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Flexural Behaviour of Reinforced Concrete Beams with Openings Strengthened by Textile Reinforced Concrete (TRC) Wrap

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Abstract: This paper presents an experimental study of reinforced concrete beams with circular and square openings at the flexure zone. Selected beams were strengthened using Textile Reinforced Concrete (TRC) wraps. A total of six beam specimens measuring 250 mm (height) x 200 m (width) x 1700 mm (length) were cast using high strength concrete with a compressive strength of 64 N/mm^2. The beams tested consisted of a solid control beam, unstrengthened concrete beams with openings and strengthened concrete beams with openings. The effect of circular and square openings on the flexure zone of concrete beams was investigated. All the beams were simply supported and tested up to failure under four-point loading. From the test results, it was found that the presence of openings at the flexure zone significantly reduces the strength and stiffness of the beams. The use of TRC wrap around the beam openings increases the ultimate capacity and stiffness of the beams. In addition, it also reduces excessive vertical cracks and deflection in beams considerably compared to unstrengthened concrete beams with openings.

Keywords: Textile Reinforced Concrete wraps, opening, concrete beam, strengthening, flexure

1. Introduction

A modern building usually contains an air conditioning system, sewerage, water supply as well as power supply. All these utilities have become essential for our daily activities. For high rise buildings, these utilities are normally placed beneath the soffit of the beam and covered with suspended ceilings for aesthetic value. Thus, not all the space provided in the building is utilised. Moreover, the space of the building will depend on the size of ducts that needs to be accommodated in the building. Therefore, to reduce the use of dead space in a building, beams with openings were introduced.

Concrete beam with an opening is constructed to allow the easy passage of utility services such as air-conditioning services, water supply as well as electricity. The use of this overall dead space helps save structure height and leads to a more economical design. The opening can be provided in various shapes and sizes which depend on the size or type of pipe or duct which passes through the opening (Mansur & Tan, 199). The most common shapes used in practice are circular and rectangular openings.

However, the presence of openings in concrete beam may affect beam strength, serviceability and stiffness due to changes in the cross-sectional dimensions of the beam (Chin et al., 2011; Chin et al., 2012; Shubbar et al., 2017). In

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addition, selection of shape and size of the opening also affects the crack pattern and failure mode of the beam. Chin et. al (2011) has found that square openings experience higher stress concentrations at sharp corner of the opening which causes a reduction in the load carrying capacity of the beam compared to circular openings.

According to Shoeib & Sedawy (2017), a circular opening is considered large when the diameter of the opening exceeds 40% of the depth of web of the beam. Meanwhile, a square opening is considered large if the height exceeds one-fourth of the depth of web of the beam. They also studied the shear strength reduction of beams due to the type of opening. It was found that circular openings can delay cracking propagation compared to square openings. Sheikh (2014) has also concluded that the circular opening is the best shape which resulted in the least reduction in the ultimate beam load.

Moreover, the location of an opening at either the flexure zone or the shear zone is also important as it can affect behaviour of the beam. Previous studies have found that the best location for an opening is at the middle of the beam span which is considered a pure flexure zone (Bukhari & Ahmad, 2008) compared to the shear zone. This is because shear failure mechanism is more complicated and catastrophic than flexural failure (Hamid et al., 2017); Thamrin et al., 2011). Moreover, reinforcement ratio of tension reinforcement also has an effect on the behaviour of beams with or without openings (Hamid et al., 2014; Aykac et al., 2013).

In order to improve the structural performance of beams with openings, strengthening technique is introduced as it more economical and sustainable than reconstruction (Truog et al., 2017). There are many materials that can be used to strengthen concrete beams such as Carbon Fiber Reinforced Polymer (CFRP) laminates and plates (Salleh et al., 2017), Textile Reinforced Concrete (TRC) wraps and steel pipes (Hauhuar et al., 2017; Jamellodin et al., 2016; Jamellodin et al., 2016). The application of CFRP to strengthen beams with large circular and square openings has been studied intensively (Chin et al., 2011; Chin et al., 2012). It was found that strengthening the opening at the flexure zone of beams significantly increased beam strength and reduced deflection and cracks compared to unstrengthened beams.

