Behaviour of RC Beams with Strengthened Web Openings under Vertical Loads

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Abstract. This study aims to investigate experimentally the behavior of self-compacting reinforced concrete beams with in-plane loaded openings strengthened with different techniques in the opening zone. The experimental program consists of testing five specimens with a rectangular opening at the midspan, one of the beams serves as a control beam (without strengthening), and four beams are strengthened at the opening zone with several methods including steel fibers, semi-rhombus crossed bars, jacketing with steel plates, and utilizing the composite section technique. The response has been discussed in terms of the first cracking load, ultimate load, maximum deflection, failure modes, loading history, crack patterns, toughness value, ductility index, and crack width to recognize the best strengthening proposal opening. Test results indicate that the technique of strengthening the WT-rolled steel recorded an increase in the ultimate load capacity, toughness, and ductility of about 21%, 91%, 44%, respectively, relative to the control beam. However, the beam strengthened by steel fiber reinforced concrete around the opening yielded an increase in the cracking and the load-carrying capacity of about 33.3%, 10.95%, respectively. Concerning the specimen strengthened by the crossed steel bar making a semi-rhombus shape around the opening yields a slight enhancement in the loading capacity of about 8.5%. Furthermore, strengthening the opening with steel plates increases the beam's load-carrying capacity by about 11.23% compared to the control beam.

Keyword. Self-Compacting concrete, Web opening with vertical load, Steel plates jacketing, Composite section.

1. Introduction
It is necessary to pass service pipes, ducts of cooling and heating systems through transverse openings in the floor beams as they play a vital role in high-rise buildings because the floor height in most cases is limited. An opening in the beam's web may lead to several disadvantages, including reducing the beam's strength and stiffness, excessive cracking, and deflection due to a high-stress concentration at the corners of the opening. To overcome the above problems, the openings must be strengthened. Such openings may be circular, square, or rectangular. The rectangular opening is the most critical because of the sharp angles that may result in the rapid initiation of cracks. Several types of research classified the openings as a small opening if the ratio of the depth (or diameter) of the opening to the overall depth of the beam is less than 40% [1]. Others classified the circular opening as large when its diameter exceeds 0.25 times the beam web depth [2]. Another classification of openings depends on the range of effect on the overall response of the beam. It is then termed as a small opening when it has no significant effect on the original behavior of the beam [3]. Among the studies that have
considered the effect of opening on RC beams' response was achieved by Abdel Hafez, 2009 [4] when the behavior of reinforced high strength concrete beams with rectangular web openings has been studied. Results showed that the increasing opening length from (0.27 to 0.53) times shear span length reduced the cracking and ultimate loads by (40 and 22.3%), respectively. Amiri and Masoudnia, 2011[5] concluded through a finite element study on the influence of the circular opening size on RC beams' behavior that circular opening with a diameter less than (48%) depth of beam did not influence the ultimate load. In contrast, a reduction in (26%) capacity was observed when the diameter exceeded this limit. Al-Sheikh, 2014[6] investigated the effect of size and shape of openings without strengthening the opening at different locations. Results showed that introducing small and large openings at the flexure zone reduced the load capacity by (1.5 and 10%), respectively. While reductions by (2.5 and 64%) when such openings have been located at the shear zone. Aziz, 2016 [7] tested experimentally and analytically the behavior of RC beams containing circular openings. Reductions in the ultimate shear strength by (12, 22, and 41%) have been obtained for specimens with an opening at a distance (L/2, L/3, and L/6) from the edge, respectively. Latha and Kumar, 2017[8] investigated analytically by FEM the behavior of RC specimens with a circular opening. It was concluded that the opening of a diameter less than 0.44 of the depth of beam (D) had no significant effect on behavior. In comparison, the load capacity decreased by (34.29%) when the circular opening of diameter is more than 0.44D. Pillai and Johny, 2018 [9] investigated the behavior of RC beams with different shape openings by utilizing FEM. Reductions in shear strength by (17%) in circular opening and (19.21%) in square and rectangular, respectively were observed. Regarding the strengthening of web openings in RC beams, Studies can be divided into two groups. The first one contains the strengthening of web openings in RC beams before the casting, such as the study of Suresh and Prabhavathy, 2014[10]. They investigated RC beams' response experimentally when using steel fibers and steel plates to upgrade the opening region. It was reported that the strengthening with steel fibers increased the load capacity by (5 to 30%) and that using steel fiber with steel plates (4mm) thickness increased the load capacity by (50 to 110%). Shakir, 2016[11] conducted an analytical study using (FEM) to investigate the performance of high strength RC beams containing large openings when using jacketing of openings with steel plates and increasing top and bottom steel ratios. Test results indicated that adopting high top and bottom steel ratios (8 %) improved the load capacity by 59%. Also, utilizing partial and full jacketing strengthening of the opening improved the load capacity by 10 and 29% when using a 3 mm thickness of the steel plate and by (22 and 44%) for a thickness (5 mm) of steel plate.

