Experimental investigation of the structural behaviours of self-compacted reinforced concrete hollow beams with in-place circular openings

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Abstract. This paper aimed to experimentally investigate the structural conduct of self-compacted concrete hollow beams with various in-place openings. For this purpose, ten reinforced concrete hollow beams were tested under two concentrated and symmetrical loadings. The primary parameter in this study was the location of the openings, and specimens were divided into two groups in addition to the control beam: group one included six beams with openings in front or front and rear of the web, while the second group contained three beams with an opening in the bottom flange of the beam. The results showed that all reinforced concrete specimens suffered from higher deflection and stiffness reductions. The load-carrying capacity was decreased in ranges between 5.2% and 16% for group one and 5.5% to 9% for group two compared to the control beam. A reduction was also observed in the ductility index values, ranging from 2.8 to 1.5 compared to the control beam.

Keywords: Self-compacted concrete; Hollow beam; Circular opening; In-place opening; Flexural.

1. Introduction
Box concrete sections are commonly used in beams, especially for bridges with long spans, to reduce dead load and save on the costs of construction materials. Hollow sections in general and open beams, in particular, have been frequently adopted in bridges, buildings, offshore structures, and towers, which helps by providing a conventional passage for mechanical and electrical pipes and/or other utilities. However, the presence of an opening in a structural member such as a beam can reduce its load-carrying capacity, increase its service load deflection, and cause cracks in the building, and these openings transform simple beam behaviours into more complex behaviours [1]. In the design stage, adequate strength and serviceability can be guaranteed by following the methods available in the literature [2-4]. The requirement of structural improvement has led to a focus on increasing reinforcement quantities and using a complex framework, which leads to weak compaction issues, though these can be tackled by utilising self-compacting concrete (SCC). Compared to normally vibrated concrete (NVC), SCC can also enhance productivity and working conditions due to the elimination of compaction [5].

One of the circumstances that necessitate the creation of holes in a newly constructed building derives from contractor requests for drilling to simplify arrangements of pipes that have not been carefully considered during the design stage. Mansur et al. [6] studied the effects of creating circular openings through the webs of nine T-beams. The results indicated early diagonal cracking and significant reductions in strength and stiffness of the beams due to creating an opening near the support region. In 2012, Ali and Hemzah [7] investigated the behaviour of reinforced concrete horizontally curved ring beams with and without openings, and unstrengthened and strengthened (internally with steel reinforcement or externally using CFRP laminates); their experimental work included casting and testing four reinforced concrete curved beams. Various variables were considered in the experimental programme, including the openings present in the beam, internal strengthening using reinforcing steel (stirrups), and external strengthening using CFRP laminates. The specimens were then tested under the action of four-point loading. The test results revealed that the presence of openings had a
tremendous effect on the behaviour and ultimate strength of ring beams, while the strengthening of these openings with internal steel reinforcement or external CFRP laminates increased the ultimate strength and affected post-cracking behaviour and failure modes in all specimens. In 2014, Al-Sheikh [8] performed an experimental study on the behaviour of reinforced concrete beams with various form of opening with various diameters at various places. Twenty-seven beams were cast, including a control beam without an opening; all other beams were provided with an opening. The size effect of openings with various placements was studied in terms of ultimate strength, maximum deflection, and mode of failure. These beams were tested under four-point loading, which showed that the ultimate failure load of the reinforced concrete beam with an opening at the shear span showed the most significant reduction, while at flexural zone, it showed the smallest reduction. Furthermore, the ultimate failure load in beams with rectangular openings was 4% smaller than for beams with square openings, and the ultimate failure load in beams with circular openings was 8% greater than in beams with square openings. In 2019, Abtan and Abdul-Jabbar [8] tested eight reinforced concrete beams in two groups. The first group contained solid beams and two hollow beams with the location of the hollow core in the first beam was in the middle of the beam section while for the second beam the hollow core located at the bottom of the beam section. This group was used to select the optimum hollow core section for the next group. The second group consisted of five beams identical in terms of everything but the positions of their web openings, which were arranged symmetrically, without any special reinforcement around the openings. All RC beams were identical in dimensions, reinforcement, and the type of the concrete and opening size. The results showed a decrease generated due to the hollow-core position at the midsection of 2% and in the bottom section by 14% compared to the solid section. The decrease in the opening provision was about 20.4% as compared to the hollow core beam without an opening in the web, and about 22% compared to the solid beam.