Recently, an experimental test was conducted to investigate the cracking behaviour of beams strengthened by CFRP and TRC (Hauhuar et al., 2017). It showed that concrete beams strengthened using TRC experienced similar cracking behaviour to the beams strengthened by CFRP. TRC can also improve load carrying capacity of beam up to 27% (Truog et al., 2017). However, limited findings related to TRC strengthened beams with openings have been reported. In this study, an experimental test was conducted on unstrengthened and strengthened concrete beams with openings. The aim of this study is to investigate the flexural behaviour of strengthened concrete beams with circular and square openings. Analyses on beam strength, deflection, crack patterns and failure mode of the beams were discussed.

2. Experimental Programme

The experimental programme consists of material testing on steel reinforcement bars and concrete. A total of five reinforced concrete beams with differently shaped openings and strengthening arrangements were tested until failure under four-point loading.

2.1 Material Properties

All beam specimens were cast with ready-mixed concrete with a compressive strength of 64 N/mm^2 after a curing period of 28 days. A slump height of 85 mm was recorded during the slump test. Coarse aggregates measuring 20 mm and fine sand were used in concrete mix. Tensile test was carried out for longitudinal steel bars and steel stirrups according to BS EN ISO 6892-1:2016 (BS EN ISO, 2016). Nominal yield strength of 502 N/mm^2 was obtained for longitudinal steel bars whereas nominal yield strength of 486 N/mm^2 was obtained for steel stirrups.

In this study, a bi-directional TRC wrap was used as the external strengthening material. As shown in Fig. 1, TRC wrap was made from alkali resistant glass (ARG) with a width of 1000 mm and tensile strength of more than 500 N/mm^2.

2.2 Test Specimens

All the beam specimens had a rectangular cross section of 200 mm (width) x 250 mm (height) x 2000 mm (length). Effective depth and span of the beam were 198 mm and 1700 mm, respectively. Beams were reinforced with two deformed steel bars with a diameter of 10 mm which had a tensile area of A_s = 157 mm^2. Two deformed steel bars were also provided in the compression zone with a diameter of 6 mm with a compression area of A_{sc} = 56.5 mm^2. Meanwhile, mild steel stirrups with a diameter of 6 mm and a spacing of 125 mm were provided within the shear zone with an area of A_{sv} = 56.5 mm^2.

The geometry and dimension of all tested beams are shown in Fig. 2. In total, five reinforced concrete beams were prepared for the tests. This includes control beam without an opening, unstrengthened concrete beam with openings and strengthened concrete beam with openings. Details of each tested beam are listed in Table 1. Beam BC represents a solid control beam. Beam BCO represents a beam with a circular opening. Beam BSO represents a beam with square openings. Meanwhile, Beam BCO-S and Beam BCO-S remain as beams with circular and square openings respectively. Both beams were strengthened using TRC wraps.

Circular and square openings were located at the mid-span of the beam. Size of 80 mm in diameter was formed for the circular opening and 71 mm x 71 mm was formed for the square opening. Ratio of the circular opening depth and square opening depth to the effective beam depth was 0.4 and 0.36, respectively. These can be considered as large openings as the diameter of the circular opening exceeds 40% of the effective beam depth while the height of square opening exceeds 0.25 of the beam depth (Mansur & Tan, 1999; Amiri & Hosseinalibygie, 2004).

Circular opening was formed by using polyvinyl chloride (PVC) pipes and the square opening was formed by a box made of plywood which was inserted at the middle of the beam span before concreting. After 28 days of curing, Beam BCO-S and Beam BSO-S which consist of circular and square openings respectively were strengthened with TRC wrap around the opening area. The U-wrap arrangement was applied within the flexure zone.

Fig. 1 - Textile Reinforced Concrete (TRC) wrap.

