Effect of Using High-Strength Concrete and Ultra-High-Performance Concrete Material on Reinforced Concrete Beam with Opening under Flexural Load

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Abstract: Beams with opening are increasingly applied as alternative passages for services, such as electrical, plumbing, and telecoms. However, opening efficacy on the beam behavior under loading has been rarely explored. This study evaluates the effects of a square opening in the solid beam with different sectional sizes on the performance of reinforced concrete (RC) beams under flexural load. Two types of materials for the beam section are considered: high-strength concrete (HSC) and ultra-high-performance concrete (UHPC). The finite element model is developed to simulate simply supported RC beams subjected to flexural load. Four beams are modeled using HSC and UHPC with square openings in different sectional sizes, and nonlinear analysis is conducted by applying incremental load. Furthermore, a parametric investigation is resulted to evaluate the ability of various sizes of opening on the performance of beam under flexural load. Analysis results show that the created web openings in solid beam decrease the capacity of beam. However, solid small opening in beam can resist nearly the similar load of solid beam without any opening. Moreover, the load capacity of UHPC beams with opening is higher than that of HSC beams with opening.

1. Introduction
Reinforced concrete (RC) beams with transverse web opening is a structure member that allows service facilities in buildings to be concealed without being exposed, as shown in Figure 1 this design philosophy enables reduced headroom of structure, thereby leading to an economical and sustainable design. This technique can positively influence stiffness such that deformation and excessive deflection, internal moments, and distribution of force in continuous beams can be reduced under the load.
Yang et al. (2006) and (Farzad Hejazi et al., 2009) investigated the depth and width of openings in beam elements and discovered that the mid-span deflection is unaffected during initial stages of load application [1, 2]. However, the deflection is affected after the initiation of diagonal cracks. The rigidity of the beam component with web opening is unaffected by the strength parameter of concrete, and the shear strength of concrete is considerably reduced in deep beams with open space when compared with solid deep beams. Ahmed et al. (2012) explored RC beams with web openings and investigated the categorization of these kinds of openings, making some rules for opening location, and the structural behavior of Reinforced Concrete beams with web openings [3].

Mohaisen et al. (2012), F. Hejazi et al. (2016) and Abdi et al. (2015) studied the performance of simply supported RC beam with repaired and unrepaired opening around the edges. In this study, the consequence of using the RC beams with edge opening under shear forces was examined [4-6]. The test was conducted under two-point load to determine the deflections to certain limits right before the collapse, and steel plates were used to repair the sample. The beam capacity before and after repairs was determined for shear force resistance. The results showed that repairing is a successful technique for such a case. Mahmoud (2012) discovered the method of strengthening concrete beams with shear zone openings by employing orthotropic carbon fiber-reinforced polymer (CFRP) modeling; the author also observed that using the element for representing CFRP laminates is better than Link10 element in improving the output because of its orthotropic attributes [7]. Moreover, CFRP strengthening system improves the distribution of cracks at the opening region. The obtained load–deflection curves improve significantly as a result of the CFRP strengthening.

Aykacet al. (2013) investigated the performance of regular circular reinforced concrete beams or square web openings under flexural load by experimenting on nine rectangular RC beams until failure [8]. The results indicated that using diagonal reinforcement at the corners of the openings is an effective method for reducing shear failure, and using diagonal reinforcement influences the ductility and flexural rigidity of beam with openings. Saksena and Patel (2013) investigated similar beam with web openings by using five models [9]. The test revealed that, when the opening diameter is high, the ultimate strength is reduced and the cracking pattern and failure mode of beam are affected. Diagonal shear reinforcement is best employed for effective restraint and control of crack width and great performance. Therefore, diagonal reinforcement and stirrups at the top and bottom of the opening are highly recommended. Hafiz et al. (2014) studied about the results of the usage of opening in workability of RC beams without any particular reinforcement in the opening region [10]. The results indicated that there is not any specific effect on the ultimate load capacity when rectangular RC beams were used with the circular openings with a diameter below 44% of its depth, while those with an opening beyond 44% of the depth lower the ultimate capability at least 34.29%. The RC beams with circular opening perform better than equivalent square opening by approximately 9.58% in terms of load capacity. Investigating about the specific outcome of the opening web in RC hollow beam under various loads was down by Jabber et al. (2016). The results showed that the web openings decrease the capacity of beam but do not radically change the characteristics of beam [11]. Furthermore, the
twisting capacity of ultra-high-performance concrete (UHPC) beams makes high-strength concrete (HSC) beams double.