The current research target aimed to experimentally investigate the structural behaviour of self-compacted concrete hollow core beams with circular in-place openings, as well as examining the effect of changing the opening’s location with regard to load-carrying capacity, deflection, failure mode, and ductility.

2. Experimental Set-up

A self-compacted concrete mix (SCC) was designed according to Alyhya et al. and Abo Dhaheer et al. [11–13] that was used for casting beams with various openings as well as the control beam (without an opening). After 28 days’ curing, various circular openings were made using a core machine to simulate the drilling of openings in an existing beam. The experimental programme included casting and testing ten simply supported hollow SCC beam specimens in two groups, in addition to the control beam. Group one contained six beams with a circular opening in the front or in the front and rear of the web in different combinations of the opening location, as shown in Fig 2. The second group had three beams with circular openings in the bottom flange of the beams in different opening locations, as shown in Fig 2. The opening location for all beams was determined to be more than 0.5 of the effective depth of the beam (0.5D) from the supports or concentrated loads and adjacent openings according to Mansur et al. [2]. For symmetry, an identical opening was created on each side of the beams. The location of the opening was the major variable in this research, and thus, dimensions, reinforcement, concrete type, and opening dimensions were kept constant for all tested beams. The hollow segment was created using compressed cork with dimensions (180*180*1,300 mm), and this was installed inside the steel cage using spacers, as shown in Fig 3. The considered openings were circular in shape as these are more likely to be created in an existing beam without affecting the integrity of the surrounding concrete by using a coring machine. The specimens had dimensions of 1,500x300x300 mm length, width, and height, respectively. A space of 100 mm from each end of the beam was left solid to match the state of beams under real conditions. The flexural and shear reinforcement for all beams was designed according to ACI-318 [4], featuring 2Ø10 mm steel bars at the top and 2Ø12 mm bars at the bottom, with shear reinforcement of Ø10@90 mm at the first and last quarter and Ø10@ 110 mm stirrups at the second and third quarters. All beams were tested under two-concentrated loads over a clear span of 1400 mm. Schematic representation photographs of the mould, reinforcement details, and the locations of the openings are shown in Figs 1 to 2.
For easy recognition of any beam description, acronyms are utilised in which letter “C” refers to the control beam, “H” refers to the hollow section, the number (10) refers to the opening diameter and “F” or “R” indicate whether the opening was in the front or in the front and rear. “S” or “M” indicates whether the opening was near the support (shear zone), or in the middle of the beam (flexural zone), respectively. Table 1 shows the details of the tested specimens.

**Table 1.** Details of tested beams

| Group No | Beam Designation | Opening Diameter mm | Number and Location of Openings |
|----------|------------------|---------------------|---------------------------------|
| HC       |                  |                     | Hollow control beam without opening |
| H10SF    |                  |                     | Two openings in the front of the beam only at (250 mm) from the support (shear zone) |
| H10MF    |                  |                     | One opening in the front of the beam only at the middle of the web (flexure zone) |
| Group 1  | H10SMF           | 100                 | Three openings in the front of the beam: two at (250 mm) from the support (shear zone) and the third one at the middle of the web (flexure zone) |
|          | H10SFR           |                     | Two openings in the front and rear of the beam at (250 mm) from the support (shear zone) |
|          | H10MFR           |                     | One opening in the front and rear of beam at the middle |
|          | H10SMFR          |                     | Three openings in the front and rear of beam: two at (250 mm) from the support (shear zone) and the third one at the middle of the web (flexure zone) |
|          | H10SB            |                     | Two symmetric openings at the bottom flange of the beam at (250 mm) from the support |
| Group 2  | H10MB            |                     | One opening at the bottom flange of the beam at the middle |
|          | H10SMB           |                     | Three openings at the bottom flange of the beam: two of them at (250 mm) from the support and the third one in the middle |
**Fig 1.** Reinforcement details for all hollow beams

**Fig 2.** Location of openings for (a) Group 1 and (b) Group 2
2.1 Material Properties
Locally available sulphate resisting Portland cement was used for preparing the SCC for this experimental work as most structures that use SCC touch the ground and could be exposed to sulphate attack. Natural sand with a maximum size of 4.75 mm was utilised as fine aggregate, and crushed black gravel with a maximum size of 19 mm from Al-Nibaey was used. In addition, limestone powder (LP) was used as a filler to produce successful SCC. High range water reducing admixture, based on Polycarboxylates and known commercially as viscocrete-5930, was used as a superplasticizer. Deformed steel bars with nominal diameters of 10 mm for stirrups and 12 mm for main reinforcement were used in the tested model. The testing was carried out according to ASTM A615 (2016). [9]. The yield stresses ($f_y$) were 490 and 516, and ultimate strengths ($f_u$) were 517 and 608 MPa for the 10 mm and 12 mm steel bars, respectively.