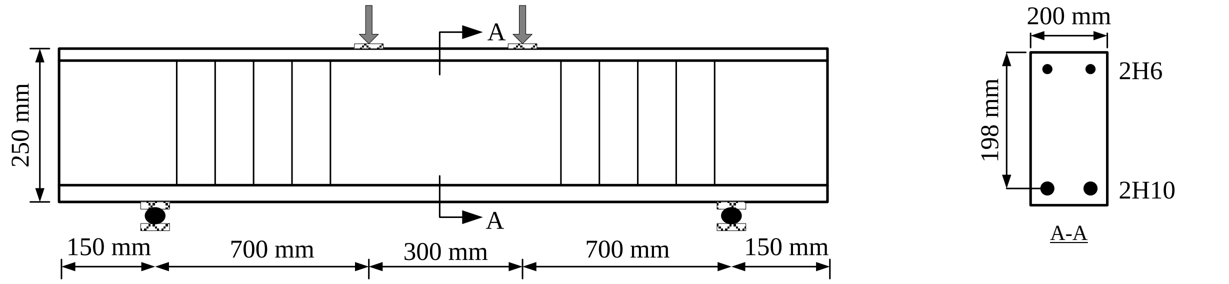
Table 1 - Beam specimens.

Beam	Types of Opening	Strengthening
BC	-	-
BCO	Circular	-
BSO	Square	-
BCO-S	Circular	TRC
BSO-S	Square	TRC

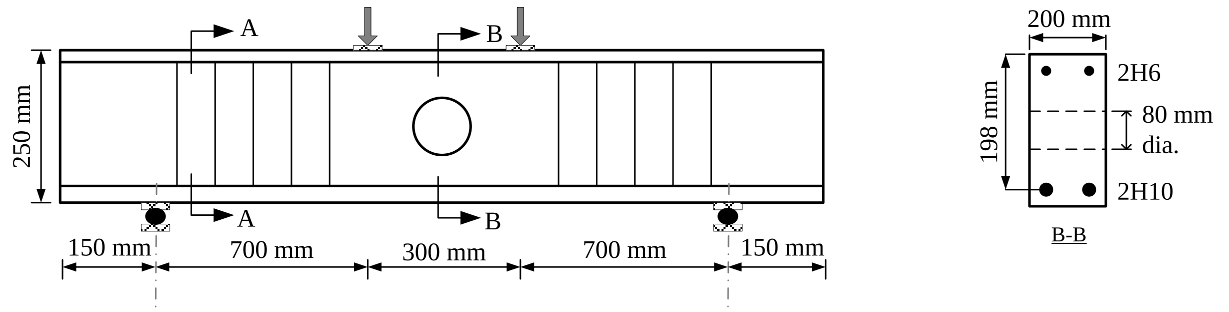
2.3 Strengthening Schemes by Textile Reinforced Concrete (TRC) Wrap

In the process of strengthening, TRC wrap was cut into a size of 700 mm x 300 mm which was based on the height and width of the beam for the U-wrap system. Strengthened area was located within the flexure zone and the opening of the beam. In order to ensure good bonding between concrete surface and TRC wrap, the targeted area to be strengthened was grinded and cleaned thoroughly from dust.

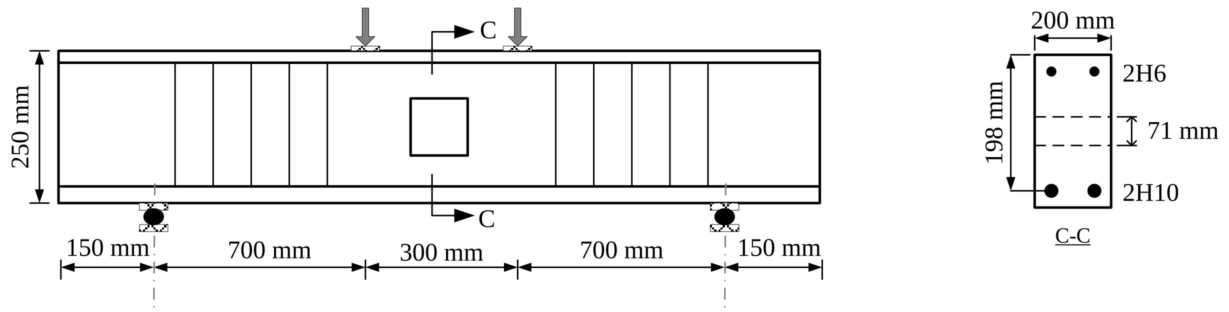
An epoxy resin, Sikadur 30, was used as the bonding agent. It was prepared using a resin-hardener ratio of 4:1. A thin layer of epoxy resin was placed onto the smooth beam surface before the TRC wrap was applied around the concrete beam which covered the flexure zone. The epoxy resin was also applied onto the TRC wrap as shown in Fig. 3. All the strengthened beams such as Beam BCO-S and Beam BSO-S were cured for 7 days before the beam test to provide sufficient bonding between the beam surface and the TRC wrap. Fig. 4 shows the strengthening configuration of the TRC wrap around the beam opening.



