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Shear strengthening of RC deep beams with circular openings using externally bonded SFRP composites

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ABSTRACT: This study presents an experimental investigation performed on reinforced concrete (RC) deep beams with circular openings strengthened using externally bonded sprayed fiber reinforced polymer (SFRP) composites. The research parameters investigated were openings size, thickness of SFRP and orientation of SFRP. A total of 8 RC deep beams with circular openings were constructed and tested under three-point bending. Test specimen had a cross section of 100 x 500 mm and a total length of 1050 mm. Two circular openings, one in each shear span were placed symmetrically about the mid-point of the beam. SFRP was applied either on both lateral faced or on three faces (U-shaped) excluding the top face. An anchorage system was utilized to enhance the bond between concrete and SFPR. It was found that externally bonded SFRP and anchored with mechanical anchors are very effective to enhance the shear strength of deep beams. The strength gain caused by the SFRP was in the range of 64%-130%. Also, SFRP applied on 3 sides (U-shaped) was found to be more effective than 2-sided SFRP in shear strengthening.

1 INTRODUCTION

The Reinforced Concrete (RC) deep beam is a beam with the depth comparable to the span length. Based on ACI 318-05, an RC beam is defined as a deep beam if the span length-to-depth ratio is less than or equal to four (ACI-318, 2005). There are several applications of RC deep beams, such as transfer girders in bridges and buildings. Rectangular and circular openings of various sizes are sometimes made in the web of the beams to allow for the passage of utilities ducts and conduits for air conditioning and electrical cables. If the web opening is located amidst the load path that joins the support and the loading points, the opening may disturb the flow of the load, resulting in a decrease in the shear capacity. Extensive studies have documented attempts to strengthen RC deep beams without web openings and with web openings. Zhang et al. 2004 investigated the shear behavior of RC deep beams with externally bonded carbon fiber reinforced polymer (CFRP). It was found that externally bonded CFRP are very effective to restore shear capacity of RC deep beams. Islam et al. 2005 explored the prospect of strengthening structurally deficient deep beams by using an externally bonded fibre reinforced polymer (FRP) systems. RC deep beams were strengthened using carbon fibre wrap, strip or grids. Test results have shown that the use of externally bonded FRP system leads to a much slower growth of the critical diagonal cracks and enhances the load-carrying capacity of the beam to a level quite sufficient to meet most of the practical upgrading requirements. Maaddawy&Sherif 2009 examined the potential use of externally bonded carbon fiber reinforced polymer (CFRP) composite sheets as a strengthening solution to upgrade reinforced concrete (RC) deep beams with openings. Two square openings, one in each shear span, were placed symmetrically about the mid-point of the beam. Test parameters included the opening size, location, and the presence of the CFRP sheets. Externally bonded CFRP shear strengthening around the openings was found very effective in upgrading the shear strength of RC deep beams. The strength gain caused by the CFRP sheets was in the range of 35–73%.

Recently, a new strengthening technique Sprayed Fiber Reinforced Polymer (SFRP) composites has been applied to strengthen concrete members (Banthia& Boyd 2000). In the SFRP technique, chopped fibers of a controlled length are sprayed with a polymer resin using a spray gun that is mounted with a chopper unit and epoxy containers. Banthia et al. 2002 investigated the performance of the SFRP and compared with uni-directional FRP. The experimental results showed that that the SFRP retrofitted girder had a 96% increase in the ultimate load over an un-retrofitted specimen, whereas the FRP retrofitted girder had a 33% increase in the ultimate load. The SFRP technique was also effective to increase the strength and stiffness of shallow RC beams. Boyd 2000 investigated the influence of various types of SFRP strengthening schemes on the shear strength of shallow RC beams. Soleimani&Banthia 2012 investigated the performance of SFRP shear strengthening of RC beams. In their research, an anchoring technique using through bolts and nuts with a roughened concrete surface were introduced to enhance the bond between the concrete surface and the SFRP. Hussain&Pimanmas 2014investigated axial load behavior of concrete confined with SFRP and shear strengthening of RC deep beams using externally bonded SFRP. SFRP was found very effective to increase strength and ductility of RC members. The present study mainly focused on shear strengthening of RC deep beams with circular web openings using SFRP. Two different sizes of circular web openings were investigated. The deep beams with openings were strengthened with a variety of SFRP thicknesses and strengthening configurations.

