Numerical Study on Strengthening Of RC Deep Beam with Openings

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Abstract – Reinforced concrete deep beams are widely used as transfer girders in offshore structures and foundations, walls of bunkers and load bearing walls in buildings. 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/mechanical requirements and a change in the building's function would reduce the element's shear capacity, thus rendering a severe safety hazard. When such enlargement is unavoidable adequate measures should be taken to strengthen the beam and counteract the strength reduction. This research aims to investigate how to increase the structural strength of reinforced concrete deep beam with openings. Two approaches are under consideration; internal strengthening and external strengthening, the first is the effect of steel reinforcement bars near the opening, and the second is attaching FRP layers around the opening. The software ANSYS 16 is used to handle the nonlinear finite element analysis. The FRP strengthened structures may fail by de-bonding of fibres from the concrete surface. Mechanical anchoring systems has been introduced in order to prevent the de-bonding of FRP composite sheets from the beam surface. The size, shape and location of the openings varied for different models. Square openings of sizes 180 x 180mm & 120 x 120mm and circular openings of diameter 160mm & 100mm were provided. Externally bonded fiber reinforced polymer sheets were found to be very effective in enhancing the ultimate load and strength of the RC deep beams. Introducing reinforcement bars around both the square and circular openings also enhance the ultimate strength of the beam. Increase in the opening size, regardless of the shape led to the reduction in the shear strength of the beams. The mechanical anchors was found to be effective in preventing the de bonding failure.

1. INTRODUCTION

A beam with the depth comparable to the span length is considered as a deep beam. Reinforced concrete deep beams find its applications in offshore structures, tall buildings, walls of bunkers, foundations etc. The creation of web openings is often required for the accommodation of electrical and mechanical conduits. The existence of openings cause geometric discontinuity and also the current code of practices do not include the provision for design of deep beams with openings. The presence of web openings in deep beams leads to early diagonal cracking and also in the significant reduction in the shear strength. There are two types of openings 1) Pre planned openings 2) Post planned openings. In pre-planned openings the size and location of the opening will be known during the design stage itself. In this case adequate internal strengthening can be provided during the design stage itself. But in the case of post planned openings internal strengthening is not applicable. The only possible criteria is to externally strengthen the structural element using fibre reinforced polymer. This is the only method which can be used to regain the strength of the element up to the original capacity. From the previous experimental studies it is clear that reinforced concrete deep beams strengthened by FRP composites fail by de bonding of the fibres from the beam surface. To avoid such failures mechanical anchoring systems has been introduced to securely attach the FRP to the beam surface.

There are 2 methods to strengthen the RC deep beams with opening which including internal strengthening and external strengthening. Internal strengthening used the different patterns and quantities of steel bar erected around the opening while external strengthening material by pasting the externally bonded composite materials around the opening in varying arrangement and configuration schemes. Internal Strengthening Method is favourable when the opening is pre-planned before the construction or during the design stage. The location and size of opening are known in advanced.The web reinforcement played an effective role in controlling the propagation of crack width, upgrading the ultimate shear strength, and deflection that due to stress concentration around the openings. The existence of longitudinal bars on the upper and lower of the opening are very effective in controlling the flexural strains and cracks around the opening. In order to increase the ultimate strength and decrease the deflection of the deep beams with opening, diagonal bars were installed for corner reinforcement as well as the small stirrups at the openings top and bottom**.** External Strengthening Method is much beneficial when the opening is introduced after the construction which cannot meet any design consideration and analysis about the opening. The openings were drilled in an existing structure while the problem may arise during and after the process. This happened often due to the M&E engineers re-locate the opening location to simplify the arrangements of ducts and pipes in order to achieve the huge savings in term of costs, materials and time. External strengthening can be classified into traditional method and modern method. Referring to the traditional method, steel plate can be installed on to the RC beams by adhesive bonding and bolted construction. This can increases the serviceability & ultimate load capacity of the RC beam section and available for maintenance & inspection. Disadvantages of using steel plate as external strengthening are taking part of corrosion that become heavy when come in bigger size and need specialized in handling & installation.