2.2 Preparation for SCC
The European Guidelines for producing SCC (EFNARC, 2005) [10] were followed throughout the designing, mixing, and testing of the SCC mixes. In this study, a mix as designed by Alyhya et al. and Abo Dhaheer, et al. [11–13] was used to achieve a target concrete strength of 30 MPa at 28 days. Several trials were carried out in the concrete laboratory of the Civil Engineering Department/Engineering college at the University of Kerbela before the final mix proportion was selected. The amount of material by weight required to produce one cubic meter of concrete is presented in Table 2.

| Parameter          | Weight by kg/m$^3$ | EFNARC Guidelines       |
|--------------------|--------------------|--------------------------|
| Cement             | 380                | 380-600                  |
| Limestone powder   | 160                | ----                     |
| Water              | 190                | 150-210                  |
| Superplasticizer   | 4.5                | ----                     |
| Fine Aggregate     | 800                | (48-55)% of the total aggregate |
| Coarse Aggregate   | 800                | 750-1000                 |
| w/cm               | 0.5                | ----                     |

3. Mechanical Properties of Concrete
The experimental results for the mechanical characteristics of the self-compacted concrete mix (compressive strength, tensile strength) are exhibited in Table 3. The compressive strength tests for cubes ($f_{cu}$) and tensile strength for a standard cylinder were carried out in accordance with BS. 1881-116 (1983) [14], and ASTM C496-11 [15], respectively.

| Property                        | Value (MPa) |
|---------------------------------|-------------|
| *Cube compressive strength ($f_{cu}$) | 32.5        |
| **Cylinder tensile strength ($f_t$) | 3.4         |

*Average of sixteen samples.
**Average of three samples
4. Test Result and Discussion

4.1 General Behaviour of Tested Beams

The recorded data generated for the ten beams provides a basis for assessing the effects of creating circular openings at different locations. In this section, these effects are discussed from the viewpoint of the overall response of the beam, including the failure mode, ultimate load, and deflection. Crack pattern and failure modes are exhibited in Fig. 4 for all tested specimens, while the experimental results for these beams are listed in Table 4. As the hollow control beam was designed to fail in flexure, in the first phase of the loading process, at the mid-span of the tested beams, a slight vertical deflection began once the elastic stage was exceeded during the loading progress, and the development of the first crack was observed in all beams at the flexural zone. As the load was further increased, a non-linear behaviour stage began as the cracks propagated and moved towards the neutral axis (close to the utilised load or openings). Diagonal cracks began to appear and spread to both sides of beams. The major cracks were flexural cracks, as predicted, for all tested specimens which started in the tension zone; all beams failed in the flexural except two beams that failed in shear and thus exhibited sudden failure due to the presence of the opening in the shear zone.

Table 4. The test result of beam specimens

| Group Designation | Loading at First Crack (kN) | Ultimate Load (kN) | Maximum Deflection (mm) | Reduction Ratio (%) | Failure Mode |
|-------------------|-----------------------------|--------------------|-------------------------|---------------------|--------------|
| HC                | 55                          | 155                | 11.7                    | Flexural            |              |
| Group 1           |                             |                    |                         |                     |              |
| H10MF             | 50                          | 147                | 7.79                    | 5.2                 | Flexural     |
| H10SF             | 40                          | 144.5              | 7.59                    | 6.8                 | shear        |
| H10SMF            | 37                          | 143                | 7.5                     | 7.7                 | flexural + shear |
| H10MFR            | 45                          | 140.3              | 5.8                     | 9.5                 | Flexural     |
| H10SFR            | 40                          | 138.8              | 7.1                     | 10.5                | shear        |
| H10SMFRO          | 35                          | 130.2              | 5.91                    | 16                  | flexural + shear |
| Group 2           |                             |                    |                         |                     |              |
| H10MB             | 52                          | 146.4              | 7.4                     | 5.5                 | Flexural     |
| H10SB             | 46                          | 145.5              | 7                       | 6.1                 | Flexural     |
| H10SMB            | 40                          | 141                | 8.1                     | 9                   | flexural + shear |

