# BEHAVIOUR OF REINFORCED CONCRETE DEEP BEAMS WITH OPENINGS IN THE SHEAR ZONES

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## ABSTRACT

*Reinforced concrete deep beams are useful in high rise buildings to support high loading in a structure. In deep beam construction, openings are usually provided in beams for accessibility purpose and to accommodate essential services such as power supply, ventilation system and network system access. However, the presence of openings in deep beams may lead to many problems in the beam behaviour such as reduction in the beam strength, cause excessive cracking and deflection. Hence, this research was conducted to study the behaviour of reinforced concrete deep beams with openings. Two openings, one in each shear span, were placed symmetrically at the top of shear span near support about the mid-point of the beam. Test parameters included the opening size and shape. The openings were circular and square in shapes. The sizes of the openings considered in this study included ∅150 mm, ∅200 mm and ∅250 mm for circular whereas the size of square shape were 150x150 mm, 200x200 mm and 250x250 mm. All the beam specimens had a cross-section of 100 mm x 500 mm and a total length of 1200 mm. The beams were tested under four-point bending until failure. The results in terms of load deflection behaviour and crack patterns were discussed. Provision of circular openings could reduce the beam capacity to a range of 30 – 35% of the original beam capacity while the inclusion of square openings cause a significant loss of beam strength, about 40 – 80% as compared to the beam capacity of the solid beam.*

**KEYWORDS:** *Behaviour; deep beams; openings; reinforced concrete; shear*

## 1.0 INTRODUCTION

Reinforced concrete (RC) deep beams are widely used as transfer girders in offshore structures and foundations, walls of the bunkers and load bearing walls in buildings. In fact, deep beams are very useful in tall buildings or also known as high rise buildings. In the offshore gravity type structures, deep beams also act as a transferring and supporting elements. The presence of web openings in such beams is frequently required to provide accessibility such as doors and windows or to accommodate essential services such as ventilating and air conditioning ducts. Enlargement of such openings due to architectural or mechanical requirements and a change in the building's function would reduce the element's shear capacity, thus rendering a severe safety hazard (El Maaddawy & Sherif, 2009).

Utility pipes and service ducts are usually placed below the beam soffit and covered by suspended ceiling due to aesthetic purpose which will create a dead space. However, by

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passing the pipes and ducts through the transverse openings in the floor beams will lead to a reduction in the dead space which may result into a more compact and economic design. Openings may be of different shapes and sizes depending on the requirement of architect/mechanical engineer. The existence of web openings causes geometric discontinuity within the beam and non-linear stress distribution over the depth of the beam. In addition, current code of practices do not cover the design of deep beams with web openings (Yoo, 2011). Various shapes can be provided depends on the purpose of use, however the most common type of openings is rectangular and circular in shape (Mansur, 2006).

The behaviour of RC deep beams with openings is unlike the behaviour of RC solid beams. Mansur *et al.* (1992) and Mansur (2006) reported that due to the reduction of the cross sectional area of the beam, the behaviour of the beam will change from a simple behaviour to a more complex behaviour. Hence, the provision of openings in RC beams will leads to the reduction in beam stiffness and strength and cause excessive cracking and deflection. The behaviour of RC deep beams with openings is greatly affected by the size, shape and location of openings. Due to this, investigations were conducted to study the effect of opening size and location on the shear strength behaviour of RC deep beams (Alsaeq 2013; Amin et al. 2013).

In the past decades till present, various investigations were carried out to study the behaviour of RC deep beams with openings (Chin et al. 2014; Campione & Minafò 2012; Sahoo et al. 2012; Hemanth Kumarg 2012; Hu & Tan 2007). Chin et al. (2014), Hu and Tan (2007), reported that the web opening reduced the ultimate strength of a large deep beam significantly, if the web opening intersects the force path between the load point and the support as shown in Figure 1. Results of the crack patterns illustrate a strut-and-tie system in large pierced deep beams. Figure 2 shows the typical cracks appeared in deep beams. On the other hand, an early investigation conducted by Kubik (1981) studied the strength of RC deep beams with web openings reported that photoelastic models could be of useful to identify the locations of stress concentrations. The high stress concentrations clearly occur at the corners of the cut and under the loading points, similar to the results obtained by Hu and Tan (2007) in Figure 2. Results showed that apart from the high stress concentration occurred; regions of high intensity of tensile stress are also formed, which caused severe internal cracking.