2. LITERATURE REVIEW

Tamer El Maaddawy *et al*. (2009) worked on "FRP composites for shear strengthening of reinforced concrete deep beams with openings". The use of externally bonded carbon fibre reinforced polymer (CFRP) composite sheets for strengthening reinforced concrete deep beams were studied. A total of 13 deep beams with openings were constructed and tested under four-point bending. Two square openings, one in each shear span, were placed symmetrically about the mid-point of the beam. Opening size, location and the presence of CFRP sheets were the parameters examined.

It was concluded from the test results that externally bonded CFRP shear strengthening around the opening was found to be very effective in enhancing the shear strength of RC deep beams. The increase in the strength due to CFRP was in the range of 35 % - 73 %. A method of analysis for shear strength prediction of RC deep beams containing openings strengthened with CFRP sheets was studied and examined against test results.

H. K. Lee *et al.* (2011) worked on "Behaviour and Performance of RC T-Section Deep Beams Externally Strengthened in Shear with CFRP sheets". The work was done to investigate the behaviour and performance of reinforced concrete (RC) T-section deep beams strengthened in shear with CFRP sheets. Fourteen RC T-section deep beams were designed to be deficient in shear with a shear span-to-effective depth ratio (*a/d*) of 1.22. Strengthening length, fibre direction combination of CFRP sheets and an anchorage using U-wrapped CFRP sheets are the parameters considered. Crack patterns and behaviour of the tested deep beams were observed during four-point loading tests. It was concluded from the test results that the key variables of strengthening length, fibre direction combination, and anchorage have significant influence on the shear performance of strengthened deep beams. In addition, a series of comparative studies between the present experimental data and theoretical results in accordance with the commonly applied design codes were made to evaluate the shear strength of a control beam and deep beams strengthened with CFRP sheets.

H. S. Kim *et al.* (2011) worked on "Structural Behaviours of Deep RC Beams under Combined Axial and Bending Force". The paper presents experimental studies of deep reinforced concrete (RC) beam behaviours under combined axial and bending loads. In order to investigate the effect of axial loads on the structural behaviours of the deep RC beams, specimens were prepared to have different shear span-to-depth ratios and subjected to axial loads of 235kN or 470kN. From the experiments, structural behaviours such as failure modes, load-deflection relationships, and strains of steel bar and concrete are observed. As results, for the deep beam with shear span-to-depth ratio of 0.5, load at the beam failure decreases as applied axial load increases, while the deep beams with shear span-to-depth ratios of 1.0 and 1.5 shows that the applied axial load delays the beam failure. In addition, failure mode of the deep beam changes from shear failure to concrete crushing due to compressive stress at the top corners of RC beams as shear span-to-depth ratio decreases. From the experiments, it is important to notice that deep beam with relatively small span-to-depth ratio under axial load shows early failure due to concrete crushing, which cannot be directly applied to widely known design method for deep beam, strut-to-tie model.

Ashraf Mohamed *et al.* (2014) worked on "Prediction of the behaviour of reinforced concrete deep beams with web openings using the finite element method". The work was done to study the behaviour of reinforced concrete deep beams with and without web openings using finite element method. To study the effect of the reinforcement distribution on the beam overall capacity and compared to the Egyptian code guidelines. The loading scheme, the location of web openings and the reinforcement distribution are the parameters considered. The web openings crossing the expected compression struts should be avoided, and the depth of the opening should not exceed 20% of the beam overall depth. The reinforcement distribution should be in the range of 0.1–0.2 beam depth for simply supported deep beams.