The second group contains the studies of strengthening of web openings in RC beams after casting of the specimens, such as the study of Allam, 2005[3]. The efficacy of strengthening large openings in the shear region using CFRP and steel plates has been investigated. Results indicated that the steel plates had more efficiency than the CFRP sheets, with improvements in the two methods' capacity by 52 and 14%, respectively. Chin et al., 2011 [12] investigated the strengthening of RC beams with a large square and circular opening by (CFRP) laminates. Results showed that the flexure region's square opening reduced the specimen capacity and stiffness by about 48, 19%, respectively. The strengthening by CFRP restored the load capacity by 70% and 10% for circular and square opening. El-Maaddawy and El-Ariss, 2012 [13] investigated RC specimens' shear behavior containing openings and strengthened in shear with CFRP composites. Results revealed that the openings reduced the shear resistance by (72%). Fawzy, 2015 [14] investigated RC-beams' strengthening containing rectangular opening by externally epoxy-bonded steel strips plate and FRP sheets. Results showed that the continuous steel plate around the opening was more efficient than strips FRP. RC beams' ultimate capacity with opening improved when using the technique near-surface mounted for continuous steel plates. Soman and Manju, 2017[15] investigated experimentally strengthening RC beams with single circular openings by externally bonded FRP sheets. It has been concluded that the ultimate load increased for the specimens strengthened with BFRP and CFRP sheets by (13.26, 15.30%), respectively if all openings were circular. Morsya and Barima, 2019[16] studied the effect of openings on RC beams' behavior when different strengthening techniques are used. The results revealed that the use of externally bonded CFRP improved both ductility and the beam's strength. The NSM technique mounted in the flexure region could also enhance the beam's ductility by 33% with respect to the
control beam and by about 78% compared to the non-strengthened beam with an opening. Ahmed and Gerges, 2020[17] investigated analytically using FEM the behavior of RC beams with rectangular openings strengthened with CFRP laminates. It was reported that the improving compressive strength of concrete from (25 to 45) MPa led to increased shear strength by about (23%). Previous researchers focused on the beams with unloaded or lightly loaded openings. There are cases in which openings are loaded with heavily concentrated forces and the beam having dapped ends, as shown in Figure 1. In this case and others, it must support the beams by transverse larger girders to form a grid system. Two methods can achieve this. The first one is to make the girders as inverted tee beams, as shown in Figure 2a. This arrangement may result in severe stress concentration within the nib end. Thus, it is needed to analyze this D-region using the STM (Strut-and-tie) method and be designed against shear and tension forces. The second method is based on introducing opening in the girders within zones and levels that affect the performance as low as possible, as shown in Figure 2b. Therefore, the present study investigates experimentally the effect of the inclusion of heavily loaded openings on the behavior of a beam without dapped ends. The case of a beam with dapped ends will be studied in the next work. Several proposals have been adopted, including steel fibers, semi- rhombus crossed arrangement, and steel plates. In addition to utilizing the composite section technique within the bottom chord of the opening using the WT rolled steel.

![Figure 1. Reinforced concrete dapped end girder with notches.](image1)

(a) Inverted tee beam with concentrated forces at bottom flange. (b) beam with openings included vertical loads.

