 1200 mm were prepared with and without web opening at the mid span. The deep beams were designed according to Eurocode 2 (2004) [21]. The number of mixes and deep beams are illustrated in Table 2. Figure 2 illustrates the openings were made from wooden moulds by fixing the square and rectangular shapes at the deep beam's web. Two shapes of opening were considered in this study which were square and rectangular.

Table 2
Details of deep beams with and without opening at the mid-span

Mix	Vf (%)	Without opening	With opening	
			Square	Rectangular
1	0	2	2	2
2	1	-	2	2
3	2	-	2	2

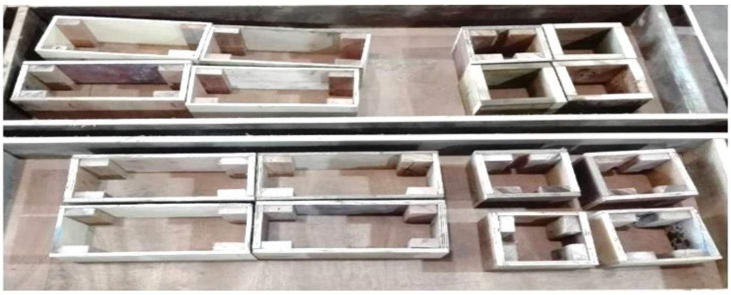


Fig. 2. Wooden squares and rectangles are used to construct the web openings

The dimension, detailing and loading arrangement of the deep beam without opening is given in Figure 3. The beam was tested under four-point bending test and had 2H12 for both tension and compression longitudinal reinforcements. R6 was installed at 150 mm centre to centre as the shear reinforcement of the beam. Square opening with 150 x 150 mm dimensions was installed to provide opening at the mid-span of the beam as shown in Figure 4. Whereas Figure 5, shows the rectangular opening (300 x 150 mm) for another group of the deep beam. The reinforced concrete deep beams were tested using universal testing machine under static monotonic loading until failure [22]. The test was conducted on the 28th day after casting. The mid-span deflected is measured by using linear variable displacement transducer (LVDT) which is located at the centre of the beam.

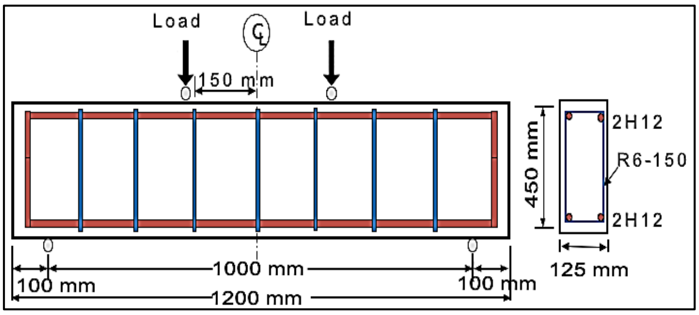


Fig. 3. Dimensions, cross-section and load arrangement of reinforced concrete deep beam

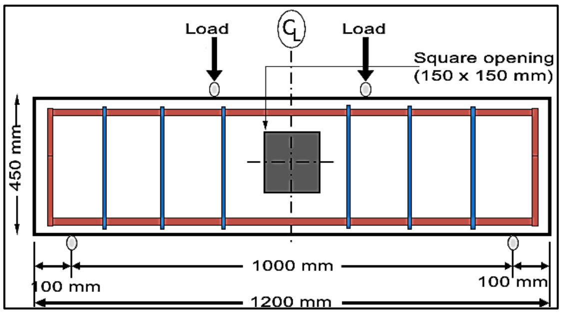


Fig. 4. Deep beam with square opening at mid span, designated as SQM

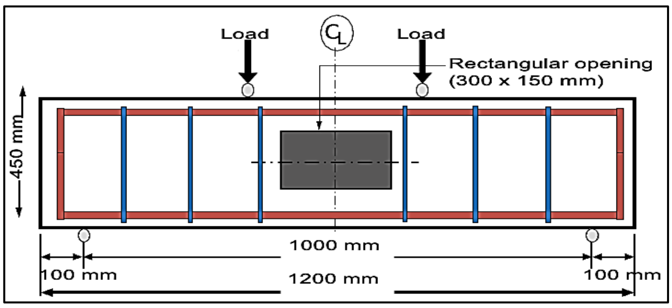


Fig. 5. Deep beam with rectangular opening at mid span, designated as RM

3. Results
3.1 Compressive and Flexural Strength

The results obtained for this study are presented as follows. The slump test was carried out on the fresh concrete incorporating steel fibers with volume fraction of 0%, 1% and 2%. All the concrete mixes passed the designed slum ranged between 10 to 20 mm with the lowest workability observed from steel fiber concrete with 2% volume fraction as can be seen in Table 3.