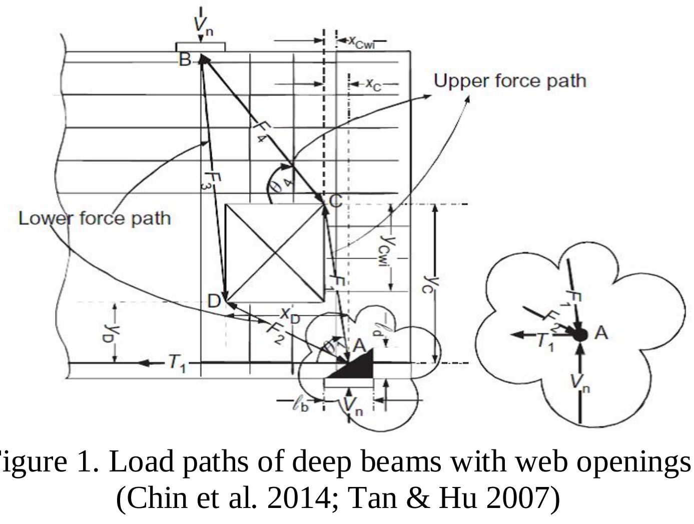



Figure 1. Load paths of deep beams with web openings
(Chin et al. 2014; Tan & Hu 2007)

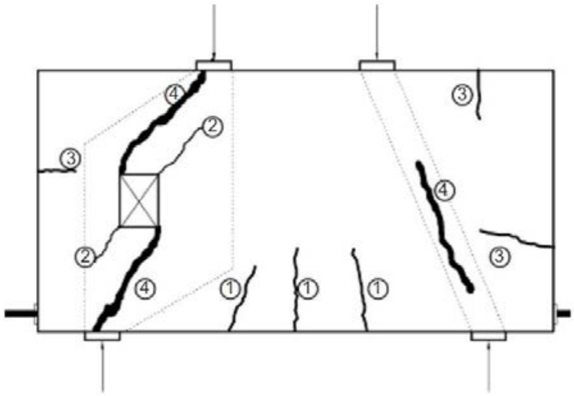


Figure 2. Typical cracks in deep beam (Chin et al. 2014; Tan & Hu 2007)

On the other hand, Yang and Ashour (2007) investigated the structural behaviour of RC continuous deep beams with web openings. The principal variables of the study include the shear span-to-overall depth ratio, and the size and location of openings. The study revealed that the continuous deep beams having web openings in the region of interior shear spans suffered a higher reduction in the load capacity with the increase in opening size. Similarly, simply-supported deep beams with web openings followed the same pattern. Also, two types of failure modes observed due to influence of the size and location of web openings regardless of the shear span-to-overall depth ratio. The two types of failure modes include a failure plane formed at the interior shear span only and at both interior and exterior shear spans. The transition of the failure modes for beams having web openings in the exterior region of shear span was dominated by the ratio of opening area to shear span area. Further investigations were conducted by Campione & Minafò (2012) to study the behaviour of RC deep beams and low shear span-to-depth ratio.

Various studies on types of external strengthening materials were conducted in order to re-gain the beam original structural capacity due to the losses caused by the presence of opening (Hussain & Pimanmas 2015; Abduljalil 2014; Mohamed et al. 2014; Hawileh et al. 2014; Hawileh et al. 2012; El Maaddawy & Sherif 2009). El Maaddawy and Sherif (2009) studied the potential use of carbon fiber reinforced polymer (CFRP) composite sheets as a strengthening material solution to upgrade RC deep beams with openings. A total of thirteen (13) deep beams with openings were cast and tested under four-point bending. The test specimen had a cross-section of 80 x 500 mm and a total length of 1200 mm. Two square openings, one in each shear span, were placed symmetrically about the mid-point of the beam. Test parameter included the opening size, location and the presence of CFRP sheets. It is reported that the failure mode of the un-strengthened deep beams with openings was dependent primarily on the opening size. The specimens failed suddenly by a formation of two independent diagonal shear cracks in the chords above and below the opening.