![Figure 2. Proposals to support transverse beam on a girder.](image2)

2. Experimental program

2.1. Materials properties

The self-compacting concrete mix (SCC) has been used to cast all experimental work specimens, with cube compressive strength (56 MPa). However, for the FIB specimen, a steel fiber reinforced self-compacting concrete (SFRSCC) mix with (1.0%) steel fibers and compressive strength of (61 MPa) has been used in the opening region. The constituent materials are composed of sulfate resisting cement type (V) conformed to the Iraqi specifications (No.5/1984)[18]. Natural sand with a maximum size of 4.75 mm. Coarse aggregate with a maximum size of 20 mm. However, for the SFRC mix, a maximum size of 14 mm has been used. Both coarse and fine aggregate are tested to confirm the requirements of IQS (No.45/1984) [19]. Clean tap water is used for casting and curing. Limestone powder is used to improve the segregation resistance and increase the amount of powder (cement +
filler). The particle size of the limestone powder conformed to the requirements of EFNARC [20]. Epsilon HP 580 is utilized as a superplasticizer to produce concrete with low water content and high workability (ASTM-C494/C494M-13) [21]. Three steel reinforcement sizes are used; bars of diameters 16 mm and 12 mm are used as the main rebar at the longitudinal and stirrup reinforcement in the opening zone, respectively. Also, bars of diameter 10 mm are used as stirrups. Table 1 shows steel bars’ properties and accorded with (ASTM A615-4) [22] specifications. Steel plates utilized as strengthening materials in the PLT specimen have a thickness of 2.85 mm and tensile strength of 586 MPa. The WT-rolled steel used in the TEE specimen is utilized as strengthening materials with (90*82.35) mm total depth and width of flange, respectively, with the tensile strength of 333 MPa. Both steel plates and WT-section are placed before concreting of the beam and accorded with (ASTM E8/E8M – 16a) [23] specifications. Micro steel fibers with a length of 13 mm, a diameter of 0.2 mm, and an aspect ratio of 65 are used in the FIB specimen. It is complying with the requirements of (ASTM A 820/A 820M–06) [24]. Table 2 lists the constituent materials of the SCC and SFRSCC adopted in the present study.

| Table 1. Steel bars properties.  |
|---------------------------------|
| Bar dia.(mm) | Φ 10 | Φ 12 | Φ 16 |
| Yield stress (MPa) | 576 | 590 | 600 |
| Ultimate strength (MPa) | 674 | 684.3 | 693.4 |

| Table 2. Details of concrete mixes.  |
|-----------------------------------|
| Constituents materials (per 1 m³) | (SCC) | (SFRSCC) |
| Cement (kg) | 400 | 400 |
| Fine Aggregate(kg) | 962 | 962 |
| Course Aggregate(kg) | 780 * | 780 ** |
| Limestone Powder(kg) | 75 | 75 |
| Water (kg) | 125 | 125 |
| Water/ Cement Ratio | 0.315 | 0.315 |
| Super plasticizer (L) | 6 | 6.8 |
| Steel fiber ratio | - | 1% |

* max. size is 20mm; **max. size is 14mm.

2.2. Description of specimens

Five simply supported RC beams with a rectangular opening, one control specimen, and others are strengthened with different proposals and tested under one point load adopting. The total span of a typical specimen is (1700 mm), with a c/c span of (1500 mm) and the cross-section (450mm) and (170 mm) width. The scheme of loading, dimensions, and reinforcement are shown in Figure 3. The scheme of strengthening proposals for the opening region is shown in Figure 4. Moreover, the designations of the tested beams are shown in Table 3.

| Table 3. Description of the specimens.  |
|---------------------------------------|
| Beams Symbol | Types of strengthening at opening zone |
| CONT | Control. |
| FIB | Steel Fiber. |
| SCR | Semi- Rhombus Crossed bars. |
| PLT | Steel Plates. |
| TEE | A composite bottom chord with WT-Rolled Steel. |
(a) Scheme of loading and dimensions of typical beams.

(b) Scheme of Reinforcement of the control beam.