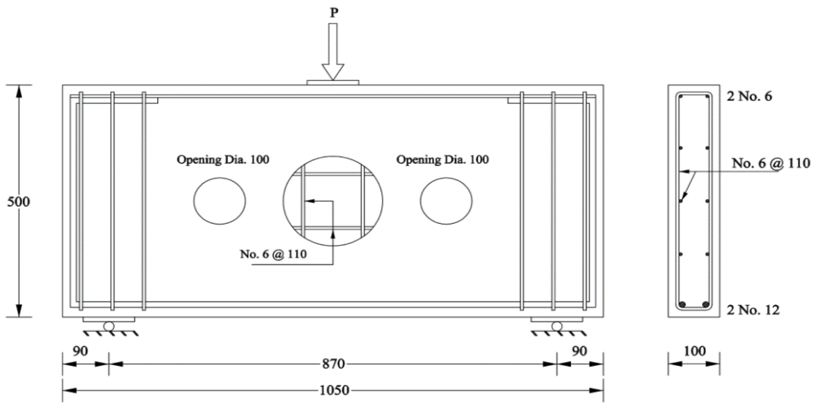


Figure 1. Group A beam details (unit in mm)

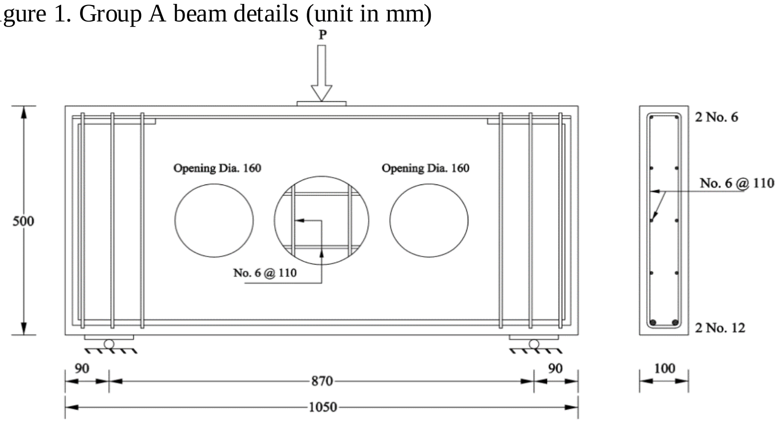


Figure 2. Group B beam details (unit in mm)

2 EXPERIMENTAL PROGRAM

2.1 *Test Specimen and Test Matrix*

In the experimental programme, RC deep beam specimens were cast and strengthened by SFRP technique. Beams were designed in such a way to cause shear failure prior to any flexural distress. A schematic representation of the specimen and reinforcement details is illustrated in Figures 1 & 2. All beams were 1050 mm long, having a rectangular cross-section of 100 ×500 mm and the effective span length of 870 mm. The flexural reinforcement consisted of 2 No. 12 (deformed bars). Vertical and horizontal web reinforcements of No. 6 (round bars) were provided at 110 mm centre-to-centre spacing. Clear concrete cover of 15 mm was provided on all beam faces.

2.2 *Test Matrix*

The experimental program consisted of 8 RC deep beam specimens. The entire test matrix (see Table 1) is divided into two based on size of web openings. Each group contained four beams and one beam in each group was used as a control un-strengthened specimen. Each specimen was assigned a designation that represented the fiber thickness, the strengthening configuration and the size of the openings. As an example, a specimen designation 5B-160 was interpreted as follows: 5B = 5 mm thickness of SFRP with strengthening configuration B and 160 indicated a circular opening with a diameter of 160 mm.