Most of the past investigations focused more on small openings with the common shape of openings used in the construction industry such as circular and rectangular. The study of deep beams with large openings is rather limited. Hence, in this paper, the behaviour of RC deep beams with openings located at the top of the shear span near support was studied. The openings considered in this study were circular and square in shape. The results were discussed in terms of load deflection behaviour and crack pattern.

## 2.0 EXPERIMENTAL PROGRAM

A total of seven (7) RC deep beams were considered in this study. The beams including a solid beam as reference beam while the remaining beams were with openings located at the top of shear span near support. A schematic diagram of the test specimen illustrating the reinforcement layout is shown in Figure 3. All the beams had a cross-section of 100 mm x 500 mm and a total length of 1200 mm. As for the steel reinforcement, four 16 mm diameter bars were used as the tension reinforcement, whereas two 10 mm diameter bars as the compression reinforcement. Shear reinforcement of 6 mm diameter was spaced at 150 mm center to center in both vertical and horizontal directions.

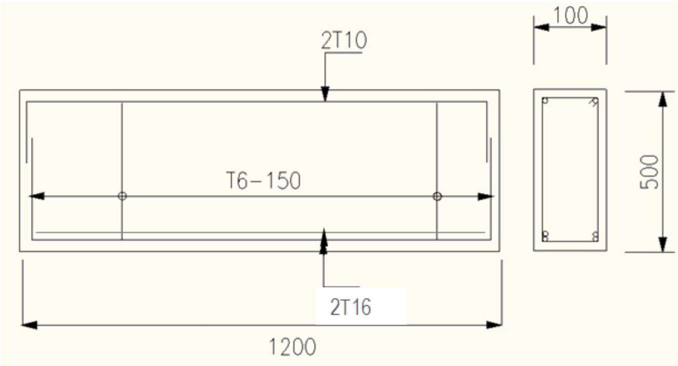
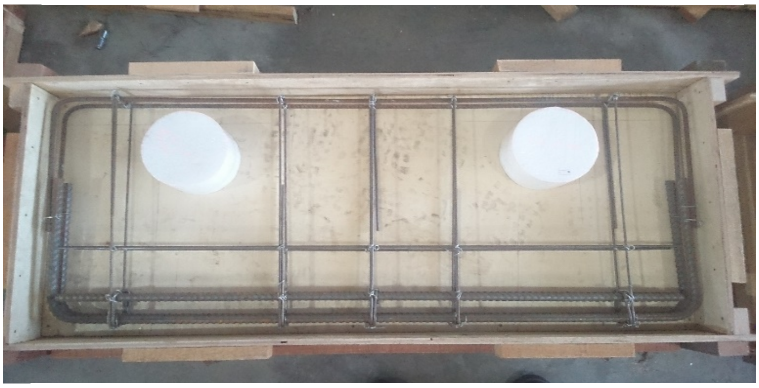



Figure 3. Schematic diagram of reinforced concrete deep beam

All the specimens had two openings, one in each shear span, placed symmetrically at the top of shear span near support. The openings were created using polystyrene for circular openings and wooden planks for square openings as shown in Figure 4. The sizes of circular openings considered were ø150mm, ø200 mm and ø250 mm, while the sizes of square openings including 150 x150 mm, 200 x 200 mm and 250 x 250 mm which corresponded to opening height-to-depth (a/h) ratios of 0.3, 0.4 and 0.5, respectively. The beams with openings were cast to resemble the case of the inclusion of an opening in an existing beam. Nine (9) 150x150x150 mm concrete cubes were cast with the beams to determine the compressive strength. The beams were cast in wooden formworks using ready mixed concrete of grade 35 MPa. After 24 hours, the beams were removed from the formworks and cured for 28 days using wetted gunny bags. All the beams were tested to failure under four-point bending. Figure 5 depicts the test setup profile of the testing using Magnus Frame of 500 kN. Table 1 summarizes the beam specimens considered in this study.