**Figure 3.** Scheme of loading and reinforcement of the control beam.

**Figure 4.** Strengthening proposals for the opening region.
2.3. Test measurement and instrumentation
The specimens are tested in the structural test laboratory of the Faculty of Engineering at the University of Kufa by using a 2000 kN calibrated electrohydraulic testing machine (PHILIPP HOLZMANN), as shown in Figure 5.

![Image](image.jpg)

Figure 5. The universal machine utilized in testing.

3. Results and discussion

3.1. Crack patterns

3.1.1. Control specimen (CONT). Figure (6-a) shows the history for crack propagation of the reference beam CONT. It can be seen that the first crack occurred nearly mid-span as a flexural crack within a load level of (60 kN). With additional loading, the cracks shifted away from the center and diagonally propagated towards the bottom corners of the opening, transferring the behavior to deep beams. With increasing load, the cracks tend to change the angle of inclination from being diagonally oriented at lower parts of the beam to be horizontally at the upper corner level, revealing that the opening zone at this level being under direct tension. At a load of (365 kN), the beam failed by diagonal cracks on the sides of opening corners, causing a diagonal shear mode failure.

3.1.2. FIB specimen. Figure (6-b) shows the map of crack propagation of the specimen at failure. The first observed crack occurred at a load of 80 kN at the bottom of the beam as a flexural crack. Therefore, the steel fiber produced considerable improvement in cracking load of about 33.3 % compared with specimen without steel fibers. Comparing with the CONT specimen, it can be seen that more diagonal cracks developed away from the opening zone towards the support. The addition of steel fibers improved the capacity of transmitting the stresses. Hence, assisted in preventing the localization of stresses and then improved the strengthening of the beam. Almost the presence of steel fibers contributed to delay the propagation of cracks in the top corners of the opening and increase the ultimate load capacity by about 10.96 %.

3.1.3. SRC specimen. Figure (6-c) illustrates the crack patterns of the SRC specimen at the failure. It can be seen that the first crack was initiated at approximately the same load as in the control specimen of 63 kN at nearly the center of the middle zone as a flexural crack. Comparing the SRC specimen's crack patterns with that of the control specimen, it can be observed that few cracks formed at both sides close to the opening. This may be attributed to the inclined legs of the additional steel arrested
initiation of more cracks, then reducing the number of cracks and controlling the propagation rate. It can be noticed that the cross-section led to a slight enhancement of the ultimate load capacity by 8.5%.

3.1.4. PLT specimen. The crack patterns for the PLT specimen is shown in Figure (6d). It can be noticed that the first flexural crack occurred within a load level of 70 kN with an increment of about (16.7%) compared to the control specimen. With additional loading, the cracking shifted away from the opening zone and diagonally propagated towards the bottom corners of the opening; meanwhile, it showed good enhancement in the diagonal cracking load by about 15.38% compared with the control beam. Compared to the CONT specimen, it can be observed that the cracks propagated through the opening zone with less intensity of cracks. This may be attributable to the steel plates contributing to increasing the strength of the opening zone and affecting the migration rate of cracks to the distant parts of the load application. It can be observed that the steel plates led to an increase in the load-carrying capacity by 11.23%.

3.1.5. TEE specimen. Figure (6e) illustrates the crack patterns of the TEE specimen at failure. The first flexural crack was initiated at a (75 kN) load level (25%) more than the control. With progress in loading, the diagonal crack developed at a load level of (80 kN) at the bottom corners of the opening. Compared to the CONT specimen, it can be obviously seen that cracking propagated around the opening zone and shifted up instead of being shifted to the opening's sides. This may be attributed to how the WT-rolled steel improved deflection resistance and strength of the bottom chord considerably. Thus, more resistance is provided, and more strength of the concrete of the compression zone exhausted up to crushing. The Number of cracks increases up to a load level that some slippage occurred. Consequently, a wide horizontal crack at the beam's mid-depth to separate the composite and non-composite parts are produced from each other. Thus, it is expected that making the stirrups to be perpendicular with the crack orientation may improve the behavior. It can be observed that the WT-section contributed to an increase in a load of capacity by 21.37%.

