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Shear behaviour of reinforced concrete beams with small web openings

Dhiaa Neama Jabbar [a], Ali Al-Rifaie [b], Ahmed Mahdi Hussein [a], Ali A. Shubbar [c,d], Mohammed Salah Nasr [a,*], Zainab S. Al-Khafaji [e,f]

[a] *Technical Institute of Babylon, Al-Furat Al-Awsat Technical University (ATU), Iraq*
[b] *College of Engineering, Al-Muthanna University, Samawah 66001, Iraq*
[c] *Department of Building and Construction Technical Engineering, College of Technical Engineering, The Islamic University, 54001 Najaf, Iraq*
[d] *Department of Civil Engineering, Liverpool John Moores University, UK*
[e] *Al-Furrat Al-Awsat Distribution Foundation, Ministry of Oil, Babylon, Iraq*
[f] *Department of Civil Engineering, Al- Mustaqbal University College, Babylon, Iraq*

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ABSTRACT

In the current investigation, four reinforced concrete beams with square cross sectional area were poured and tested up to failure under the action of three-point loads. Three of them were designed to contain small web openings of different shapes, square, rectangular and circular while the other beam had no openings (control beam) for the purpose of comparison of findings. The load–deflection traces were successfully obtained for the tested specimens. The results indicated that perforating reinforced concrete beams with small web openings leads to a slight reduction in their ultimate loads corresponding to an increase in the ultimate deflection. Also, it was concluded that the beams with circular web openings had better shear resistance than other shapes selected here.

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1. Introduction

In practice, openings may be provided in reinforced concrete beams to be used as an access for ducts and pipes used for electrical, mechanical and sewage services. Presence of such openings produces a sudden change in the cross-sectional area leading to the propagation of stress concentration at the opening edges. This will partially reduce the stiffness and then the load carrying capacity of the beam. Web openings take different configurations but the most common shapes are circular and rectangular. Regarding openings size, the previous studies classified the web opening based on their size. Hence, the terms beam with small and large openings were widely used in the literature [1]. However, Ahmed et al. [2] considered that identifying an opening as either small or large depends on the structural behaviour of the beam. Hence, the opening can be considered small if the common beam theory applies. In addition to static behaviour, some studies were carried out to investigate the dynamic response of beams with and without openings [3,4]. This reflects the variation in behaviour of beam with web openings under static and dynamic loading in addition to other circumstances.

Different studies were carried out to study the behaviour of beams including large web openings. An experimental work was performed to investigate the performance of the reinforced concrete beams having large web-openings reinforced with CFRP [5]. The findings showed that the presence of large openings in the mid-span decreases the beam capacity by around 50%, while strengthening with the CFRP lead to increase in the ultimate load by 80–90%. Another study has been done by Aykac et al. [6] to study the flexural behaviour of cellular reinforced concrete beams. This test results showed that increasing the number of openings leads to raising the possibility of Vierendeel mechanism. Saeed Al-Sheik [7] found that the presence of an opening in a beam may result in developing shear cracks around the opening due to the stress concentration. Hawileh et al. [8] developed a 3D finite element model to investigate the behaviour of RC deep beams with web openings and strengthened with CFRP in to enhance shear strength. The results indicated that the load capacity of the strengthened beams was 74% higher than those having no CFRP. Another FE studies were also presented to investigate the response

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* Corresponding author.
E-mail address: mohammed.nasr@atu.edu.iq (M.S. Nasr).

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of RC beams having different configurations of web openings [9–11]. It was confirmed the efficiency of using FE modelling to predict the behaviour of perforated RC beams.

On the other hand, limited studies were carried out to study the response of reinforced concrete perforated beams under quasi-static loading. According to the authors' knowledge, the study conducted by Amiri et al. [12] was the only research that dealt with small openings. In this study, the shear and flexural behaviour of reinforced concrete beams having small circular was studied. The main finding was the reduction in ultimate strength increased and the mode of failure may be changed if the opening diameter exceeded 1/3 of the beam depth. Besides, Ahmed et al. [2] concluded that future work should take into account of evaluation the existing design approaches of RC beams with small openings. This emphasized the gap of knowledge that should be covered in the current research. However, it is decided here to experimentally investigate the shear behaviour of reinforced concrete beams having small web openings to cover such gap of knowledge. The test results presented in the current study will be of note and will assist in understanding the response of RC beams perforated with small openings. Also, it will be applicable to make a reliable comparison with those with large openings. This study will be followed by a series of studies for further understanding of such case.

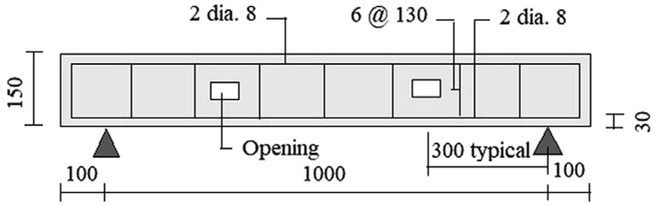

Fig. 1. Details of tested beams with web openings (all dimensions in mm).