Fadzil *et al.*(2015) worked on " Experimental Study on Shear Strengthening of RC Deep Beams with Large Openings Using CFRP". The work was done to experimentally study the behavior of reinforced concrete (RC) deep beams with large circular openings and openings strengthened using externally bonded Carbon Fiber Reinforced Polymer (CFRP) composites in shear. To investigate the structural behavior including the load deflection behavior, crack pattern, failure mode as well as strengthening configuration. One of the test parameters presented in this paper was surface strengthening method. 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. It was concluded that the 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%.

3. OBJECTIVES OF THE PRESENT WORK

- Effectiveness of internal and external method of shear strengthening.
- Effectiveness of anchoring system on the behaviour of FRP strengthened RC deep beams with openings.
- To determine the most suitable strengthening method to increase the strength of deep beam economically.
- To study the effect of various opening sizes and shapes.

4. ANALYTICAL STUDY

The FE models consisted of sixteen RC deep beams with openings of different location, shapes and size. The specimens were divided into eight groups according to the opening shape, size and location. Each group consisted of RC deep beams with openings. One specimen in each group was used as a control unstrengthen specimen. The specimens in group A, group B, group C and group D are externally strengthened with GFRP and openings are provided at the centre of each shear span. The specimens in group E and group F are internally strengthened.

The cross section of all the deep beams were width = 100 mm and total depth = 500 mm. The total length of deep beam was 1050mm, effective length of the beam was 870 mm, and the shear span length was 435 mm. Two opening shapes (i.e., circular and square) were used with two different sizes for each shape. The size of the square opening was 120 × 120 mm and 180 × 180 mm, and the diameter of circular opening was 100 mm and 160 mm. Each beam contained two numbers 12mm diameter bars (yield strength of 415 MPa) at the bottom face, and top two number 6mm diameter bars (yield strength of 250 MPa) at the top face. The web reinforcements consisted of 6mm diameter bars provided at 110 mm spacing in both vertical and horizontal directions. Stirrups were used as the vertical web reinforcement, and straight bars were used as the horizontal web reinforcement. Closely spaced vertical stirrups were provided at both ends of the beams to avoid premature failure at these locations. The 28-day concrete compressive strength was 25MPa. The longitudinal steel reinforcement was Grade 415 deformed steel bars while the web reinforcement was Grade 250 smooth bars.

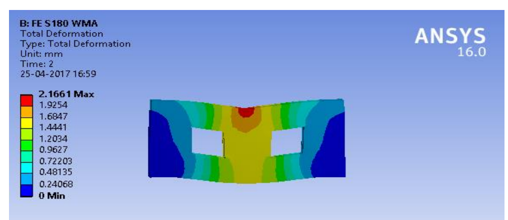
Mechanical anchors with a diameter of 7mm and a length of 25mm, full threaded hex headed bolts with a diameter of 4mm and a length of 35mm and nuts and washers are used in the work. The MB anchoring system develops the bond force through the frictional resistance between the mechanical expansion anchors and concrete. In this paper the effective simulation of these mechanical anchors has been done using ANSYS 16 Software.

For internal strengthening two reinforced steel bars are placed around each side of the square opening. These bars have the same material properties for the two main bottom reinforcement.

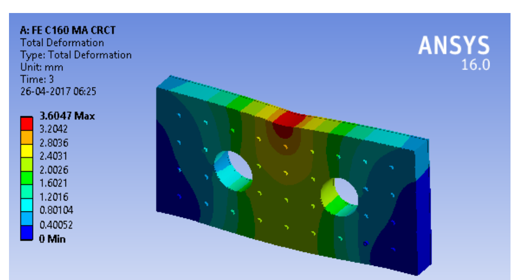
A clear 15mm thick concrete cover was provided in all sides of beams. Each specimen was assigned a designation that represented the strength of concrete, the strengthening configuration, the shape and size of the opening. As an example a specimen designation FE-S12-WMA T was interpreted as follows: FE-finite element model, S indicated a square opening with a size of 120 × 120 mm, WMA as without mechanical anchors and T as top face of the beam.