Table 4 shows the opening dimensions, the compressive strength, cracking load, the ultimate load, modes of failure, and maximum deflection at ultimate stages for the tested specimens.

| Specimen | Opening dimensions (cm) | Compressive strength (MPa) | Flexural Cracking Load (kN) | Ultimate Load Pu (kN) | Max. Deflection (mm) | Failure Mode |
|----------|------------------------|---------------------------|-----------------------------|-----------------------|---------------------|--------------|
| CONT     | 15x13                  | 56                        | 60                          | 365                   | 5.04                | Diagonal shear failure at the corner of opening. |
| FIB      | 15x13                  | 56 – 61$°                | 80                          | 405                   | 5.7                 | Diagonal shear failure at the corner of the opening. |
| SRC      | 15x13                  | 56                        | 63                          | 396                   | 5.54                | Diagonal shear failure at the corner of the opening. |
| PLT      | 15x13                  | 56                        | 70                          | 406                   | 5.64                | Diagonal shear failure at the corner of the opening. |
| TEE      | 15x13                  | 56                        | 75                          | 443                   | 6.9                 | Diagonal shear failure at the bottom chord with the full crushing of the top chord. |

$° The compressive strength of steel fiber reinforced concrete in the opening region.
Figure 6. Crack patterns for the tested beams.
3.2. Load mid-span deflection

Figure 7 shows the load mid-span deflection curves of the tested beams. Comparing the deflection for beams SRC and CONT. It can be seen that the specimens yielded corresponding in their behaviors until approximately 50% of the failure load for SRC. After that, the beam SRC shows a slight increase in the load capacity until failure at load 396 kN. Slight enhancement in the ultimate load capacity by about (8.5%) and increased deflection by about (9.27%) have been noticed. This may be referred to as the cross section reinforcement does not significantly affect the strength of the beam. For the FIB and CONT specimens, it can be noticed that using steel fiber reinforced concrete in the opening region results in increasing the failure load capacity of the beam by about (10.96%) and maximum deflection by (13.1%). This is attributed to steel fiber delayed the formation of the cracks at corners and contributed to transferring the stresses induced at the opening zone such that more concrete areas contributed to resisting the applied loads and restrained the early failure. Consequently, less the concentration of the stresses at corners. For the PLT and CONT specimens, it can be seen that the behavior of the PLT beam exhibited greater loads and deflections about (11.23,12.9%), respectively, in comparison with the control beam. It can be concluded that the steel plates enhanced the performance of the opening region. For the TEE and CONT specimens, it can be seen a noticeable difference can be seen between the specimens over all the stage of loading, which may be attributed to the composite section can significantly increase the beam stiffness at the opening compared to the CONT specimen. Furthermore, it can be seen that the composite section did effectively upgraded the behavior of the beam TEE compared to the control beam and yielded more enhancement in the ultimate load capacity of about (21.37%) and an increase in the deflection by (36.9%). Thus, from Figure 7, it can be concluded that the composite section and the steel plates strengthening techniques are more efficient than using the steel fiber and the steel bar as rhombus shape strengthening techniques in increasing the beam stiffness.

3.3. Ductility ratio

The ductility is defined as the ability to resist inelastic deformation without reducing ultimate load until failure [25],[26]. Several approaches have been suggested when the level at which steel yields is not known. In the present work, Δy is assumed to be the displacement from an equivalent elastoplastic system with reduced stiffness by the secant at 75% of the ultimate lateral load (Pu)[25]. The ductility ratio can be estimated by using equation 1.

\[ \mu \Delta = \frac{\Delta u}{\Delta y} \] (1)

Where: \( \mu \Delta \): ductility index, \( \Delta u \): deflection at ultimate load, and \( \Delta y \): that represent the deflection corresponding to load level (0.75Pu), as shown in Figure 8. Table (5) shows the ductility ratio for the
specimens tested in the present work. It can be seen that the useful (effective) ductility increases with strengthening the opening region with respect to the control beam. Furthermore, it can be observed that the ductility for the FIB specimen is slightly higher than the CONT specimen by about 5.83%. This is attributed to the steel fiber reinforced concrete utilized in the opening zone. It can also be seen that the semi-rhombus crossed bars are used as a strengthening SRC beam at the opening shows an increase in the ductility of about 2.5% with respect to the control beam. Also, it can be observed that the steel plates yielded enhancement of the ductility for the PLT beam by 21.67% compared to the control beam. The beam strengthened with the composite section shows a significant increase in the ductility by about 44.2% compared to the control beam. The composite section (WT) has been considered a better strengthening proposal for the opening region because the WT-section yielded more deformations before failure.