Table 1. Test matrix details

Groups	Beam designation	Openings size	SFRP thickness	SFRP configuration
Group A	CON-100	100	-	-
	3A-100	100	3	A
	5A-100	100	5	A
	5B-100	100	5	B
Group B	CON-160	160	-	-
	3A-160	160	3	A
	5A-160	160	5	A
	5B-160	160	5	B

2.3 *SFRP Strengthening*

In this research, the SFRP strengthening of RC deep beams was performed using glass fibers. The specimens were strengthened with two SFRP thicknesses (i.e., 3 mm and 5 mm) and two strengthening configurations (i.e., A and B). For strengthening configuration A, the SFRP was applied onto side faces of the beam only. For strengthening configuration B, the SFRP was applied onto the side and bottom faces (Fig. 3) in the form of U shape. Prior to the SFRP application, the concrete surfaces were roughened using a hammer and a chisel to enhance bonding with SFRP. The SFRP was applied onto the specimens by a local contractor using an UltraMax chopper/Saturator unit manufactured by Magnum Venus Plastech. After the SFRP was applied, an aluminum ribbed roller was used to remove any entrapped air and to obtain a uniform thickness of the SFRP. A typical SFRP strengthened RC deep beam is shown in Figure 4.

2.4 *Material Properties*

The 28-day cylindrical compressive strength of concrete for specimens in both groups A and B was 24 MPa. The fibers used for the SFRP was a glass-fiber roving manufactured by Jushi Group Co., LTD under the product name “ER13-2400-180” as shown in figure 5. The primary resin used for SFRP was polyester resin manufactured by QualiPoly Chemical Corporation in Taiwan under the product name “QL-7241”. The catalyst which was used to initiate the curing of resin was “ButanoxM-60”, manufactured by Keum Jung Akzo-Nobel Peroxides Ltd., China.

2.5 *Mechanical Properties of Material Properties of SFRP*

The tensile strength of SFRP composite was determined following the test methods of ASTM Standards D638 (ASTM D638, 1999) with slight modification in the size of test strip as shown in Figure 6. The density and the fiber-volume fraction were measured using ASTM methods D792 and D2584 (ASTM D792, 2000; ASTM D2584, 2002), respectively. The average test results are summarized below;

Tensile strength = 95 MPa; Density = 1.47 g/cm^3; Fiber volume fraction = 30-40%

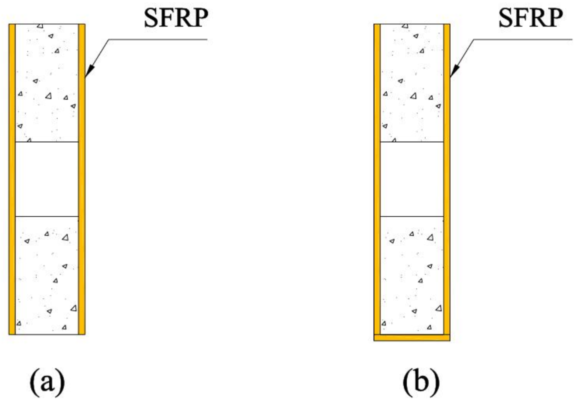


Figure 3. SFRP strengthening configurations; (a) SFRP configuration A, (b) SFRP configuration B

Figure 4. Typical SFRP strengthened RC deep beam with openings

Figure 5. Glass fiber roving

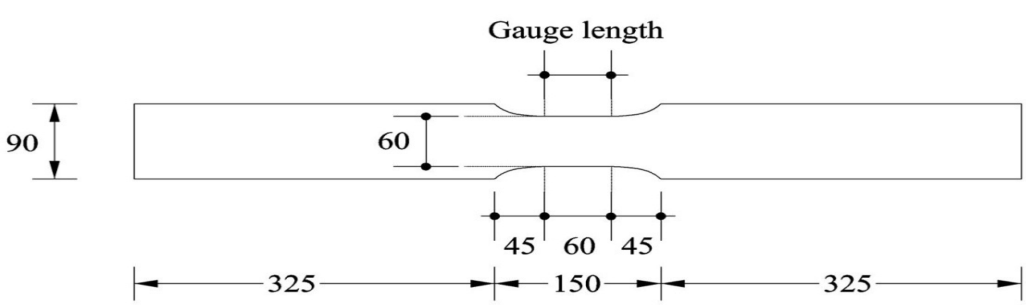


Figure 6. SFRP tensile strip details (unit in mm)