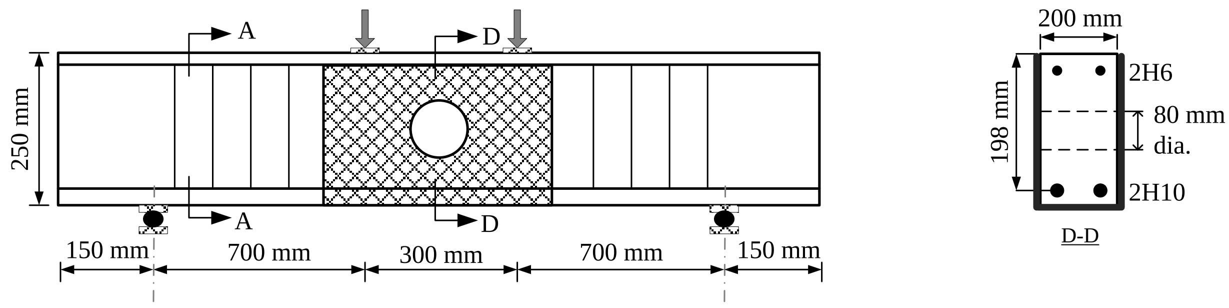
(a) Control Beam



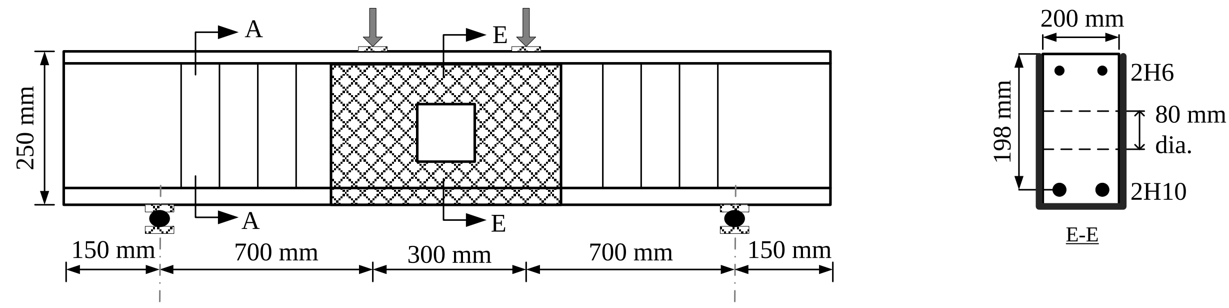
(b) Beam with circular opening



(c) Beam with square opening



(d) Strengthened beam with circular opening



(e) Strengthened beam with square opening

Fig. 2 - Beam geometry and dimension.

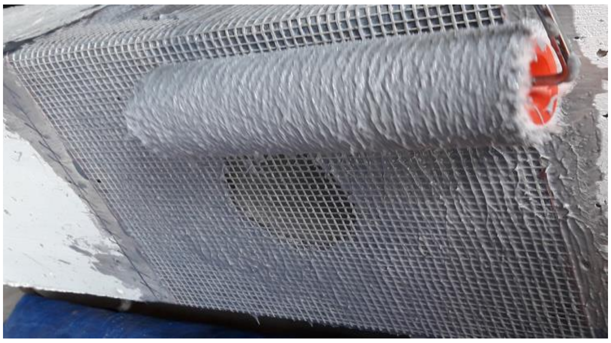


Fig. 3 - Strengthening configuration with TRC wrap.