(a) Deep beam with 150 x 150 mm square opening



(b) Deep beam with 150 mm dia. circular opening

Figure 4. Concreting of deep beams (a) 150 x 150 mm square opening (b) 150 mm dia. circular opening

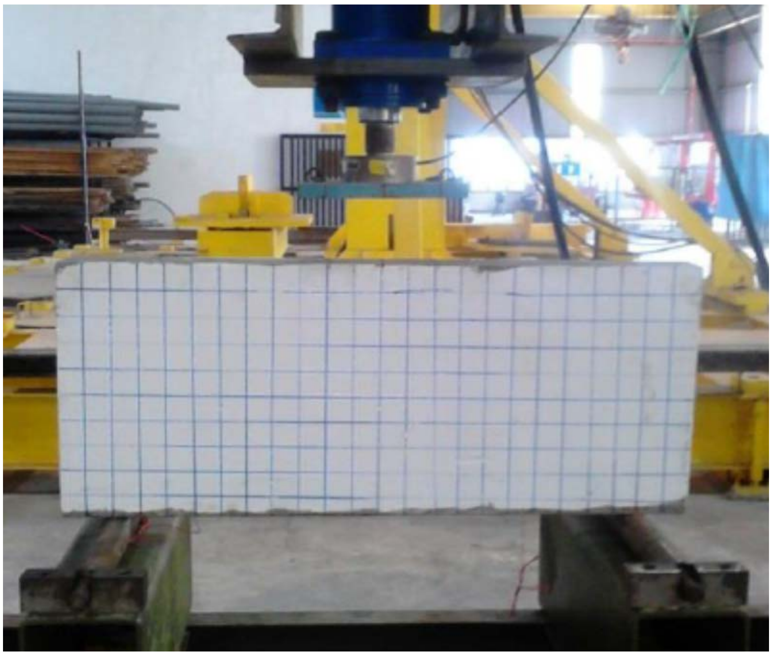


Figure 5. Test setup profile of four-point loading

Table 1. Summary of RC deep beams with and without openings

| Beam No | Opening | | Location |
|---|---|---|---|
| | ***Shape*** | ***Size (mm)*** | |
| CB1 | - | - | - |
| BCO1 | Circular | Ø150 | At the top of shear span near support |
| BCO2 | Circular | Ø200 | |
| BCO3 | Circular | Ø250 | |
| BSO1 | Square | 150 x 150 | |
| BSO2 | Square | 200 x 200 | |
| BSO3 | Square | 250 x 250 | |

## 3.0 RESULTS AND DISCUSSIONS

The results are presented in terms of load deflection behaviour and crack pattern.

### 3.1 Load deflection behaviour

The load deflection curve comparison of deep beam with circular opening and control beam is compared as shown in Figure 6. The experimental results obtained for CB1 show that the maximum load that the beam was able to sustain was 42.97 kN with a deflection of 4.70 mm. On the other hand, it was found that BCO1 achieved the highest ultimate load with greater stiffness as compared to CB1 with the maximum load of 46.59 kN. However, as observed in beam BCO2 and BCO3, the ultimate load attained was 30.55 kN and 27.99 kN respectively. It was found that with an increase in the opening diameter, the ultimate load of the beam reduces with an increase in deflection. Reduction of a portion of concrete area in the beam reduces the strength of the beam thus causing beam failure.

In order to study the effects of circular openings in the beam behaviour, the results of reference beam, CB1 obtained from the load-deflection curves were compared to the results of deep beams with circular openings. Table 2 lists the results obtained in terms of yield load, ultimate load, deflection and losses in the beam capacity. It was found that providing openings of diameter 200 mm reduces the strength by 28.9% while providing openings of diameter 250 mm reduces the strength by 34.9%. However, the beam capacity of BCO1 increases as compared to the control beam, CB1, about 8.42%. This is due to the symmetrical section of the circular shape. Stress tracjectory will be tangential around the opening which will cause the intensity to bounce back. Hence, the strength of the beam increases.

