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Experimental Study on Shear Strengthening of RC Deep Beams with Large Openings Using CFRP

Siew Choo Chin[1*], Fadzil Mat Yahaya[1], DOH Shu Ing, Andri Kusbiantoro[2] and Wen Khai Chong[1]
[1]Faculty of Civil Engineering & Earth Resources, [2]Faculty of Technology,
Universiti Malaysia Pahang, Lebuhraya Tun Razak, 26300 Gambang, Kuantan, Pahang, Malaysia

Abstract: *This research deals with the experimental study on the behaviour of reinforced concrete (RC) deep beams with large circular openings and openings strengthened using externally bonded Carbon Fiber Reinforced Polymer (CFRP) composites in shear. The structural behavior including the load deflection behaviour, crack pattern, failure mode as well as strengthening configuration was investigated. A total of three (3) specimens of beams with design strength of 35 MPa were tested to failure under 4-points loading. The beam specimens included a solid RC deep beam as a control beam and two RC deep beams with large circular openings to determine the behaviour of un-strengthened and strengthened beams using CFRP wrap. The beams had a cross section of 120 mm x 600 mm and a length of 2400 mm. The openings were placed at the support on both sides of the shear span, at a distance 300 mm from the edge of the beam. The circular opening was designed to a standard of 0.45h which is considered as large circular opening with a diameter of 270 mm. Shear span-to-depth ratio (a/h) was 0.83 in which the distance between the loading point and the support was 500 mm. One of the test parameters presented in this paper was surface strengthening method. RC deep beam with the presence of large circular openings in the shear zone experienced substantial strength loss with a reduction of 51% as compared to the original structural capacity of the control beam. Comparing with the control beam, surface strengthening method could only manage to re-gain the beam capacity up to 56%.*

Keywords: *carbon fiber, circular, deep beams, openings, strengthening, surface method.*

1. Introduction

Reinforced concrete (RC) deep beams are widely used as transfer girders in offshore structures and foundations, walls of bunkers and load bearing walls in buildings. In fact, deep beams are very useful in tall buildings, also known as high rise buildings. In the offshore gravity type structures, deep beams also act as 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 ventilation systems and air conditioning ducts. Enlargement of such openings due to architectural/mechanical requirements or a change in the building's function would reduce the element's shear capacity, thus creating a severe safety hazard [1].

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, 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 in a more compact and economic design. Openings may be of different shapes and sizes depending on the requirement of the architect/mechanical engineer. The existence of web openings causes geometric discontinuity within the beam as well as 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 [2]. Various shapes can be provided depending on the purpose of usage; however the most common types of opening are rectangular and circular in shape [3].

Openings can be classified into two types; pre-planned and post-planned [4]. Pre-planned opening is the case whereby the shape, location and size of the opening are known during the design stage, before construction. Thus, internal strengthening around the opening is designed during the design stage to fully strengthen the deep beams with openings [5]–[7]. As for post-planned opening, drilling process is usually required due to relocation of building services in the existing structure/building. In this condition, strengthening of beams externally by using external strengthening material, known as fiber reinforced polymer (FRP), is a method used to re-gain the strength of the deep beams with opening up to the original structural capacity of the solid beam. The most commonly used external strengthening material is carbon fiber reinforced polymer (CFRP) since it is widely accepted by the research community and the industry due to its outstanding characteristics such as high tensile strength, light-weightness, resistance to corrosion and ease of application on site.

In the past decades, many attempts were conducted to investigate the behaviour of RC deep beams and strengthening behaviour of RC deep beams using external strengthening method to re-gain the original strength of the beam [8]–[10]. Recent studies were focused more on the behaviour of RC deep beams with openings (without strengthening) and the behaviour of RC deep beams with openings strengthened by FRP material [1], [11]–[14]. Various strengthening configurations were studied [15]. However investigations on the most effective strengthening method to re-gain the beam strength up to the original beam capacity of the solid beam seem to be lacking. This paper investigates the behaviour of un-strengthened and strengthening behaviour of RC deep beams with large circular openings in terms of crack pattern, failure mode and load-deflection behaviour. Strengthening configuration in terms of surface strengthening is considered in this study.