5. FINITE ELEMENT ANALYSIS

Deep beams were modelled as simply supported beams. Steel plates were provided at the supports and also at the loading locations. Steel plates were provided in order to avoid stress concentration problems and to prevent localized crushing of concrete elements near the supporting points and load application locations. This provided a more even stress distribution over the support area. All specimens were loaded to failure under the condition of a concentrated load applied at the mid span. The load was applied at a constant rate of 10 kN/minute. Figure 1 shows the deflection diagram of deep beam with square opening and circular opening.



(a)



(b)

Figure 1: Deflection diagram of deep beam with (a) square opening and (b) circular opening

Table 1 shows the results obtained for different models after analysing in ANSYS software. The ultimate load and deflection obtained for different models is shown.

Table 1: Results of externally and internally strengthened models with opening

Group	*Beam*	*Ultimate load (kN)*	*Deformation (mm)*
A	CB S180	111.5	1.825
	FE S180 WMA	168	2.166
	FE S180 MA	242	3.01
B	CB S120	156	2.07
	FE S120 WMA	208	2.54
	FE S120 MA	291	3.38
C	CB C160	175	2.3006
	FE C160 WMA	214	2.636
	FE C160 MA	272	3.604
D	CB C100	193	2.65
	FE C100 WMA	238	3.278
	FE C100 MA	311	4.02
E	FE IS S180	202	3.25
	FE IS S120	238	3.04
F	FE IS C160	233	3.48
	FE IS C100	257	3.33

Equivalent stress for a particular load 100 kN are determined for all the models. Table 2 shows the equivalent stress results of externally and internally strengthened models with opening.

Table 2: Equivalent stress results of externally and internally strengthened models with opening

Group	*Beam*	*Equivalent stress (MPa)*
A	CB S180	156.84
	FE S180 WMA	132.34
	FE S180 MA	105.87
B	CB S120	142.58
	FE S120 WMA	118.19
	FE S120 MA	95.221
C	CB C160	134
	FE C160 WMA	113.58
	FE C160 MA	92.41
D	CB C100	125.5
	FE C100 WMA	102.73
	FE C100 MA	82.173
E	FE IS S180	134.78
	FE IS S120	126.25
F	FE IS C160	115.51
	FE IS C100	106.40

6. RESULTS AND DISCUSSIONS

Models in group A :Models in group A are reinforced concrete deep beams with 180mm × 180 mm square openings.. The ultimate load obtained for CB-S-180 was 111.5 kN and the maximum deflection obtained was 1.825mm. The ultimate load obtained for FE-S180-WMA was 168 kN and the maximum deflection obtained was 2.166 mm. The ultimate load obtained for FE-S180-MA was 242 kN and the maximum deflection obtained was 3.01 mm. The minimum load increase of 54.54 % was obtained for the model FE S180 WMA, 109.09 % of load increase for the model FE S180 MA. Figure 2 shows the Load Deflection curve for all the models in group A.

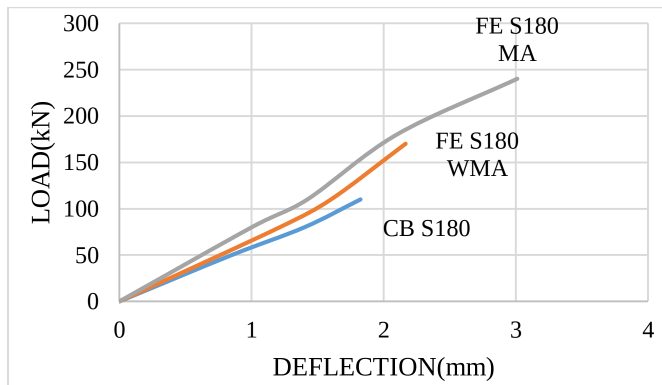


Figure 2: Load Deflection curve for all the models in group A.