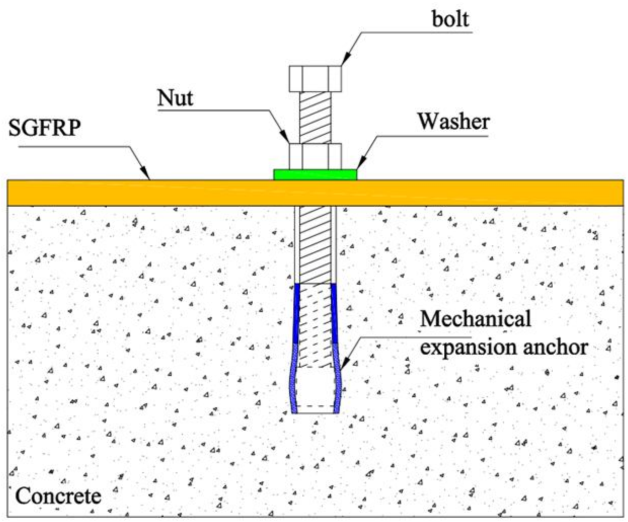


Figure 7. MB anchoring system

2.6 *MB Anchoring System*

The “MB anchoring system” as proposed by Hussain&Pimanmas 2014 was used to avoid de-bonding of the SFRP from the concrete surface. The mechanical expansion bolt (MB) anchoring system consisted of mechanical expansion anchors with a diameter of 7 mm and a length of 25 mm, full-threaded hex-headed bolts with a diameter of 4 mm and a length of 35 mm and nuts and washers (Fig. 7). The installation details of MB anchoring system can be found in Hussain&Pimanmas 2014.

2.7 *Loading Setup*

The specimens were tested under a concentrated load applied at the mid-span in a simply supported arrangement. The length of the beam measured from support to support was 750 mm. Linear variable differential transducers (LVDTs) were placed under the beam at the mid span to measure vertical deflection as shown in Figure 8.

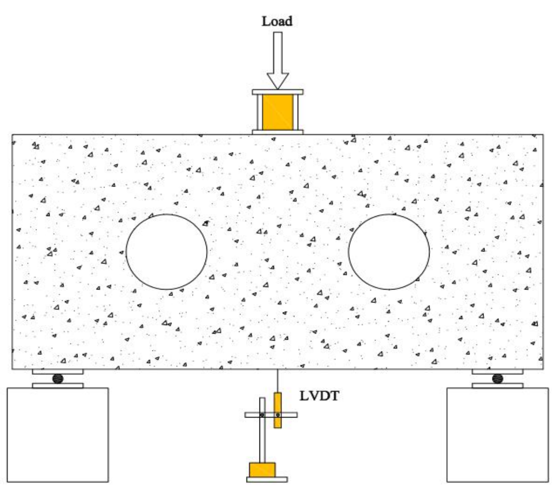


Figure 8. Loading setup

3 RESULTS AND DISCUSSION

3.1 *Load Deflection Behavior*

The load deflection behavior of strengthened RC deep beams with openings varies significantly depending on the thickness of SFRP and configuration as shown in Figures 9 & 10. This variation provides a useful measure of the performance of SFRP strengthened RC deep beams with openings. The effectiveness of SFRP strengthening, SFRP thickness and SFRP configuration is evaluated and discussed in the following section. The test results are summarized in Table 1:

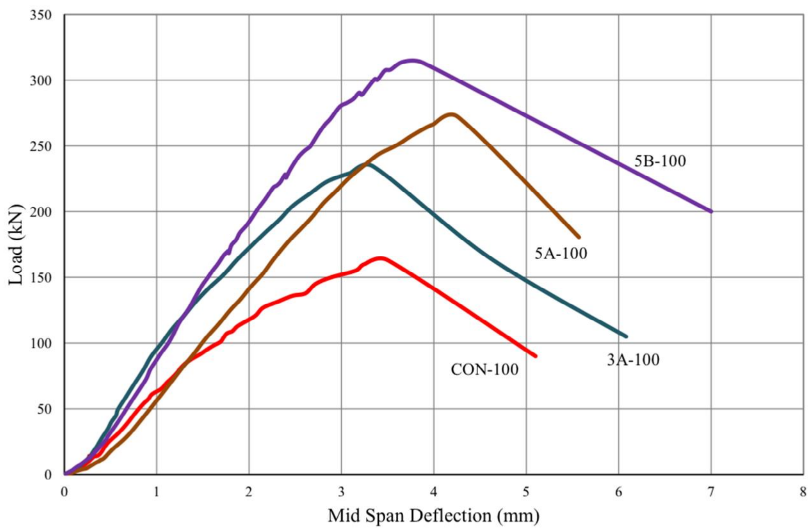


Figure 9. Load deflection response of Group A beams

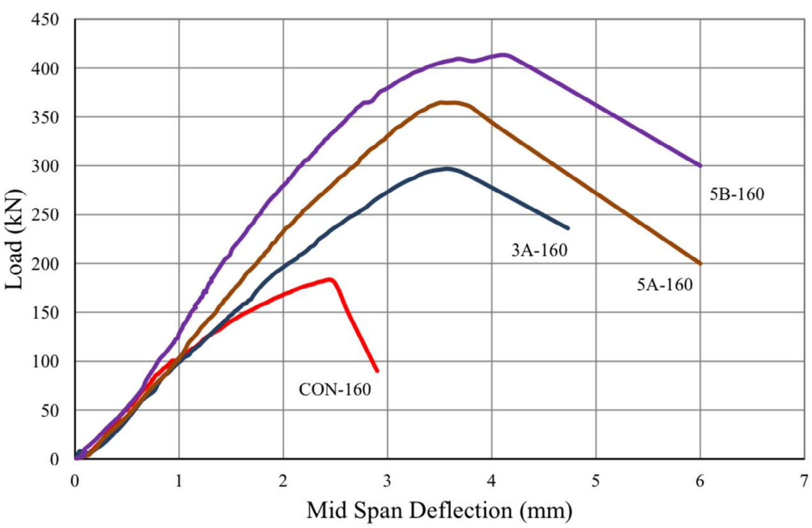


Figure 10. Load deflection response of Group B beams

Table 2. Test results

Groups	Beam designation	Peak load (KN)	% Increase in peak load	Mid span deflection (mm)
Group A	B-100	197.40	-	2.34
	3A-100	348.66	77.00	3.62
	5A-100	374.36	90.00	3.48
	5B-100	453.81	130.0	4.52
Group B	CON-160	181.20	-	2.50
	3A-160	296.61	64.00	3.60
	5A-160	364.52	101.0	3.51
	5B-160	411.90	127.0	4.02

3.2 *Effect of SFRP thickness*

3.2.1 *Group A*

To investigate the effect of SFRP thickness on the ultimate load and deflection of RC deep beam with openings, load deflection curves of specimen 3A-100 (3 mm thick SFRP) and 5A-100 (5 mm thick SFRP) along with the control beam are shown in Figure 18, and the comparison of ultimate loads is displayed in Figure 24(a). It can be seen that both ultimate load and mid-span deflection were elevated with an increase in SGFRP thickness. Beam 3A-100 and 5A-100 reached 77% and 90% higher ultimate load than the control beam (CON-100), respectively.

3.2.2 *Group B*

Similar to group A beams, both ultimate load and mid-span deflection were elevated with an increase in SFRP thickness for SFRP strengthened beams of group B. Load deflection curves of Group B beams are shown in figure to evaluate the effect of SFRP thickness. Beam 3A-160 and 5A-160 reached 64% and 101% higher ultimate load than the control beam (CON-160), respectively.