2. Methodology

2.1. Specimen Details

A total of three (3) RC deep beams were considered in this study. The beams include a solid beam as the reference beam while the remaining beams were with openings located at the middle of the shear span. All the beams had a cross-section of 120 mm x 600 mm and a length of 2400 mm. As for the steel reinforcement, two 16 mm diameter bars were used as the tension reinforcement, whereas two 10 mm diameter bars act as the compression reinforcement. Shear reinforcement of 6 mm diameter was spaced at 300 mm and 150 mm center to center in both vertical and horizontal directions, respectively. Arrangement of reinforcement bars for the control beam and RC deep beam with circular opening are shown in Figs. 1 and 2.

RC deep beams with the provision of two openings, one in each shear span, placed symmetrically about the mid-point of the beams. The openings were created using polystyrene for circular openings. The size of circular openings considered was 270 mm in diameter, with an opening diameter-to-depth (d/h) ratio of 0.45. In this experimental work, the circular opening was considered as large opening as the ratio of the opening diameter to the total beam depth is greater than 40% [5]. The beams with openings were cast to resemble the case of the inclusion of an opening in an existing beam.

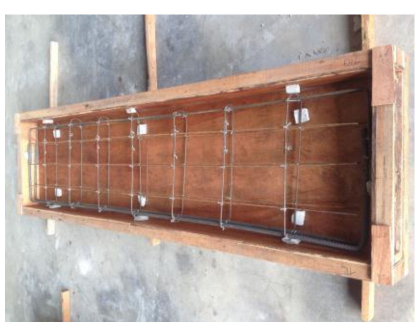

Fig. 1: Arrangement of reinforcement bars for control beam

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Fig. 2: Arrangement of reinforcement bars for RC deep beam with circular openings

2.2. Material Characteristics

Ready-mix concrete of grade 35 MPa was used in this experimental study. In order to achieve concrete strength uniformity, all the beam specimens were fabricated using the same batch of concrete. The beams were cast in wooden formworks. After 24 hours, the beams were removed from the formworks and cured for 28 days using wetted gunny bags. TABLE I summarizes the beam specimens considered in this study. The type of CFRP wrap used is called SikaWrap 231C with 4.90 GPa tensile strength and 230 GPa tensile modulus. It is 1.27 mm in thickness and has a 2.1% elongation failure. The CFRP wrap was bonded onto the surface of the beam specimens using epoxy resin, Sikadur 330, with a thickness of 3 mm using wet application method. Surface preparation was conducted before any application of the CFRP wrap. Such preparation work including sandblasting, grinding and cleaning is to ensure that the surface of the beam specimens were free from dust and dirt as well as for better adhesiveness between the CFRP wrap and epoxy resin. All the beams were cured for one week after the application of CFRP wrap before testing.

TABLE I: Beam Specimens

Beam	Opening		
	Shape	Center Distance (from support)	Conditions
CB	-	-	-
NS-BCO	Circular	135mm	Without CFRP
SS-BCO	Circular	135mm	With CFRP

2.3. Test Setup

All the beam specimens were tested until failure under four point loading by using Magnus frame of 500 kN. The test setup is depicted in Fig. 3. As shown in the figure, the beam specimen was placed on two supports which were at a distance of 1800 mm apart. The applied load was transferred through two loading points which positioned at a distance of 800 mm apart with the aid of a spreader beam. Beam deflection was monitored and recorded via linear variable displacement transducer (LVDT), placed at the bottom soffit of the beam. The crack propagation and crack pattern were marked until beam failure.