4.2 Crack Patterns and Modes of Failure for Tested Beams

The mode of failure for each tested beam was determined based on the appearance of the cracks. The experimental evidence showed that three types of failure occurred. The flexural failure, as shown through vertical cracks, developed in the tension zone. The second type of failure was shear failure, shown as inclined cracks, which went up to the point of the loading on the incline, while the third type was flexural-shear failure, in which the cracks usually started in the vertical direction before, as the load increased, moving in a diagonal direction because of the combined effects of shear and flexure, as shown in Fig. 4.
Fig 3. Cracks formation for all hollow beams
4.3. Effect of Openings on Ultimate Strength

As shown in Table 4, creating openings in existing beams leads to a reduction in their stiffness due to the removal of parts of the concrete and this leads to a reduction in the ultimate failure load. As illustrated in Fig 5, for group one, when the opening was induced in the front of the beams in samples H10MF, H10SF, and H10SMF, the reductions in load-carrying capacity were found to be about 5.2%, 6.8%, and 7.7% compared to the control beam. However, when the opening was induced in the front and rear of the beams, in samples H10MFR, H10SFR, and H10SMFR, the reduction ratios were 9.5%, 10.5%, and 16% compared to the control beam. The H10SMFR beam was found to be the worst case in this group, as shown in Fig 6, because it showed a considerable reduction in strength, due to unexpected changes in sectional configuration. Furthermore, the failure mode changed from beam-type failure to frame type failure as the opening edges were exposed to a high concentration of stresses, which led to stiffness decreasing for the tested beam and an increase in the number and deflection of the cracks. For group two, with openings in the bottom flange of the beams, the ultimate load reduction ratios were 5.5%, 6.1%, and 9% for beams H10MB, H10SB, and H10SMB, respectively, compared to the control beam. In this group, H10SMB was found to be the worst, with the largest reduction in ultimate load.

Fig 4. First cracking and ultimate loads for beam specimens in (a) group 1 (b) group 2
4.4. Deflection of Tested Beams

The load-deflection curves for all phase of loading process for the tested beams are shown in Fig. 6 and Fig. 7, respectively. In the elastic stage, all curves were similar, and the beams showed linear conduct; the first crack took place between loads of 35 KN and 55 KN, which resulted in the first variation in the slope of the load-deflection curves. Each beam then behaved in a specific manner after the first crack load. In comparison with the other beams, the control beam’s (HC) behaviour showed larger loads and deflections and the greatest stiffness, due to the absence of openings. Load deflection curves for the tested beams in-group one exhibited a smooth increase in both deflections and applied loads. After the elastic stage, these curves separated from each other. For group two beams, the load-deflection curve also behaved similarly linear conduct was noted until the start of the first cracks at an average load level of 40 KN; this was followed by non-linear behaviour with significant stiffness reduction up to the yielding of tensile steel followed by ultimate failure.
4.5. Ductility

From the load-deflection relationship, the deflection ductility index, ($\mu$), can be determined. Based on deflection computation at the mid-span of the beams, the deflection ductility index, ($\mu$) presented in Table 5. The deflection ductility index for the control beam was 5; for group one with openings were present in the front of the beams, the ductility index values ranged from 2.8 to 2.14. However, the deflection ductility index values when the openings were present in the front and rear of the beam, was less than 2. For the second group, the ductility index values ranged from 2.5 to 2.1 compared to the control beam. The flexibility and the load-carrying capacity of the hollow core beams with transverse openings were significantly decreased, and the tested beams showed brittle behaviours according to the data recorded in Table 5.

Table 5. Ductility index of tested beams

| Group Number | Beam Designation | Maximum Deflection $\Delta u$ mm | Yielding Deflection $\Delta y= 0.7 Fu$ mm | deflection Ductility Index $\mu = \Delta u/ \Delta y$ |
|--------------|------------------|----------------------------------|---------------------------------------------|-----------------------------------------------|
| Group 1      |                  |                                   |                                             |                                               |
| HC           | 11.7             | 2.35                             | 5                                           |                                               |
| H10MF        | 7.79             | 2.75                             | 2.8                                         |                                               |
| H10SF        | 7.59             | 3.2                              | 2.4                                         |                                               |
| H10SMF       | 7.5              | 3.5                              | 2.14                                        |                                               |
| H10MFR       | 5.8              | 2.9                              | 2                                           |                                               |
| H10SFR       | 7.1              | 3.7                              | 1.9                                         |                                               |
| H10MSFR      | 5.91             | 3.87                             | 1.5                                         |                                               |
| Group 2      |                  |                                   |                                             |                                               |
| H10MB        | 7.4              | 2.95                             | 2.5                                         |                                               |
| H10SB        | 7                | 3                                | 2.33                                        |                                               |
| H10SMB       | 8.1              | 3.87                             | 2.1                                         |                                               |

5. Conclusions

Based on the test results for ten rectangular SCC hollow beams as presented and discussed in this paper, the following conclusions pertain:

1- Due to the creation of a circular opening, the recorded failure mode of a beam is likely to change according to the opening position and number.