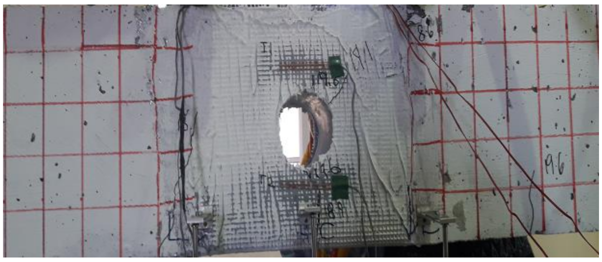


Fig. 4 - Strengthening configuration with TRC wrap.

2.4 Test Setup

Fig. 5 shows the beam setup during a four-point loading test. The beam test was conducted using a Universal Testing Machine (UTM) with a static load of 500 kN. Beam specimen was simply supported as it was placed on a pin and roller support at each end. Two point loads were applied 300 mm apart to the beam. Loads were applied until the beams failed. During the test, the deflection of the beam was measured by three linear variable displacement transducers (LVDT) with a 50 mm stroke. The LVDTs were placed at the point loads and the mid-span.

60 mm electrical resistance strain gauge was used to measure concrete strain. It was attached to the top of the compression surface of the beam's mid-span. During the test, crack formation on the beam surface was marked and labelled with corresponding incremental loads. Mode of failure was also recorded.

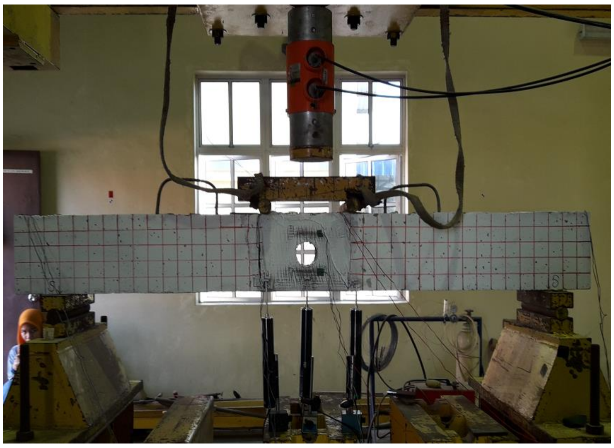


Fig. 5 - Test setup.

3. Results and Discussion

Experimental results in terms of ultimate load, deflection, crack pattern and modes of failure for all beam specimens were analysed. Flexural performances of concrete beams with circular and square openings as well as unstrengthened and strengthened concrete beams were compared in this study.

3.1 Load-deflection

Fig. 6 shows load-deflection curves among unstrengthened concrete beams such as the control beam, Beam BC, beams with circular opening (BCO) and beams with square opening (BSO). It can be seen that the control beam obtained a higher load capacity of 27.4 kN compared to Beam BCO and Beam BSO. This revealed that the presence of openings affects beam strength [2]. It may be due to the reduction in the cross sectional area of the concrete beam at the flexure zone which affects load distribution and crack propagation. The presence of openings also reduced the deflection of Beam BCO and Beam BSO.

On the other hand, a similar load carrying capacity was obtained by Beam BCO and Beam BSO which indicated that differently shaped openings do not significantly affect beam strength. However, Beam BCO experienced lower stiffness compared to the control beam.

Application of the TRC wrap as a strengthening material has increased the load capacity and stiffness of the beam as shown in Fig. 7 and 8. The strengthened concrete beams, BCO-S and BSO-S, obtained higher load capacities of 31.5 kN and 28.7 kN, respectively compared to unstrengthened concrete beams (Beam BC, Beam BCO and Beam BSO). Due to the superior performance of the TRC wrap, stiffness of the beams also increased. Hence, it can be concluded that strengthening of beam openings with TRC wrap was significant for increasing strength and stiffness of the beam.

Summary of test results is shown in Table 2. It can be seen that strengthened beam with circular opening, BCO-S, obtained the highest load capacity compared to other beams. This indicates that TRC wrap tends to increase the strength of beams with openings. All the beams failed in flexure except for the beams containing square openings which experienced shear failure at the opening.