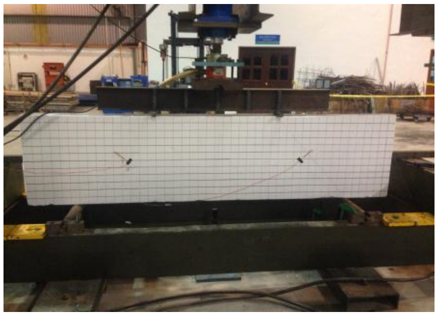


Fig. 3: Test Setup

2.4. Strengthening Configuration

Strengthening configuration considered in this study is shown in Fig. 4. CFRP wrap with vertical fibers perpendicular to the beam axis was bonded on the beam surface using epoxy adhesive. The width of the CFRP wrap on both sides was 500 mm.

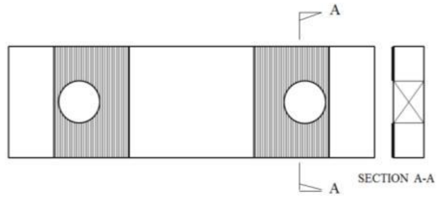


Fig. 4: Strengthening Configuration

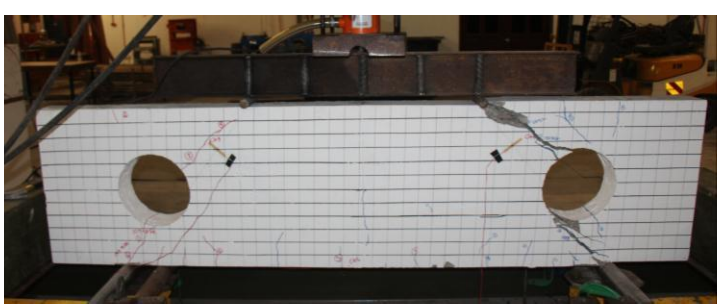
3. Result and Discussion

3.1. Crack Pattern and Failure Mode

Failure of both the solid beam (CB) and un-strengthened beam with openings (NS-BCO) were due to the formation of diagonal cracks at the shear region that appeared between the loading point and support. During the testing, the load was periodically stopped for cracks observation and then the crack pattern was recorded.

Referring to the crack pattern of control beam (CB) in Fig. 5(a), vertical cracks were seen propagating from the edge of the beam along the flexural zone. As observed in the un-strengthened beam with openings, NS-BCO in Fig. 5(b), the failure mode was in shear. Similarly as observed in CB, flexural cracks were seen along the tension zone during the loading stage. Upon beam failure, two independent diagonal cracks were seen propagating from the loading point towards the opening, as well as from the opening to the support. In the case of strengthening, no flexural cracks were traced along the mid-span of beam SS-BCO as depicted in Fig. 5(c). Mild diagonal cracks were seen on the surface of the CFRP wrap in both shear span at the top and bottom chords of the openings. Furthermore, diagonal cracks were also exhibited on the other surface of beam SS-BCO (without strengthening) which lead to beam failure with further incremental of load. There was no sign of CFRP debonding detected from the surface strengthening. The crack pattern and failure mode of each beam specimen are depicted in Fig. 5.

a) Control Beam



b) RC Deep Beam with Circular Openings (NS-BCO)

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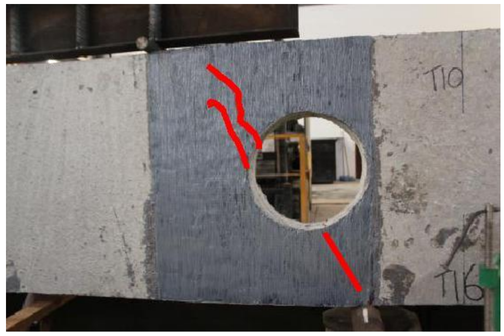

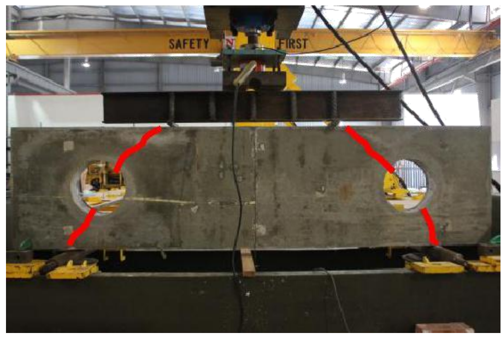

c) Surface Strengthening of RC Deep Beam with Circular Openings (SS-BCO)