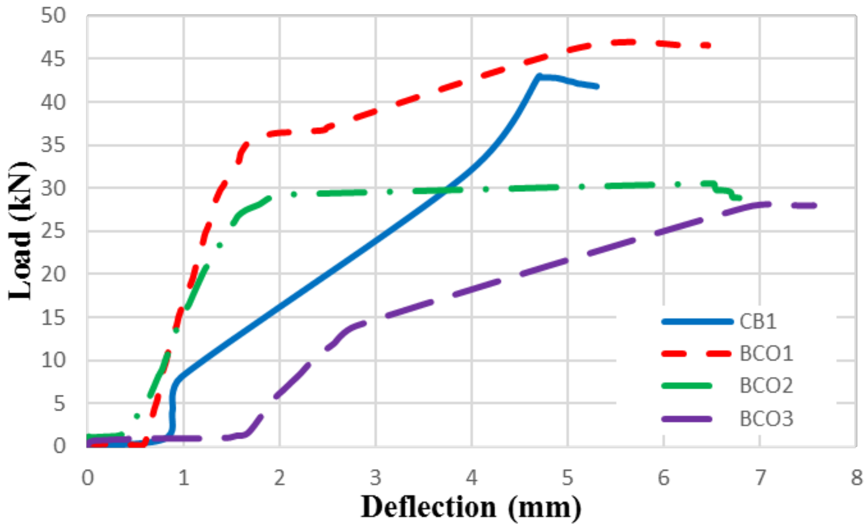



Figure 6. Comparison of load deflection curves between reference beam, CB1 and deep beams with circular openings BCO1, BCO2 and BCO3

Table 2. Experimental results of beams with and without openings

| Beam No | Yield Load (kN) | Deflection (mm) | Ultimate Load (kN) | Deflection (mm) | Losses of Strength (%) |
|---|---|---|---|---|---|
| CB1 | 8.03 | 0.98 | 42.97 | 4.70 | - |
| BCO1 | 30.32 | 1.50 | 46.59 | 6.21 | (+) 8.42 |
| BCO2 | 27.46 | 1.30 | 30.55 | 6.51 | (-) 28.9 |
| BCO3 | 13.99 | 2.80 | 27.99 | 7.33 | (-) 34.9 |
| BSO1 | 8.51 | 1.11 | 24.47 | 1.71 | (-) 43.1 |
| BSO2 | 3.24 | 5.22 | 20.85 | 10.08 | (-) 51.5 |
| BSO3 | 3.51 | 1.89 | 7.55 | 2.31 | (-) 82.4 |

Figure 7 shows the load deflection curve comparison of control beam, CB1 and deep beams with square openings at the top of the shear span near support. As shown in the figure, BSO1 demonstrated the highest ultimate load among beams with openings, 24.47 kN. The second highest ultimate load was achieved by beam BSO2, 20.85 kN. Beam BSO3 with the largest size of square opening, 250 x 250 mm exhibited the lowest ultimate load obtained, which was about 7.55 kN. This signifies that the greater the size of the openings, the greater the losses in beam strength. Table 2 lists the experimental results and comparison was made. From the Table, it shows that beam BSO1 and BSO2 had reduced the beam strength to about 40 – 50% due to the square opening of size 150 mm and 200 mm, respectively. Meanwhile, beam BSO3 had the largest reduction of beam capacity due to the presence of the largest opening size of 250 mm, about 82.4%. Similar to that of deep beams with circular openings, the greater the size of the opening, the greater the reduction of the beam capacity. In terms of the shape of the opening, beams with square openings showed significant reduction as compared to circular openings. This is due to the shape of square openings which consists of four sharp corners/edges which is subjected to high stress concentration that leads to cracking and failure of the beam.