UHPC is an HSC and was developed 90s. UHPC is a matrix that consists of a high volume of cement, fiber, silica fume, water reducers, and very low volume of water. These characteristics make UHPC a specific kind of concrete with unexpected performance according to strength and durability. The production and application of UHPC represent a breakthrough and an up-to-date innovation and technology of the construction industry. The discovery of this technology has enabled designers to implement sophisticated designs, especially in tower buildings, bridges, repair works, and nuclear facilities [12].

Yang et al. (2010) studied the performance of UHPC beams under bending using two approaches; one is that the UHPC was located in one end of the form and make it possible to flow to the other end side, and the other is that the UHPC was situated at mid-span and allowed to flow to both ends of the form. Interestingly, the results showed redistribution of stresses through the appearance of multiple cracks before fiber pull-out [13]. The inclusion of UHPC at the end of the beam yield better result than at mid-span. Yang et al. (2013) studied the behavior of UHPC in torsion beams with various parameters, such as volume fraction of steel fibers, transverse reinforcement ratio, and longitudinal reinforcement ratio [14]. The findings showed that the volume fraction of steel fibers increases with the ultimate torsional strength. In addition, the ultimate torsional strength and torsional stiffness after initial cracking increase with the stirrup ratios, and the ultimate torsional strength increases with the longitudinal rebar ratios. Yoo and Yoon (2015) investigated the practically of UHPC structures which were made various types of steel fibers. The outcomes showed that using steel fibers considerably made the load capability better and more, cracking response, and post-cracking stiffness but lowers ductility properties [15]. Zagon et al. (2016) studied on the shear behavior of steel fiber-reinforced UHPC I-shaped beams with or without web openings, and they observed that all the failures occur through the web openings. The critical shear crack that leads to failure is located in the web opening, and the failure is more ductile than that of the beams without diagonal reinforcement [16].

The abovementioned studies did not fully examined the effect of opening on solid beam using UHPC and HSC materials. Thus, the present research appraises the usage of opening on solid beam with different opening sizes and material types (HSC and UHPC) under flexural load.

2. Methodology

1.1. Beam with opening

RC beams can be categorized according to the sizes and positions of web opening. Web openings are available in trapezoidal, diamond, circular, triangular, rectangular, and irregular shapes. Among them, rectangular and circular openings are mostly used in practice. In many studies, the sizes of openings are categorized into “large” and “small” without explicit clarification. Small openings are usually in square, circular, and nearly square shapes. Ahmed (2012) mentioned that a openings which are circular and have the diameter more than 0.25 times the depth of the web [3]. The present study investigates beam with rectangular opening using different materials of concrete such as HSC and UHPC. The consequence of different the size of openings section on the capacity of beam is investigated by using finite element (FE) method. Four beams are considered the solid section and beams with different opening sizes, similar to those in Lopes et al. (2009) previous works [17].

1.2. Constructive model

Transverse opening in RC beams is a facility that allows the utility line to pass through the structure. In this study, four beams are modeled: the solid section (S) and solid beams with square openings of 100mm × 100 mm (S100), 200mm × 200 mm (S200), and 300mm × 300 mm (S300) (Table1). The clear span (Lc), depth (d), and width (b) of the beams are 6000, 600, and 600 mm, correspondingly (Figure 2). Concrete damage plasticity for HSC and UHPC materials is considered during modeling, and all factors for damaged plasticity are measured following the experimental test by Jankowiak and
Lodygowski (2005) and by Chen and Graybar (2011) [18,19]. In addition, by using principle stress and strain and yield stress in RC and maximum yield stress can result in analyzing the damage. The yield stress (fy) for reinforcement is 400 MPa. The models are symmetrically loaded by reducing two-point load at constant positions of applied load, and the spacing from the support to the opening center is 500 mm for all models. The finite element model application (ABAQUS) was used in order to model the beams in this study.

**Table 1. Beams Notation**

| Notation | Beam type |
|----------|-----------|
| S        | Solid beam |
| S₁₀₀     | Solid beam with 100mm square opening (16.6%) |
| S₂₀₀     | Solid beam with 200mm square opening (33%) |
| S₃₀₀     | Solid beam with 300mm square opening (50%) |

(a) S model: solid beam.

(c) S₁₀₀ model: (100*100) mm opening section, the square opening with depth equal to 16.6% from the depth of the beam.

(d) S₂₀₀ model: (200*200) mm opening section, the square opening with depth equal to 33% from the depth of the beam.

(e) S₃₀₀ model: (300*300) mm opening section, the square opening with depth equal to 50% from the total depth of the beam.