3.3 *Effect of SFRP Configuration*

In this experiment, three strengthening configurations, namely configurations A and B were studied (see Fig. 3). To compare the effectiveness of different strengthening schemes, ultimate loads of beams are compared in the figure. As can be seen, the strengthening configuration B demonstrates a consistently superior performance over strengthening configurations A. RC deep beam specimens' 5B-100 and 5B-180 attained 40% and 26% higher increase in the ultimate load as compared with beams 5A-100 and 5A-180, respectively.

3.4 *Effect of Opening Size*

From the experimental test results, it can be seen that there is found decrease in shear strength with increase in circular openings size. The tendency of strength decrease is observed for both un-strengthened and SFRP strengthened RC deep beams with openings. The comparison of ultimate loads for both un-strengthened and strengthened beam specimens are shown in Figure 12. For un-strengthened specimens, when the circular opening size is increased from 100 mm diameter to 160 mm diameter, the reduction in the peak load was found to be 8.2%. Similar tendency (i.e. decrease in strength with an increase in the opening size) was also observed in SFRP strengthened RC deep beam specimens as shown in Figure 12.

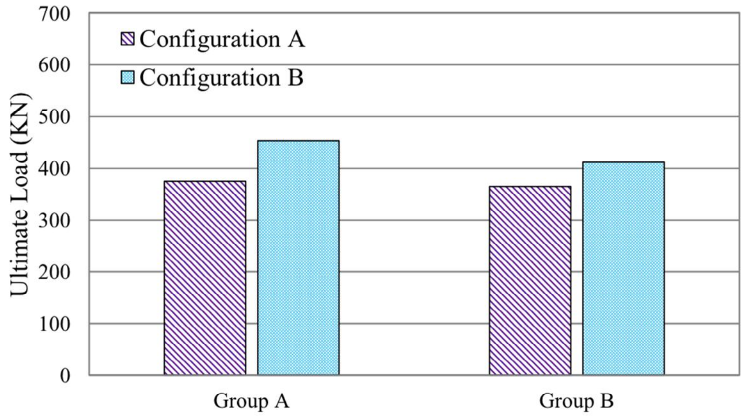


Figure 11. Effect of SFRP configurations

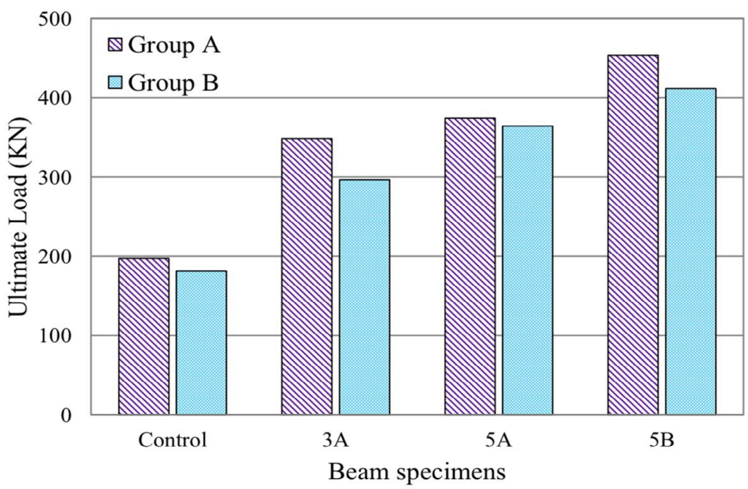


Figure 12. Effect of openings size

4 FAILURE MODES

The un-strengthened control beams of both groups showed a similar failure mode regardless size of the openings. In these beams, the failure occurred when the inclined cracks suddenly formed towards the loading and supporting regions as shown in Figure 13 & Figure 14. A similar failure mode for RC deep beams with circular openings is also reported in the previous studies (Kumar 2012). However, the SFRP strengthened beams in both groups, failed by the formation of inclined crack ruptures in the fiber at the top and bottom chords of the openings as shown in Figure 15.