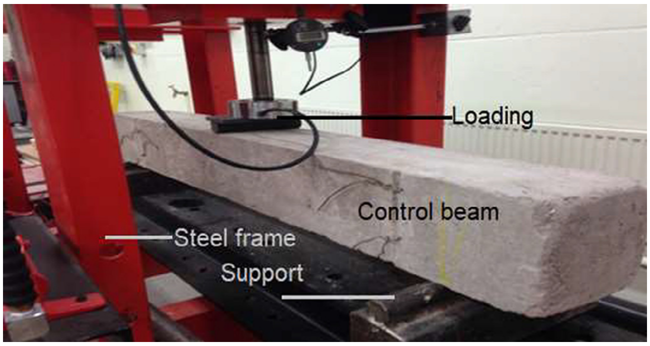

Fig. 2. Test setup.

2. Experimental work

Four beams of 150 × 150 × 1200 mm were fabricated and tested in the current study with different opening shapes, circular, square and rectangular as shown in Table 1. Required tests for steel reinforcement and concrete were performed according to British standards. The results of such tests showed that the average concrete compressive strength was 25 MPa and the yield stress of steel reinforcement of 253 and 345 MPa for stirrups and longitudinal reinforcement, respectively. Fig. 1 shows the details of the reinforced concrete beams tested. Firstly, the reinforcement steel bars were cut to the required length then both the stirrups and longitudinal reinforcement were tied together. With each beam, three cubes were poured to obtain concrete properties. Then, the formwork was screwed with PVC pipes in the shear zone of the formwork to provide the openings in each beam. Before concrete casting, both the formwork and the cube mould were oiled to facilitate the process of specimens releasing. The casting stage was started by weighting all the material as per the mix design proportions. Then all materials involved were mixed for 2 min inside the concrete mixer beside the water. After that, fresh concrete was placed in the mould then vibrated.

The beams were released from the mould after 28 days of curing with water. Besides, the cubes were also prepared to conduct the required tests. After obtaining the cube results, the RC beams were then tested under three-points load as can be seen in Fig. 2. A hydraulic jack with a capacity of 3000 kN was used to apply the quasi-static loading while the deflection at mid-span was monitored using a small digital gauge placed on the bottom fibre at mid-span of the beam. During the test, the beam was carefully monitored in order to follow up the first crack propagation and other cracks.

3. Experimental results and discussion

3.1. Cracks patterns

During this research, the load at first crack for tested beams and the propagating of shear and flexural cracks were recorded. For the control beam, the first crack started to develop when the applied load reached 7.4 kN. For the perforated beams, similar cracking loading was obtained that varied between 6.9 and 7 kN. The flexural cracks started to propagate in the bottom fibre of the mid-span of the beam and the number of such cracks increased with each increment of loading. Additionally, directly after the onset of the plastic stage of each beam, some diagonal cracks started to appear around the openings as can be seen in Fig. 3. Then, a significant increase in the deflection was observed for small loading increment. The obtained results referred to the slight effect of the presence of small web openings on the first cracking load.

3.2. Load-deflection traces

Fig. 4 showed the load–deflection traces of the tested beams. All beams showed a bi-linear response under three points loading. The control beam slightly illustrated higher flexural elastic stiffness until the yield of steel reinforcement. Afterward, the beams started the plastic stage with considerable degradation in their stiffness. It seems that the propagation of diagonal cracks around openings

Table 1
Matrix of the beams tested.

No.	Beam code	Type of openings	Opening height % *	Opening Dimension
1	B1	Control	–	–
2	COB	Circular	30	45 mm diameter
3	SOB	Square	26	40 mm × 40 mm
4	ROB	Rectangular	17	60 mm × 25 mm

*Opening height % is the ratio of opening height (mm) to total beam depth (150 mm)

Fig. 3. Diagonal cracks around opening.

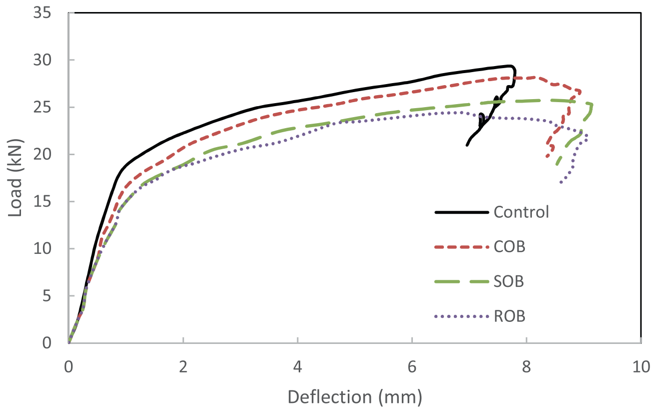

Fig. 4. Load-deflection traces for tested beams.