**Figure 2.** Modelled Beams (a) S, (b) H, (c) H₁₀₀, (d) H₂₀₀ and (e) H₃₀₀ respectively (Jabbar et al. 2016)

All the elements in the analysis are subjected to the same mesh size to ensure that the two materials share the same node; the beam models are meshed with a 100-mm element, as shown in Figure 3.
3. Results and Discussion

2.1. Solid beam with opening under flexural load

The performance of solid beams with opening under flexural load is investigated using the models in which are subjected to symmetric load by using 2-point force load and with a center-to-center space of 1000mm between supports. Loads of 300 and 600 kN are applied on the HSC and UHPC beams, respectively, because of the strength difference between the UHPC and HSC materials. Figure 4 shows the applied loads and boundary conditions at both ends for simply supported beam.

Figure 5 shows the load–deflection curves of the HSC beams. The $S_{100}$ beam differed from the solid beam. The depth of 16.6% in beam with a square opening from the depth of beam ($S_{100}$) with 186kN reacted closely to the solid beam without an opening ($S$). In the meantime, the load capacity was declined in the $S_{200}$ and $S_{300}$ beams. However, the ultimate load capacities for the $S_{200}$ and $S_{300}$ beams were gone.
down to 150 and 129 kN. Therefore, the S_{100} beam decreased the ultimate load by 38\% in comparison to the solid beam without an opening. In S_{200} and S_{300} beams, the decreases in the ultimate load in the HSC members were up to 50\% and 57\%. Thus, the openings in solid beams efficiently abridged the load capacity of beams in flexural loading. All the ultimate load capacity and maximum displacement in the models are shown in table 2.

The area under curve in the load–deflection graph represents the energy absorption of beam; the value increased by 71\% in the S_{100} beam when in comparison to the solid beam (S); the value was also increased by approximately 77\% and 78\% for the S_{200} and S_{300} beams. This outcome shows that the opening can somehow increase the flexibility of beam. In addition, the ductility of beam decreased with the increase in the opening size of S_{200} and S_{300} beams whereas increased in the S_{100} beam.

### Table 2. Load Deflection for HSC.

| Beam | Load (kN) | Incensing % | Displacement (mm) | Energy dissipation | Increasing % | Displacement at 0.85 from load | Ductility |
|------|-----------|-------------|-------------------|-------------------|--------------|-----------------------------|-----------|
| S    | 298       | -           | 188.6             | 51570010          | -            | 23.7984                    | 7.924903  |
| S_{100} | 186    | 38          | 106.9             | 14827089          | 71           | 5.05265                    | 16.82286  |
| S_{200} | 150    | 50          | 97.1              | 11600856          | 77           | 12.306                     | 6.9072    |
| S_{300} | 129    | 57          | 82.6              | 11120303          | 78           | 13.3306                    | 6.376307  |

The load–deflection curves of the UHPC beams under a 600 kN loading are described in [16], the flexibility and strength of solid beams with openings significantly reduced and caused brittle beam section.

The results illustrated that the ultimate loads for the S beam and for the S_{100} beam were 1322 and 1126 kN, respectively. This result indicates an ultimate load reduction of 15\%. The load capacities in S_{200} and S_{300} beam were reduced by 909 and 721 kN, respectively, with reductions of 31\% and 45\%, respectively. This behavior is the result of severe bending of the material at the compression zone. Therefore, to expand the total compressive stress in ultimate load the concrete region must be optimized. Furthermore, the area under curve in all solid section beams with opening increased, thereby indicating that the flexibility in the beam with opening also increased. The ductility of beam decreased with the increase in the opening size. The ductility of beam also decreased with the increase in the opening size of S_{100}, S_{200}, and S_{300} beams because of the reduction in the volume of concrete.

![Figure 5. Load Deflection Curve for HSC.](image)
Table 3. Load Deflection for UHPC.

| Beam | Load (kN) | Increasing% | Displacement (mm) | Area under curve (mm) | Increasing at 0.85 from load | Ductility |
|------|-----------|-------------|-------------------|-----------------------|-----------------------------|-----------|
| S    | 1321      | -           | 181.6             | 66628185              | 20.932                      | 8.675712  |
| S100 | 1126      | 15          | 31                | 14347611              | 78                          | 12.8726   |
| S200 | 909       | 31          | 27                | 10050666              | 85                          | 9.99064   |
| S300 | 721       | 45          | 29                | 8727642               | 87                          | 9.09454   |

Figure 6. Load Deflection Curve for UHPC.

[18] Shows that the UHPC beams with opening have better performance in terms of load capacity in compared with HSC beams with opening.

Table 4 shows the results of comparison between HSC solid beam with opening and UHPC. The ultimate load capacities for S100, S200, and S300 UHPC beams were approximately 1126, 909, and 721 kN, respectively; these beams can accommodate more load than the S100, S200, and S300 HSC beams with capacities of 186, 150, and 129 kN, respectively. The reductions in load capacity were approximately 77%, 83%, 84%, and 82% for S, S100, S200, and S300 HSC beams, respectively.