Fig. 5: Crack Pattern and Failure Mode of Control Beam, Un-Strengthened and Strengthened Beams with Openings

3.2. Load-Deflection Behaviour and Ultimate Load

Load deflection curves comparison between non-strengthened and strengthened deep beams with circular openings and control beam is shown in Fig. 6. The experimental results obtained for CB show that the maximum load that the beam was able to sustain was 425.12 kN with a deflection of 12.79 mm. With the presence of large circular openings in both shear spans, the maximum load achieved in beam NS-BCO was 207.47 kN at 8 mm deflection, with a reduction of 51% as compared to the original beam capacity of the control beam, CB. As shown in the load-deflection curve, strengthened beam, SS-BCO managed to attain an ultimate load of 239.29 kN with a deflection of 10.9 mm. With the surface strengthening configuration, the strength re-gain was only 56% of the structural capacity of the control beam, CB. From the results obtained, it is evident that the surface strengthening with vertical alignment of CFRP fiber around the circular opening increases the beam capacity and enhanced the deflection behaviour as well as increased in beam ductility before failure. The test results are summarized in TABLE II.

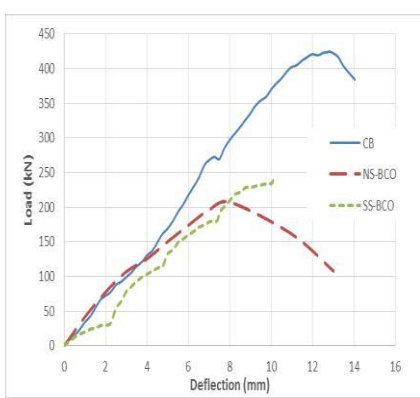

Fig. 6: Load-deflection Curves Comparison

TABLE II: Test Results

Beam Specimens	Ultimate load (kN)	Deflection (mm)	Percentage Reduction (%)	Percentage of Strength Re-gain, (%)
CB	425.12	12.79	-	-
NS-BCO	207.47	8.0	51	-
SS-BCO	239.26	10.9	-	56

3.3. Crack Pattern Analysis

Based on the crack pattern results, it was found that the crack pattern detected in the un-strengthened beam with large circular openings on the right shear span is in the form of frame-type failure. This type of failure occurs due to the formation of two independent diagonal cracks, one in each of the chord members, above and below the opening. On the other hand, the crack pattern observed in the strengthened beam with circular openings is similar to beam-type failure. The mode of shear failure at small circular opening analysed by Mansur [16], [17]. This type of failure has a 45° inclined failure plane, similar to a solid beam as assumed in which the plane is being traversed through the center of the opening as shown in Fig. 7. This implies that frame-type failure which occurred in un-strengthened beam was transformed to beam-type failure after CFRP surface strengthening in beam with large circular openings.

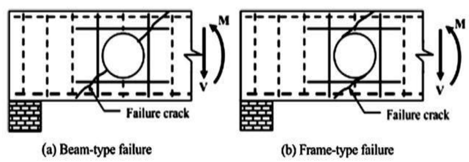

Fig. 7: Two modes of shear failure in small opening [16], [17]

4. Conclusion

An experimental study was conducted to investigate the behaviour of RC deep beams with large circular openings provided in the shear region strengthened by CFRP wrap. The mode of failure identified in deep beams with large circular openings was shear failure in which diagonal cracks were formed at the top and bottom chords of the openings. RC deep beam with large circular opening experienced substantial strength loss with a reduction of 51% as compared to the beam capacity of the control beam. Surface strengthening using CFRP wrap around the opening could increase the ultimate load capacity, about 15.32% as compared to the un-strengthened beam. Comparing with the reference beam, this strengthening method could only re-gain the beam capacity up to 56%.

5. Acknowledgements

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