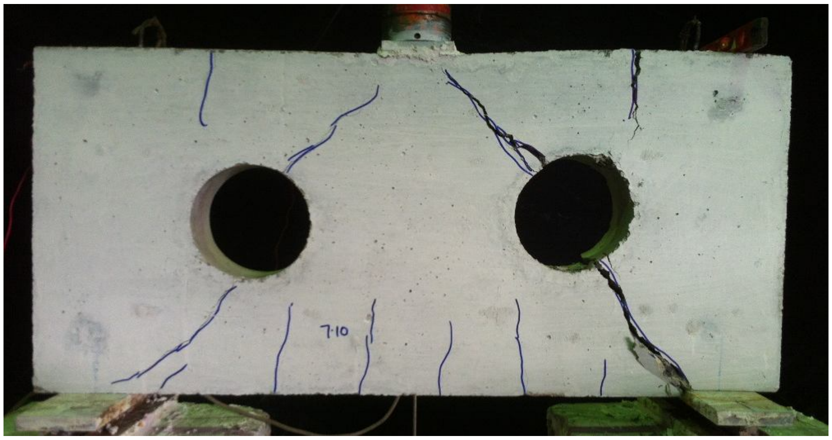


Figure 13.Un-strengthened beam specimen (openings size = 160 mm diameter)

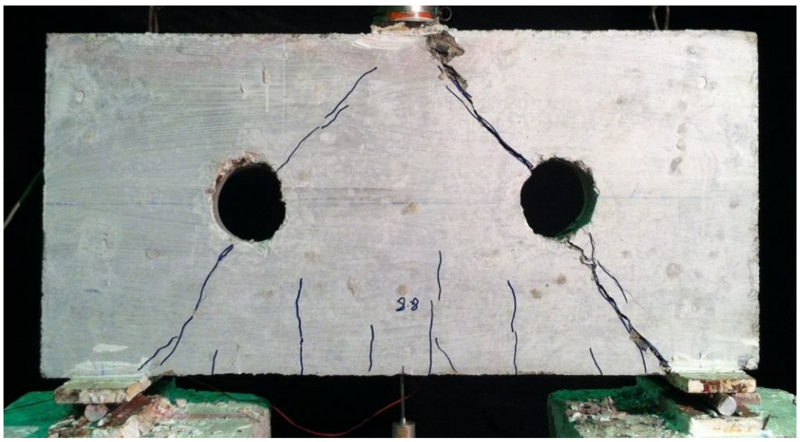
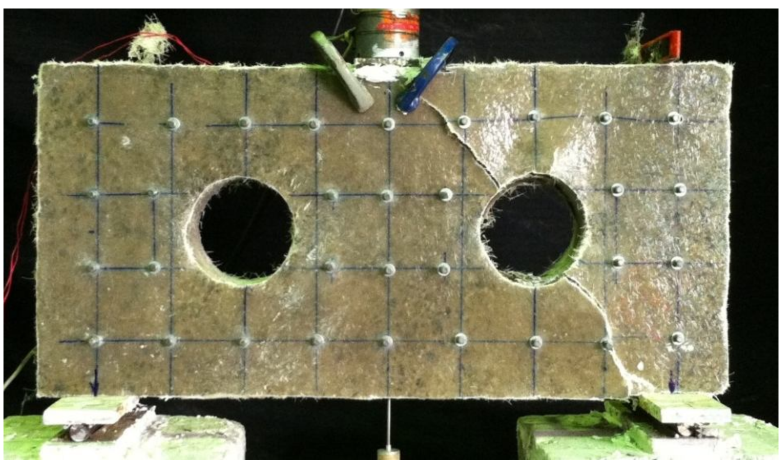


Figure 14. Un-strengthened beam specimen (openings size = 100 mm diameter)



SFRP strengthened beam specimen

Figure 15. Typical failures of RC deep beams with openings

5 CONCLUSIONS

In this paper, results of an experimental study on RC deep beams with circular openings using SFRP are reported. Based on results, it can be concluded that externally bonded SFRP and anchored with mechanical anchors are very effective to enhance the shear strength of deep beams with openings. The increase in the ultimate load of RC deep beams with opening varied with the thickness of SFRP. Also, SFRP applied on 3 sides (U-shaped) was found to be more effective than 2-sided SFRP in shear strengthening.

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