Models in group B:Models in group B are reinforced concrete deep beams with 120mm x120 mm square openings. The ultimate load obtained for CB-S-120, FE-S120-WMA, FE-S120-MA were 156kN, 208kN, 291kN and the maximum deflection obtained was 2.07mm, 2.56mm, 3.38mm, the minimum load increase of 40 % was obtained for the model FE-S120-WMA, 73.38 % of load increase for the model FE-S120-MA. Figure 3 shows the Load Deflection curve for all the models in group B.

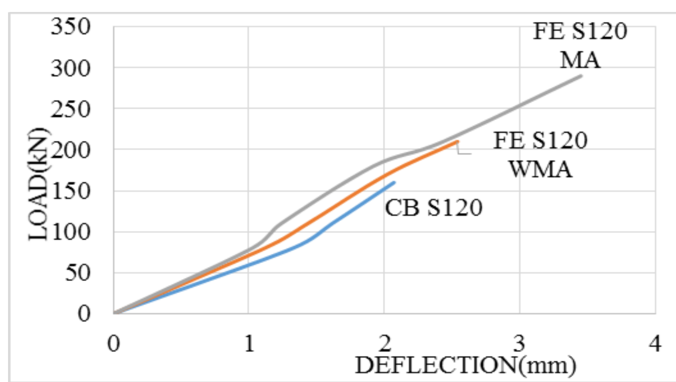


Figure 3: Load Deflection curve for all the models in group B.

Models in group C:Models in group C are reinforced concrete deep beams with 160 mm diameter circular openings. The ultimate load obtained for CB-C160, FE-C160-WMA, FE-C160-MA were 175 kN, 214 kN ,272kN and the maximum deflection obtained was 2.3006mm, 2.636 mm and 3.604mm. The minimum load increase of 23.5 % was obtained for the model FE-C100-WMA, 50.63 % of load increase for the model FE-C100. Figure 4 shows the Load Deflection curve for all the models in group C.

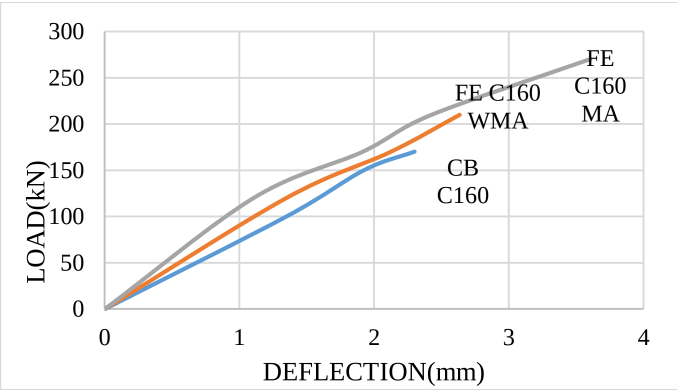


Figure 4: Load Deflection curve for all the models in group C.

Models in group D:Models in group D are reinforced concrete deep beams with 100 mm diameter circular openings. The ultimate load obtained for CB-C160, FE-C160-WMA, FE-C160-MA were 193 kN, 241 kN ,311kN and the maximum deflection obtained was 2.65mm, 3.278 mm and 4.02mm.The minimum load increase of 26.31 % was obtained for the model FE-C100-WMA, 52.63 % of load increase for the model FE-C100. Figure 5 shows the Load Deflection curve for all the models in group D.