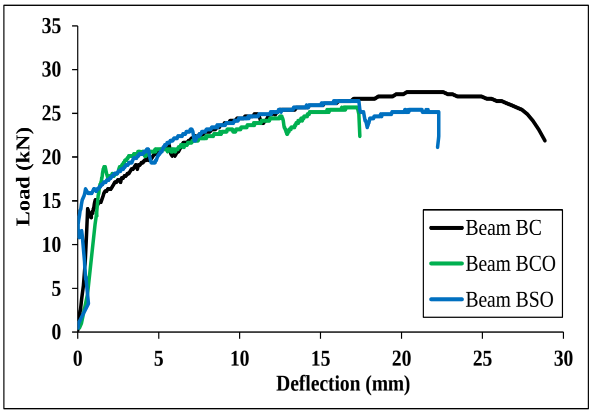


Fig. 6 - Unstrengthen concrete beams.

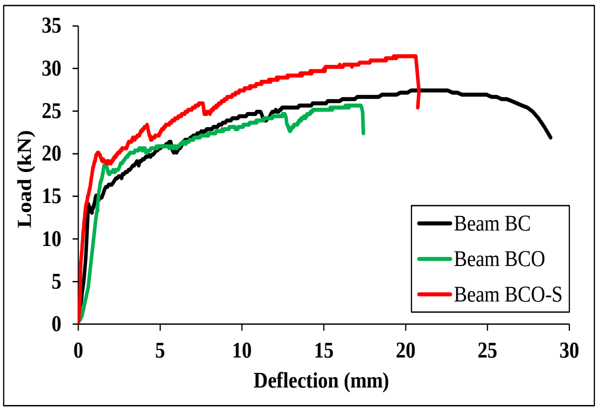


Fig. 7 - Comparison of unstrengthened and strengthened concrete beams with circular opening.

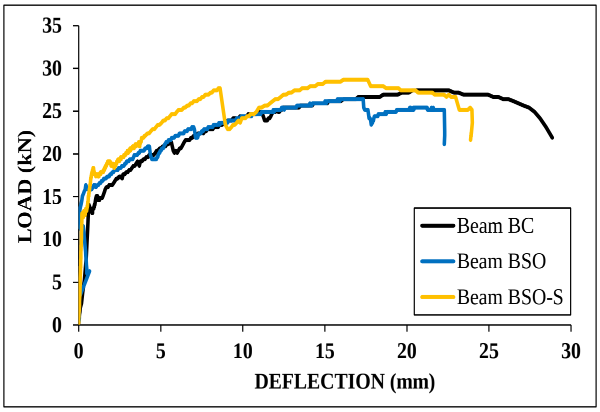


Fig. 8 - Comparison of unstrengthened and strengthened concrete beams with square opening.

Table 2 - Test results.

Beam	Ultimate Load (kN)	Deflection (mm)	Failure Mode
BC	27.4	22.6	Flexure
BCO	25.7	17.3	Flexure
BSO	26.7	17.3	Shear failure at the opening
BCO-S	31.5	20.6	Flexure
BSO-S	28.7	17.6	Shear failure at the opening

3.2 Crack Pattern

Fig. 9 shows the crack patterns of the control beam, Beam BC. From the observations made, the first crack occurred at the tension zone at the middle of the beam span. As the load increased, the new cracks appeared within the flexure zone and penetrated the neutral axis of the beam. The beam experienced flexural failure due to severe vertical cracks that formatted within the flexure region.

For unstrengthened concrete beams with openings such as Beam BCO and Beam BSO, the first crack occurred at the opening. For Beam BCO, the crack occurred at the middle of the beam span. As the load increased, the crack penetrated the circular opening which causes flexure failure due to severe cracks around the opening as shown in Fig. 10. For Beam BSO, it can be seen in Fig. 11 that severe cracks occurred at almost every corner of the square opening which indicated that it is the weakest part of the concrete beam. In this case, Beam BSO failed in shear at the corner of the opening due to critical diagonal cracks.

For strengthened concrete beams with circular openings (Beam BCO-S), the first crack occurred away from the strengthened area. However, as load increased, more vertical cracks developed within strengthened area that caused flexural failure at opening as shown in Fig. 12. Similar crack propagation was observed in strengthened concrete beams with square openings, Beam BSO-S, where first crack occurred away from the strengthened area. Due to increasing load, the diagonal cracks suddenly appeared at corner of the square opening and caused sudden shear failure at opening as shown in Fig. 13. Hence, Beam BSO-S failed severely at the opening area.