Table 3
Slump test results for steel fiber concrete

Fibers content, Vf (%)	Slump (mm)
0	20
1	22
2	17

The results of the compressive strength of the cubes carried on 7th and 28th days age of the hardened concrete is illustrated in Figure 6. It was noteworthy that all the concrete mixtures achieved more than the target compressive strength 25 MPa. It can be seen that as the amount of steel fiber content increased, the compressive strength increases as well. The 0% steel fiber concrete is taken as the control mixture and achieved 32.12 MPa on the 28th day of testing. However, inclusion of steel fibre by 1% and 2% improved the compressive strength of the concrete by 7% and 36%, respectively. The increased of the concrete compressive strength is due to the presence of the steel fiber making is harder for the crack to propagate during test, thus requiring higher strength.

The flexural strength of the steel fiber concrete also follows similar trend as can be seen in Figure 7. As the amount of steel fiber increased, the flexural strength increased as well and the highest is observed in 2% steel fiber concrete. This due to the presence of the steel fibers bridging the cracking of the concrete resulting in higher strength was required to produce larger cracking and pulling out the steel fiber from the concrete matrix.

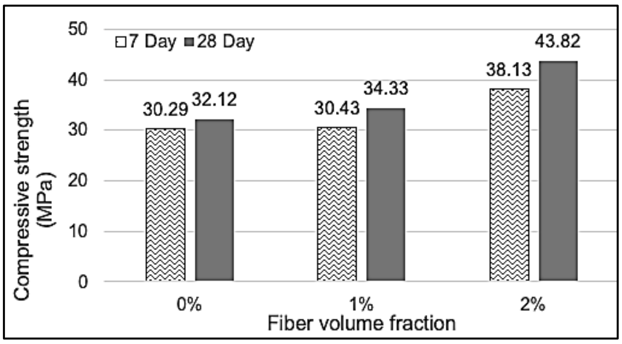


Fig. 6. Compressive strength of steel fiber concrete at 7th and 28th day

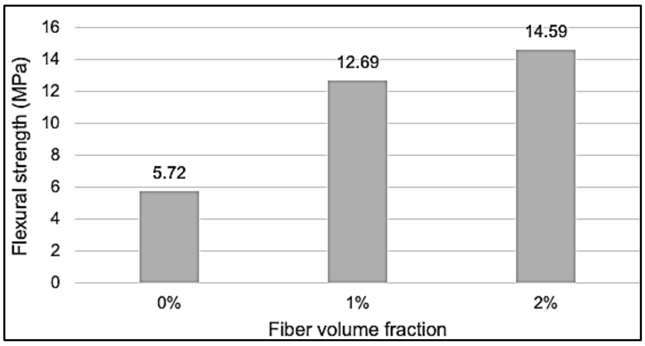


Fig. 7. Flexural strength of steel fiber concrete at the 28th day

To support the results shown in Figure 7, the behaviour of steel fiber concrete prisms at failure is given in Figures 8, 9 and 10. For the figures, it is observed that the prism with 0% steel fiber broke in two pieces at failure, whereas the prisms with steel fibers were still intact and developed excessive cracking prior to failure. This is due to the bond of steel fibers holding on the concrete producing higher strength and ductility. As the steel fibers shape used was hooked end, higher strength is required to pull-out the fibers while loading and cracking. Moreover, as the fibers were randomly distributed inside the concrete prism, the effectiveness of the steel fiber increased ensuring intact concrete upon failure.