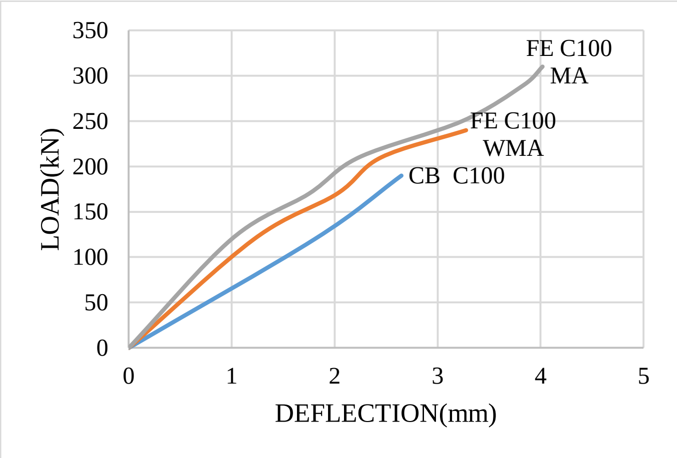


Figure 5: Load Deflection curve for all the models in group D.

Models in group E:Models in group E are reinforced concrete deep beams with 180mm × 180 mm and 120mm × 120 mm square openings. The beam are strengthened internally. The ultimate load obtained for FE IS S180, FE IS S120 were 202 kN,238 kN and the maximum deflection obtained was 3.25 mm and 3.04mm. Figure 6 shows the Load Deflection curve for all the models in group E.

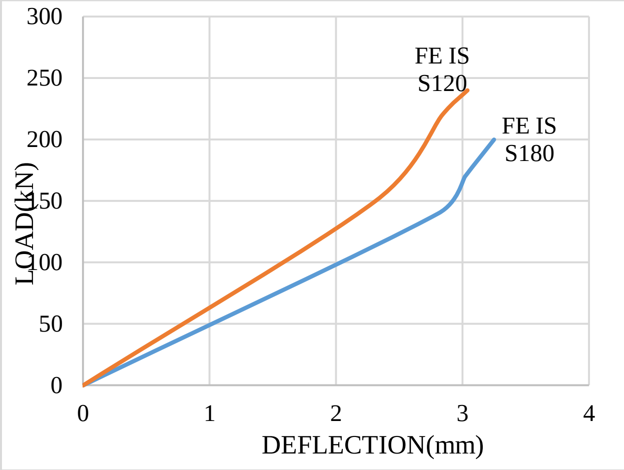


Figure 6: Load Deflection curve for all the models in group E.

Models in group F:Models in group E are reinforced concrete deep beams with 160mm and 100mm diameter circular openings. The beams are strengthened internally. The ultimate load obtained for FE IS C160, FE IS C100 were 233 kN, 257kN and the maximum deflection obtained was 2.78 mm and 3.33mm. Figure 7 shows the Load Deflection curve for all the models in group F.

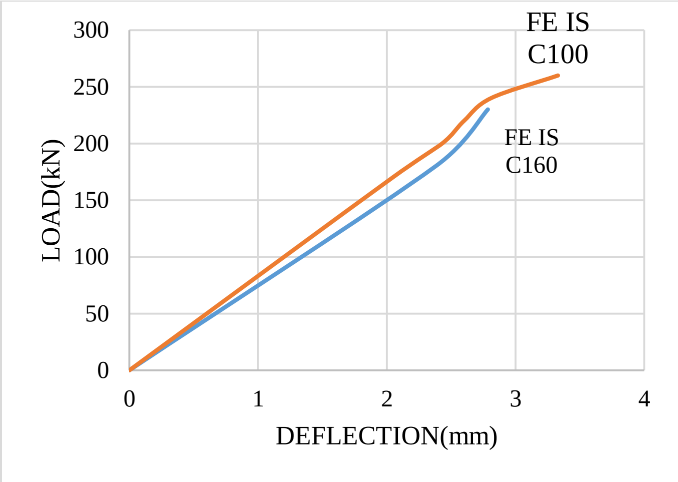


Figure 7: Load Deflection curve for all the models in group F.

Figure 8 shows the variation of equivalent stress for externally strengthened models with opening. when the models are externally strengthened , the stress was decreased. And Figure 9 shows the variation of equivalent stress for internally strengthened models with opening. when the models are internally strengthened, stress decreases was observed.