![Figure 8](image_url)

**Figure 8.** Effective stiffness determination [25].

| Specimen | $\Delta y$ (mm) | $\Delta u$ (mm) | Ductility Ratio ($\Delta u / \Delta y$) |
|----------|-----------------|-----------------|----------------------------------------|
| CONT     | 4.2             | 5.04            | 1.2                                    |
| FIB      | 4.5             | 5.7             | 1.27                                   |
| SRC      | 4.51            | 5.54            | 1.23                                   |
| PLT      | 3.85            | 5.64            | 1.46                                   |
| TEE      | 4               | 6.9             | 1.73                                   |

3.4. Toughness value

Toughness is the ability of a material to absorb energy and plastically deform without fracturing. It is equal to the area under the load-deflection curve [27]. Figure 9 shows the toughness values of the tested beams. Test results show that the conventional reinforcement of the opening region yielded the lowest value of toughness. Also, it can be seen that strengthening the beam with steel fiber concrete mix around the opening improved the toughness by about 28.3% compared to the reference beam. While strengthening the opening with the steel bar as rhombus shape shown in beam SRC shows an enhancement in the toughness about 19.95% compared to the control beam. However, when using the steel plate technique improved the beam's toughness by 32% compared to the control beam. Furthermore, it can be observed that the composite section proposal of the bottom chord of the opening resulted in the highest enhancement in the toughness by about 91% of the control beam. The presence of WT-section as a strengthening at the opening zone yielded more warning before the failure. Therefore, the composite section configuration (TEE) has been considered the better strengthening proposal for the opening region.
3.5. Crack width
Figure 10 shows the history of crack width development for the tested specimens. The crack width is measured for the first crack by crack meter tool for all tested beams and recorded the first crack width development with applying load. In the tested specimens, the first crack is starting in the nearly mid-span of the beam. It can be seen that the rate of development of cracks for the control beam is more than the other strengthened beams because of lack of resistance for cracking and lack in transferring of stresses throughout the concrete block. Moreover, it can be observed that the development of crack for the FIB specimen is lower than the other specimens due to the restraining effect of the steel fiber against the widening of cracks and efficient transfer of the tensile stresses across the induced cracks.

4. Conclusions
Based on the results of the experimental study, the following points were concluded:

1. Strengthening the beams with different techniques exhibited the same failure mode as the control beam except for the strengthening beam with the composite section in the opening region is resulted in the different behavior in the failure compared to the control beam, which accrued by diagonal shear mode failure at the bottom chord with crushing at the compression zone.
2. The strengthening of openings with different proposals improved both the load capacity and general performance of the opening zone. The increment in the load capacity for beams was about (8.5 to 21.37%) compared to the control beam.
3. The ductility of the strengthened specimens has been enhanced in a range of (2.5 to 44.2\%) compared to the specimen with the non-strengthened loaded opening. This enhancement in ductility prevents the brittle type of failure and improves the safety of the structure.

4. Using the steel fibers, crossed bars arrangement, steel plates jacketing, and composite section strengthening resulted in toughness enhancements by (28.3\%, 19.9\%, 32\%, and 91\%), respectively, compared to that of the beam with no strengthened loaded opening.

5. Some cracking width reductions have been observed for the beams with strengthened openings within the service loading stage. However, the specimen with the composite bottom chord yielded more cracking width before failure, referring to some curvature in the steel section beyond the top chord's failure by crushing. Thus, it is expected that smaller crack width may be developed when increasing the concrete volume (bottom chord) at which the rolled steel is embedded.

6. The WT-steel can be considered an adequate technique and a viable solution in strengthening the opening zone; stiffer and safe response for beams with heavily loaded opening could be obtained.

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