2- In all tested beams, the crack path passed through the weak locations (locations of openings).

3- The first hairline cracks appeared in the maximum bending moment zone for all beams based on different numbers of openings and location.

4- The opening’ location has a great effect on ultimate strength. A largest ultimate load reduction of 10.5% occurred when the location of the opening was near the support, and least effect, 9.5% reduction, was seen when the opening’s location was at the flexure zone.

5- Creating an opening in an existing beam decreases the stiffness of the beam, and lead to an increase in deflection as compared to a control beam.

6- The deflection ductility index was markedly reduced in all tested beams; the largest reduction was for the specimen H10SMFR, where the ductility index value was 1.5, and the beam showed brittle behaviour compared to the control beam.
6. Reference

[1] L Hauhnar, R Rajkumar, and N Umamaheswari, 2017, Int. J. Civ. Eng. Technol, “Behavior of reinforced concrete beams with a circular opening in the flexural zone strengthened by steel”, vol 8, no 5, pp 303–309.

[2] M A Mansur, L M Huang, K H. Tan, and S L Lee, 1992, ACI Struct. J, “Deflections of reinforced concrete beams with web openings,” vol 89, no 4, pp 391–397.

[3] K H Tan and M A Mansur, 1996, ACI Struct. J, “Design procedure for reinforced concrete beams with large web openings,” vol 93, no 4, pp 404–411.

[4] ACI318, 2011, “Building code requirements for structural concrete (ACI 318-11) and commentary”.

[5] H Okamura and M Ouchi, 2003, J. Adv. Concr. Technol, “Self-compacting concrete” vol 1, no 1, pp 5–15.

[6] M. A. Mansur and Weng Wei, 1999 , ACI Struct. J, “Effects of creating an opening in existing beams”, vol 96, no 6.

[7] H Ammar, 2012, Researchgate, “Analysis for the behavior of RC arches with openings and strengthened by CFRP laminates”, vol 8, no 4, pp 1–26.

[8] Y. Gatia Abtan and H. Dhafer AbdulJabbar, Jan 2019, J. Eng. Sustain. Dev, “Experimental study to investigate the effect of longitudinal and transverse openings on the structural behaviour of high strength self-compacting reinforced concrete beams,” vol 2019, no 01, pp 66–79.

[9] ASTM A615, 2016, “Standard specification for deformed and plain carbon-steel bars for concrete reinforcement,” Am. Soc. Test. Mater.

[10] EFNARc, May 2005, Eur. Guide. Self-Compact. Concr, “The European Guidelines for Self-Compacting Concrete Specification, Production and Use”.

[11] W S Alyhya, M S Abo Dhaheer, M M Al-Rubaye, B L Karihaloo, and S Kulasegaram, 2015, 35TH Cem. Concr. Sci. Conf. (CCSC35), “A rational method for the design of self-compacting concrete mixes based on target plastic viscosity and compressive strength”, Aberdeen, UK, pp 85–94.

[12] M S Abo Dhaheer, M M Al-Rubaye, W S Alyhya, B L Karihaloo, and S Kulasegaram, 2016, J. Sustain. Cem. Mater, “Proportioning of self-compacting concrete mixes based on target plastic viscosity and compressive strength: part ii - experimental validation”, vol 5, no 4, pp 217–232.

[13] M S Abo Dhaheer, M M Al-Rubaye, W S Alyhya, B L Karihaloo, and S Kulasegaram, 2016, J. Sustain. Cem. Mater, “Proportioning of self-compacting concrete mixes based on target plastic viscosity and compressive strength: part i - mix design procedure”, vol 5, no 4, pp 199–216.

[14] BS 1881-116, 1983, Br. Stand. Inst, “Testing concrete — compressive strength of concrete cubes”.

[15] ASTM C496-C496M-11, 2011, Annu. B. ASTM Stand, “ASTM C496-11 standard test method for splitting tensile strength of cylindrical concrete specimens”, Vol 04 02.