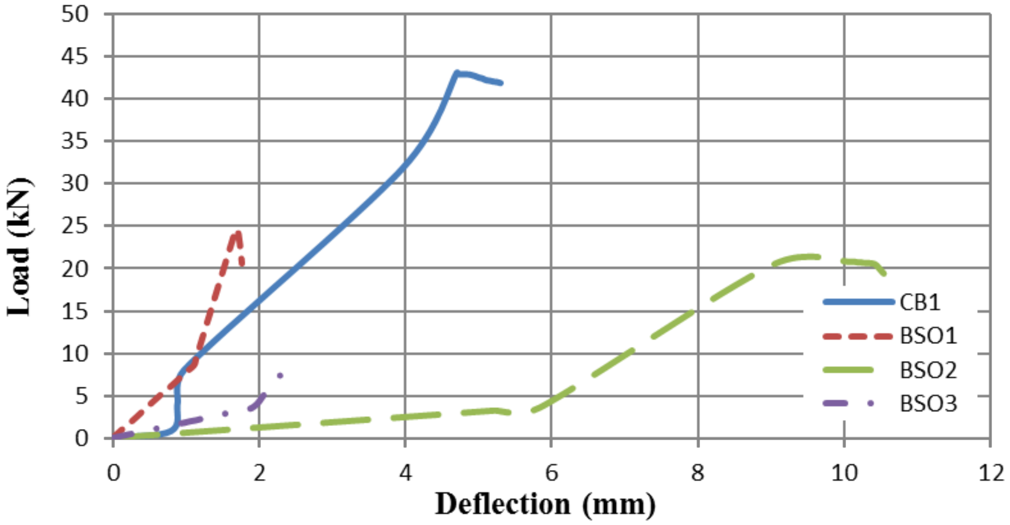



Figure 7. Comparison of load deflection curves between reference beam, CB1 and deep beams with square openings BSO1, BSO2 and BSO3

## 3.2 Crack pattern

Figure 8 shows the crack pattern of the reference beam, CB1. From the crack pattern obtained, diagonal shear cracks were formed at the edge of the beam near to the support and propagated towards the loading points. On the other hand, no flexural cracks were traced from the beam during the experimental testing up to beam failure.

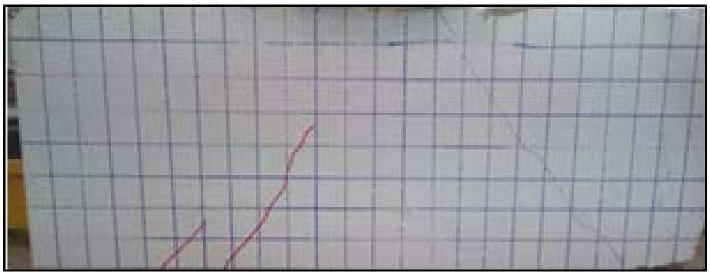
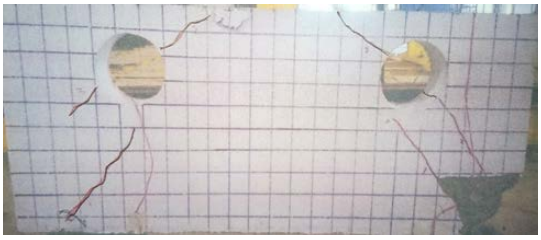
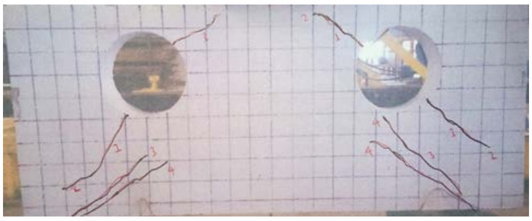


Figure 8. Crack pattern of reference beam, CB1

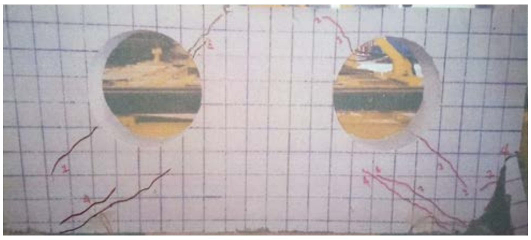
Crack patterns of RC deep beams with circular openings are depicted in Figure 9. Figure 9(a) shows the crack pattern of beam BCO1. It was observed that diagonal cracks were initially formed around the openings which then propagated towards the support and loading points, respectively. With a further increment of load, the cracks below the right opening propagated more towards the support which resulted in concrete cracking and spalling. Meanwhile, crack pattern in beam BCO2 showed two independent diagonal cracks at the top chord of both openings. Similarly, cracks were found propagated diagonally at the bottom of opening towards the support. With an increase in the load applied, new additional shear cracks were formed below the openings towards the support, as shown in Figure 9(b). As illustrated in Figure 9(c), the crack patterns of beam BCO3 were found almost similar as obtained in beam BCO2. However, the diagonal cracks at the bottom of the openings propagated towards the support were more severe than beam BCO2 which leads to crushing of concrete at the edge of the beam.