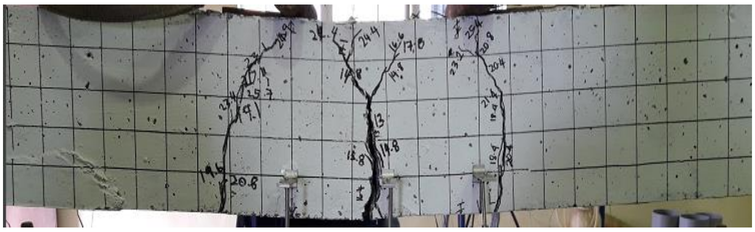


Fig. 9 - Crack pattern and failure mode of the control beam, Beam BC.

Fig. 10 - Failure mode of unstrengthened concrete beams with circular opening, Beam BCO.

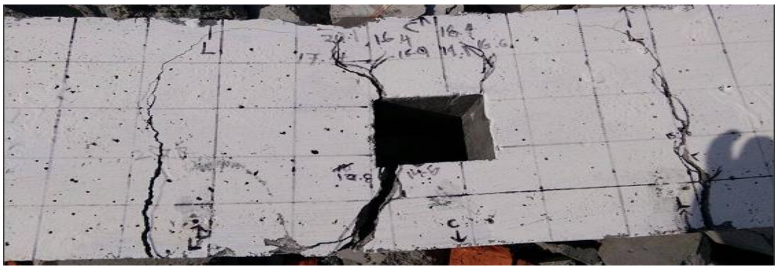


Fig. 11 - Failure mode of unstrengthened concrete beams with square opening, Beam BSO.

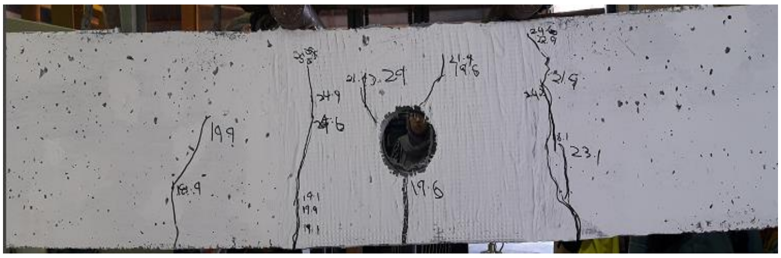


Fig. 12 - Failure mode of strengthened concrete beams with circular opening, Beam BCO-S.

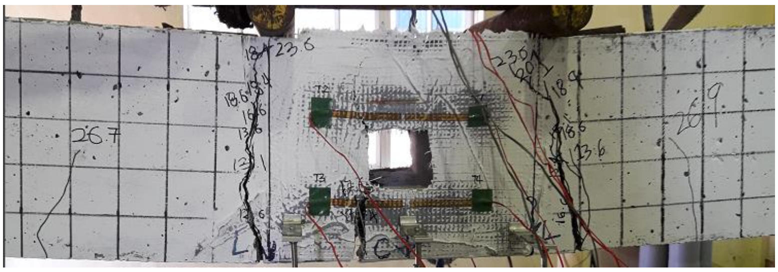


Fig. 13 - Failure mode of strengthened concrete beams with square opening, Beam BSO-S.

4. Conclusion

Based on the experimental results, the following conclusions can be drawn:

1. The control beam, Beam BC, obtained a higher load capacity and deflection compared to beams with openings such as Beam BCO and Beam BSO. The inclusion of openings in concrete beams significantly decreased beam strength due to the reduction of the cross sectional area of the beam.
2. Similar ultimate loads were obtained by Beam BCO and Beam BSO which indicated that differently shaped openings do not significantly affect the load carrying capacity of beams.
3. The application of TRC wrap as a strengthening material for beam openings significantly increased the ultimate load capacity and stiffness of beams.
4. Different crack patterns were found at circular and square openings. Beams with square openings experienced diagonal cracks at the corner of the opening due to high stress concentration. Meanwhile, beams with circular openings experienced vertical cracks near the opening area.

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