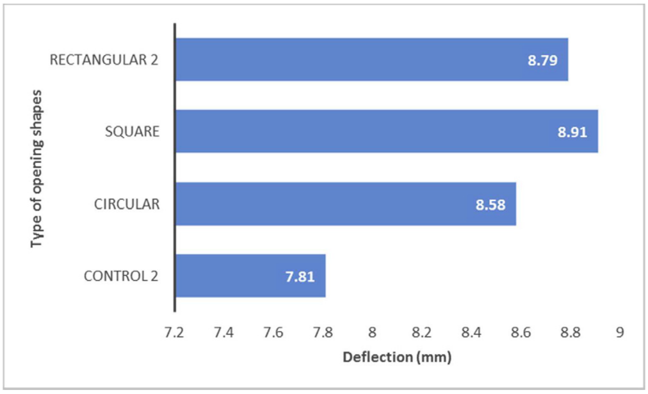

Fig. 5. Summary of test results of mid-span deflection.

accelerates the beams with openings to lose some of their strength. Such cracks referred to a combined action of flexural and shear failure at which both the flexural and shear capacity will be negatively affected.

3.3. Ultimate load

Table 2 showed a summary of the test results obtained in the current study in terms of maximum loading capacity and maximum deflection at mid-span. It should be mentioned that the area of openings of different shapes selected in the current study was approximately similar to make the comparison satisfactory.

From Table 2, it can be observed that perforated beams have lower resistance if compared with the control beam. A reduction in shear strength seems to be lost by cutting the opening area from the beam. This reduction in shear capacity reduced the flexural capacity of the beam as discussed in Section 3.2 by the development of Vierendeel mechanism. The beam with rectangular openings was recorded to be the worst case amongst other perforated beams. Its ultimate load was 25 kN which was 16.7% lower than the ultimate load of the control beam. However, the beam with circular openings illustrated the highest ultimate loading capacity amongst other openings shapes. Whilst, the beam with circular opening failed with a load of 28 kN and it only loses 6.7% of the control beam load. The beam with square openings failed with ultimate loading of 26 kN, and this load is 13.3% lower than that of control beam. In spite of using similar area of openings but with different shapes, the ultimate loading capacity of these three beams was varied. This may reflect the importance of the edge's configuration and height ratio in the behaviour of RC beams with web openings. Such configuration allows higher stress concentration on the edge of the opening which accelerate the crack propagation as can be seen in Fig. 3. Besides, various configurations of opening also come with different height and width of opening. It seems that the effect of opening width plays more important role than the opening height which make the presence of rectangular openings is the worst case.

3.4. Ultimate deflection

The point at which the beam start significantly lost its strength was considered as a failure point. In this stage the beams showed no strength and the loading starts to decrease corresponding to a reduction in the mid-span deflection. In general, all perforated beams exhibited higher deflection at mid-span than the control beam as can be seen in Fig. 5. Furthermore, the beam with square openings exhibited a maximum deflection at mid-span of 8.91 mm with an increase of 14% than the maximum deflection of the control beam. Again, the circular opening can be considered as the best shape of opening as it has the least increasing in maximum deflection compared with the other perforated beams. Again, the beam with a circular opening showed the lower maximum deflection amongst the perforated beams which was 10% higher than that of control beam. Although higher deflection induced in the perforated beams may be considered as an unfavourite feature, but such higher deflections may give a good indication that the ductility of RC beams may be enhanced if provided with web openings.

4. Conclusions

The previous studies showed that limited efforts were made to investigate the shear behaviour of reinforced concrete beams with different shapes of small web openings. The current study intended to provide experimental data to understand the shear behaviour of

Table 2
Summary of test results.

No.	Beam code	Opening shape	Opening height %	Opening dimension	Maximum deflection (mm)	Ultimate load (kN)	Decrease in load %	Increase in deflection %
1	Control	–	–	–	7.81	30	–	–
2	BCO	Circular	30	45 mm diameter	8.58	28	6.7	10
3	BSO	Square	26	40 mm × 40 mm	8.91	26	13.3	14
4	BRO	Rectangular	17	60 mm × 25 mm	8.79	25	16.7	13

such beams. Four reinforced concrete beams were fabricated and tested under three-points load. All the material properties involved were obtained successfully and comprehensive discussion was presented in terms of ultimate loading capacity and ultimate deflection in beam mid-span. Also, the control failure mode was presented and discussed.

In conclusion, the following conclusions can be drawn:

- The experimental result showed that the beam with a circular opening was the best choice as they have higher ultimate loading capacity and lower deflection compared with the other shapes of opening.
- All the tested beams showed bi-linear load–deflection curves with considerable ductility. More investigations are required to study the effect of other parameters may affect the shear behaviour of perforated RC beams such as the effect of reinforcing the openings with steel rebars and the effect of eccentricity of openings.
- The control beam showed slightly higher initial stiffness than perforated beams.

CRediT authorship contribution statement

Dhiaa Neama Jabbar: Supervision. **Ali Al-Rifaie:** Writing - original draft, Visualization, Investigation, Writing - review & editing. **Ahmed Mahdi Hussein:** Resources, Visualization. **Ali A. Shubbar:** Writing - original draft. **Mohammed Salah Nasr:** Writing - review & editing. **Zainab S. Al-Khafaji:** Resources, Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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