a) BCO1



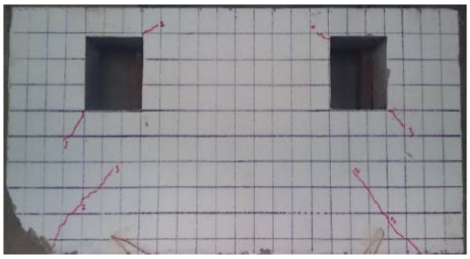
b) BCO2



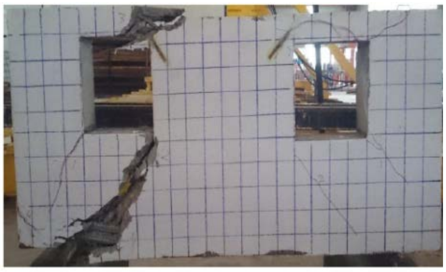
c) BC03

Figure 9. Crack pattern of RC deep beams with circular openings (a) BCO1 (b) BCO2 (c) BCO3

Figure 10 illustrates the crack pattern of RC deep beams with square openings. Crack pattern of beam with square openings of size 150 x 150 mm is shown in Figure 10(a). From the figure, it shows that diagonal cracks were initiated and formed at the corner of the openings; at the top near to the loading point and at the bottom near to the support, respectively. As the size of the opening increased to 200 x 200 mm, similarly, the cracks were formed at the corner near to the loading point and at the bottom corner near to the support in beam BSO2, as depicted in Figure 10(b). Diagonal shear cracks were clearly seen at both corners at the bottom of the openings. With the increase of load, wide crack width was observed at the point of failure; at the top corner of the opening towards the loading point and at the bottom corner of the opening propagated towards the support. Similar as observed in beam BSO1 and BSO2, the crack pattern of BSO3 is rather severe with the opening size of 250 x 250 mm as shown in Figure 10(c). Diagonal shear cracks were observed at the four corners of the opening; which penetrated from the top corner of the opening towards the loading points and from the bottom corners of the opening towards the support, respectively. The diagonal crack lines were apparent due to the increase in crack width at the top and bottom of the opening. The crack pattern is very much severe in beam BCO3 due to huge reduction of concrete area.



a) BSO1



b) BSO2

c) BSO3

Figure 10. Crack pattern of RC deep beams with square openings (a) BSO1 (b) BSO2 (c) BSO3

## 4.0 CONCLUSION

Based on the results obtained, the following conclusions can be made:

1. The provision of circular opening with diameters of 150 mm, 200 mm, and 250 mm reduced the beam capacity to a range of 30 – 35% of the original beam capacity of the reference beam. Meanwhile, the inclusion of square openings with the dimension of 150x150 mm, 200x200 mm and 250x250 mm causes a significant loss of beam capacity, about 40 – 80% as compared to the beam capacity of the control beam.

2. The crack pattern behaviour of RC deep beams with both circular and square openings varied with the crack pattern behaviour of the solid control beam due to the high stress concentration around the openings. The presence of openings cause disturbances in the natural flow path of stress which leads to high stress concentration and early cracking around the openings. An increase in the opening size causes the cracks to be more severe. In this study, BSO3 exhibited the most severe cracks.
3. Comparing in terms of shape, circular opening is the most suitable option to be provided in RC beams as square openings consists of sharp corners/edges which

is subjected to high stress concentration that leads to initial cracking of the beam.

4. In terms of size, a significant reduction of beam capacity was obtained when the size of the square opening was increased from 150x150 mm to 250x250 mm, about two times the reduction of beam capacity in beam BSO1. Meanwhile, the increase in diameter of the circular opening from 150 mm to 250 mm exhibited a small reduction of strength, about 1.2 times of the losses in beam BCO1.
5. Future work of this study may include numerical analysis to simulate the behaviour of RC deep beams with openings such as finite element analysis. Furthermore, strengthening of RC deep beams with openings using external strengthening material has to be considered in order to re-gain the beam's original structural capacity.

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