Fig. 8. Failure mode of prism with 0% of steel fiber concrete

Fig. 9. Failure mode of prism with 1% of steel fiber concrete

Fig. 10. Failure mode of prism with 2% of steel fiber concrete

3.2 RC Deep Beam without Steel Fiber

This section discusses the behavior of reinforced concrete deep beam with and without opening with 0% steel fiber inclusion. Figure 11 shows the load deflection curves of reinforced concrete deep beam with and without opening. All the crucial data extracted from the curves are summarized in Table 4. SQM represents the square opening at the mid-span, whereas RM is the rectangular opening at the mid-span. Py is the load at which the longitudinal reinforcement yields in tension and its corresponding deflection δy, Pmax were representing the maximum load carrying capacity and at its deflection δmax, whilst Pu is the ultimate load at failure and its deflection δu. This ultimate load at failure is taken to be at least 80% of the maximum load carrying capacity as recommended by design codes. The ductility ratio, μ of the beam is taken by dividing the ultimate deflection (δu) by deflection at yield (δy).

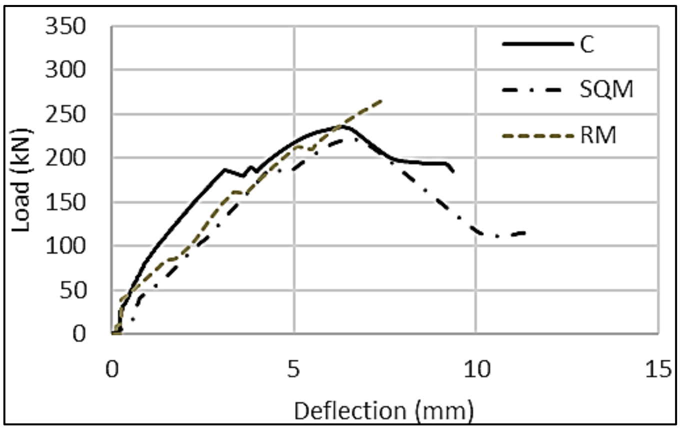


Fig. 11. Load versus deflection curves for deep beams with and without opening (no fiber)

Table 4
Strength and ductility details of deep beams with and without opening (no fibre)

Specimen	Vf (%)	Py (kN)	δy (mm)	Pu (kN)	δu (mm)	Pmax (kN)	δmax (mm)	μ =δu / δy
C	0	114.05	1.52	198.30	7.72	234.59	6.32	5.08
SQM	0	92.39	2.12	210.86	7.17	221.29	6.56	3.38
RM	0	85.62	1.69	268.11	7.57	268.11	7.57	4.48

From Figure 11 and Table 2, the presence of the web opening at the mid-span of the deep beam affects the strength and ductility of the structure. The load at yield (Py) decreases by 19% (SQM) and 25% (RM), and the ductility ratio for deep beams with opening were at less up to 34% in comparison with the deep beam without opening (C). The load at first crack for the reinforced concrete deep beam without web opening (C), was recorded at 158 kN, and for the deep beam with square (SQM) and rectangular (RM) opening, it was observed at 126kN and 99 kN, respectively. For the C beam, the cracking initiated at the mid-span of the beam and some cracking were also developed at the shear region near the support. As the loading was continuously applied, the C beam ended up in bending-shear failure as shown in Figure 12.

At load level 126 kN, the first crack on the SQM beam appeared as angled cracks close to the left support. After that, the cracks spread to the mid-depth of the deep beam and separated it into two sections, roughly in a straight line above a point of support, with one side extending vertically upward (see Figure 13). Excessive cracking at the support point, additional crack widening, and the formation of flexural cracks beneath the square opening region were the causes of the failure. Similar trend was observed for RM beam with the initiation of cracks begin near the left support. The cracking continues to propagate vertically, then inclined towards the loading applied points. Figure 14 illustrates the size and propagation of the vertical and shear cracks on top of the supports. The beam failed in shear due to the excessive cracking developed at the left support region.