Figure 7. Comparison between HSC and UHPC Load for Solid Beam with Openings.
Table 4. Comparison between HSC and UHPC in Terms of Carrying Load.

| Beams | Load (kN) | Reduction of load capacity for HSC beams % |
|-------|-----------|------------------------------------------|
|       | HSC       | UHPC                                     |
| S     | 298       | 1321                                     | 77 |
| S100  | 186       | 1126                                     | 83 |
| S200  | 150       | 909                                      | 84 |
| S300  | 129       | 721                                      | 82 |

The proposed FE models successfully model the behavior of un-strengthened and strengthened RC beams with openings. The nonlinear strain and stress distribution in tension is limited to the assumed tensile strength of concrete. The stress distributions for all beams under consideration are studied in failure mode and showed in Figure 8 and 9 for HSC and UHPC. The stress in the beam with opening was improved for the S200 and S300 in HSC and UHPC beam elements. This improvement is due to the low force applied to S200 and S300 beams because of the capacity reduction in the beam with opening. Table 5 shows the maximum principal stress values in all beam models. The stress improvements for S100, S200, and S300 beams were 7.5%, 40%, and 53%, respectively, by comparison the S beam in HSC material; the capacity of S100 beam was greater than that of S200 and S300 beams. Therefore, applying less force because of capacity reduction in opening contributed less to the improvement in principal stress in the web section of the UHPC beams resulting in 19%, 39%, and 59% for S100, S200, and S300, respectively, compared with the S beams. These results are due to the crushing of concrete in the flexural compression zone between the two loading points and around the opening.

Figure 8(a, b, c and d). Stress Distribution for HSC Beams.
Figure 9(a, b, c and d). Stress distribution for UHPC beams

TABLE 5. Stress Distribution for HSC and UHPC Beams under Flexural Load.

| Beams | HSC Max Stress (MPa) | Decreasing % | UHPC Max Stress (MPa) | Decreasing % |
|-------|----------------------|--------------|-----------------------|--------------|
| S     | 20.95                | -            | 100.03                | -            |
| S100  | 19.38                | 7.5          | 80.12                 | 19           |
| S200  | 12.48                | 40           | 60.11                 | 39           |
| S300  | 9.89                 | 53           | 40.64                 | 59           |

Figures 10 and 11 show the strain of beams under loading. The maximum strain occurred in the S200 and S300 beams; however, in the S beam, the maximum strain occurred at the mid-span for HSC beam and tension zone for UHPC beam.
Figure 10: Strain Distribution for HSC Beams

Figure 11: Strain Distribution for UHPC Beams
Table 6 presents the different strains in beams and the optimum values. The opening in the beams reduced the capacity and applied load and substantially improved the maximum strain between 39%, 442%, and 603% for the S100, S200, and S300 HSC beams. The values increased by approximately 80%, 95%, and 90% for UHPC beams compared with the solid beam. It can be concluded the decreased load capacity and beam deformation is consequence of strain reduction in S300 HSC beam.

Table 6. Maximum Strain for HSC and UHPC Beams under Flexural Load

| Beams | Strain (MPa) | Increasing (%) | Strain (MPa) | Increasing (%) |
|-------|--------------|----------------|--------------|----------------|
| S     | 3.63E-04     | -              | 9.41E-03     | -              |
| S100  | 2.21E-04     | 39             | 1.84E-03     | 80             |
| S200  | 1.64E-02     | 442            | 4.57E-04     | 95             |
| S300  | 2.19E-02     | 603            | 9.23E-04     | 90             |

4. Conclusion

In this study, the FE model of HSC and UHPC beams with different opening sizes is developed. The influence of web openings on the performance of HSC and UHPC beams with openings subjected to flexural load is investigated. The RC beam models with square openings are investigated under two-point load. On the basis of the analysis results, the following conclusions are obtained.

1. Flexural loading capability would be declined by the solid beam opening. Square opening beam that its depth is 16.6% from the depth of the beam (S100) performed nearly to the solid beam without an opening (S) for HSC and UHPC materials. Meanwhile, the capacity was decreased in S200 and S300 beams. The ductility reduced by increasing in the opening size because of the reduction in the volume of concrete.

2. The flexural load in the S100 beam decreased by 38% and 15% in S200 and S300 beams in terms of HSC and UHPC ultimate loads, respectively, in comparison to the S beam.

3. The S100 beam showed near stress and strain distribution to the S beam for both materials (HSC and UHPC) in comparison with the S200 and S300 beams because of the reduction in the capacity of these beams.

4. The area under curve in all solid section beams with opening for both materials (HSC and UHPC) increased; therefore, the flexibility in the beam with opening also goes up.

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