Fig. 12. Crack pattern of control beam without opening (no fiber)

Fig. 13. Crack pattern of control beam with square opening at mid span (no fiber)

Fig. 14. Crack pattern of control beam with rectangular opening at mid span (no fiber)

3.3 Steel Fiber RC Deep Beam with Square Opening

The load versus deflection curves for steel fibre reinforced concrete deep beam with square opening at mid-span is shown in Figure 15. The details of the loading and its respective deflection taken from Figure 15 is tabulated in Table 5. From the figure, incorporation of the steel fiber enhances the strength and ductility of the deep beams with opening significantly. The increase of the load at yield (Py) and maximum load carrying capacity (Pmax) for SQSF1 beam was 84% and 99%, respectively, higher than the C beam. Furthermore, the ductility ratio for SQSF1 (6.56) and SQSF2 (6.13) beams were both higher than C (5.08) beam showing that inclusion of fibers at appropriate amount can improve the ductility of the beam.

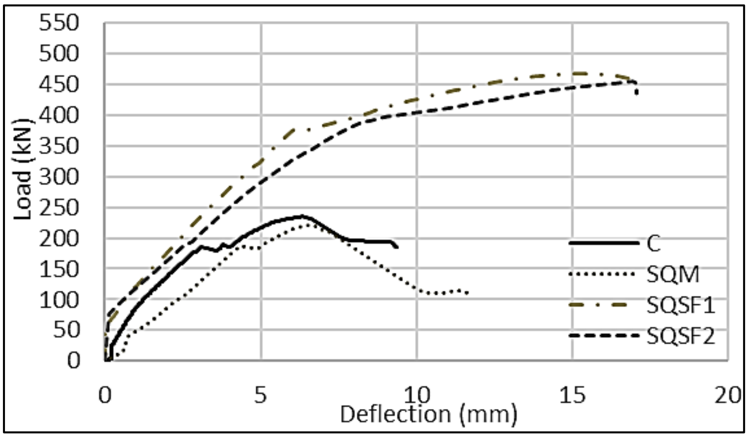


Fig. 15. Load versus deflection curves for steel fiber reinforced concrete deep beams with square opening at mid span

Table 5
Strength and ductility details of steel fiber reinforced concrete deep beams with square opening

Specimen	Vf (%)	Py (kN)	δy (mm)	Pu (kN)	δu (mm)	Pmax (kN)	δmax (mm)	μ =δu/ δy
C	0	114.05	1.52	198.30	7.72	234.59	6.32	5.08
SQM	0	92.39	2.12	210.86	7.17	221.29	6.56	3.38
SQSF1	1	209.56	2.58	457.33	16.92	466.93	15.29	6.56
SQSF2	2	193.87	2.78	443.92	17.05	453.92	16.94	6.13

The first visible crack on SQSF1 beam appeared at the corner of the square opening at the mid-span of the beam at the load level of 196 kN. As the loading increase, more diagonal cracks developed at the bottom of the beam region. The beams failure in a more ductile manner compared to the beam without opening (C beam) and without fiber (SQM beam). Figure 16 shows the cracking pattern of the SQSF1 beam at failure. For SDSF2 beam, the load at first crack was recorded at 189 kN with cracking initiated mid span of the beam. The cracking concentrated and propagated diagonally towards the square opening which ended up in flexure failure as seen in Figure 17. It was also noticeable that there were less cracking near the region of the square opening with the inclusion of the steel fiber showing the effectiveness of the fibers to compensate for the loss in shear due to the opening.

Fig. 16. Cracking pattern for SQSF1 beam

Fig. 17. Cracking pattern for SQSF2 beam

3.4 Steel Fiber RC Deep Beam with Rectangular Opening

Figure 18 shows the load versus deflection curves for steel fiber reinforced concrete deep beam with rectangular opening at mid-span. All the crucial data extracted from the curves is tabulated in Table 6. Similar trends were observed for the case of steel fiber reinforced concrete dep beam with rectangular opening. Addition of steel fiber enhances the strength and ductility of the deep beam with opening. Moreover, the results show that the strength of the steel fiber reinforced concrete beam were better when compared to the control beam with no opening (C). Load at yield (Py) for RSF1 was observed at 125.51 kN which about 10% and 47% higher than deep beam with no opening (C) and rectangular opening and no fiber (RM), respectively. Increasing the steel fiber from 1% to 2% increases the Py to 142.36 kN.

However, a significant increase was observed from the load carrying capacity which was 71% (for RSF1 beam) and 100% (for RSF2 beam) higher than the C beam. The ductility ratio for RSF1 beam and RSF2 beam were also improved up to 30% and 84%, respectively, compared to C beam. Clearly, inclusion of steel fiber improved and compensate the loss due to the rectangular opening at the mid-span of the beam. Furthermore, the steel fiber was well distributed during mixing and casting, exhibiting good crack bridging and pull-out behavior.

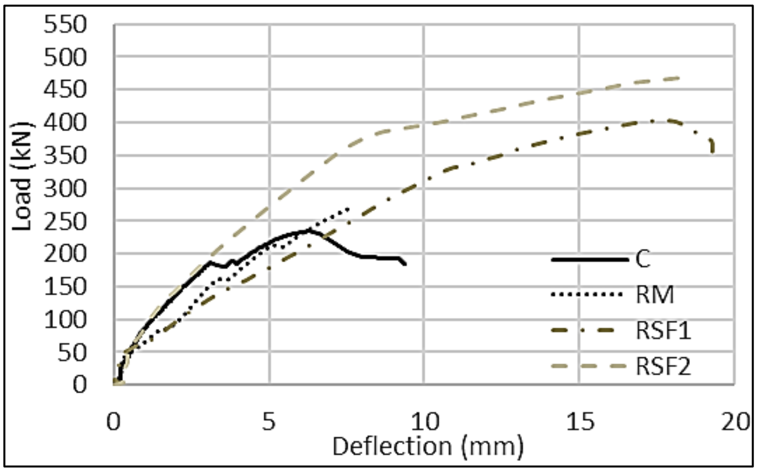


Fig. 18. Load versus deflection curves for steel fiber reinforced concrete deep beams with rectangular opening at mid span

Table 6
Strength and ductility details of steel fiber reinforced concrete deep beams with rectangular opening

Specimen	Vf (%)	Py (kN)	δy (mm)	Pu (kN)	δu (mm)	Pmax (kN)	δmax (mm)	μ =δu/ δy
C	0	114.05	1.52	198.30	7.72	234.59	6.32	5.08
RM	0	85.62	1.69	268.11	7.57	268.11	7.57	4.48
RSF1	1	125.51	2.91	350.27	19.28	402.19	17.77	6.62
RSF2	2	142.35	1.96	454.13	18.33	468.33	18.22	9.35

At 1% volume fraction, RSF1 beam visible cracking was initiated below the rectangular opening at 149 kN load level. Then, the crack developed at the near the support of the beam. The diagonal cracking under the rectangular opening and near the supports continue to propagate towards the loading point region. The beam then failed in bending-shear failure as can be seen in Figure 19. In term of RSF2 beam, the first crack appeared in at the mid span of the below the rectangular opening. The load at first crack was significantly higher than the rest of the beam, which was 206 kN. This is due to the amount of steel fiber presence inside the beam and the effectiveness of fiber bridging causing higher loading was required to pull-out the fiber and allowing for the crack opening. The cracking focused on the lower-mid span region of the beam and with the increasing of the fiber content from 1% to 2%, the failure mode now changed to bending failure. Figure 20 shows the cracking pattern observed in RSF2 beam.

Fig. 19. Cracking pattern for RSF1 beam

Fig. 20. Cracking pattern for RSF2 beam

4. Conclusions

Based on the experimental results presented, the following conclusions has been drawn with regards to the structural performance of reinforced concrete deep beams with web openings. The shape and size of the opening play a crucial role in determining the beam's behavior, while the addition of steel fibers significantly improves both the ultimate load-carrying capacity and crack resistance. Steel fiber reinforced concrete exhibits superior compressive and flexural strength compared to normal concrete, thanks to the fibers' bridging effect and pull-out behavior. By incorporating just 1% steel fiber by volume, the load at which the first crack appears in a deep beam with a web opening can be increased by a minimum of 50%. Moreover, when an optimal amount of 2% steel fiber is used, the failure mode of a reinforced concrete deep beam with a central web opening can be transformed from brittle shear failure to a more ductile bending failure, resulting in enhanced load-carrying capacity and ductility. The study also revealed that deep beams with square openings reinforced with steel fibers perform better than those with rectangular openings, indicating that larger openings pose a greater risk to the structural integrity of the beam.

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