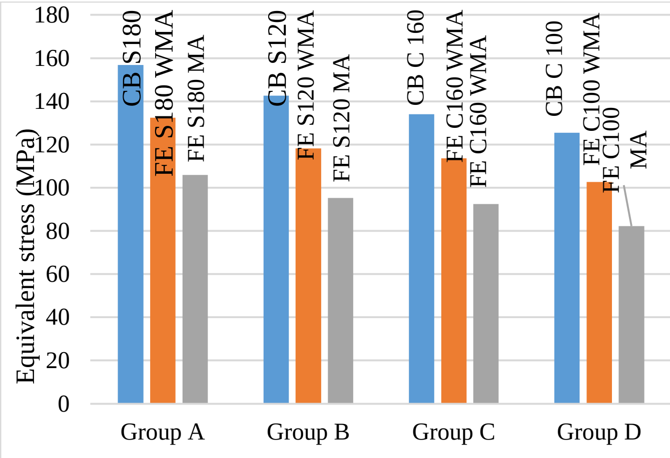


Figure 8: Variation of equivalent stress for externally strengthened models with opening

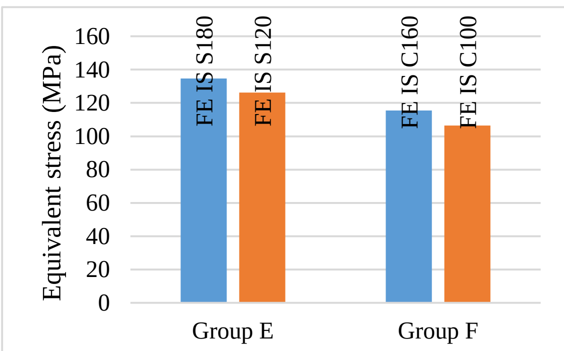


Figure 9: Variation of equivalent stress for internally strengthened models with opening

6.1 EFFECTIVENESS OF ANCHORING SYSTEMS

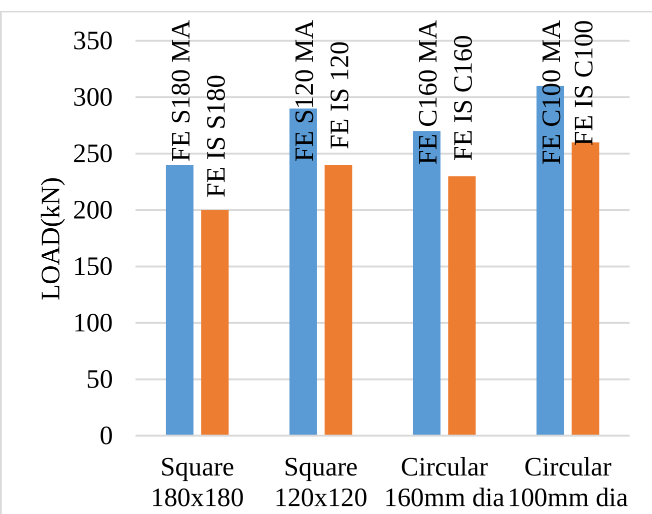


Figure 10: Effect of anchoring systems in the load carrying capacity of deep beams

In group A models, load increase of 35.29 % was obtained for the model with mechanical anchors. In group B models the load increase was 23.80 %, in group C it was 19.64 % and in group D it was 23.83 % respectively. The FE models of the strengthened deep beams without mechanical anchors failed by de-bonding of FRP sheets. But for the models with anchors no pull out was observed prior to the rupture of fibre. Figure 10 shows the effect of anchoring system in load carrying capacity of deep beams.

6.2 EFFECT OF OPENING SIZE AND SHAPE

From the finite element results, it is clear that increase in the opening size, regardless of the shape, led to the reduction in beam's shear strength. For both strengthened and unstrengthen beams the strength decrease was observed. Figure 11 shows the effect of opening size and shape.

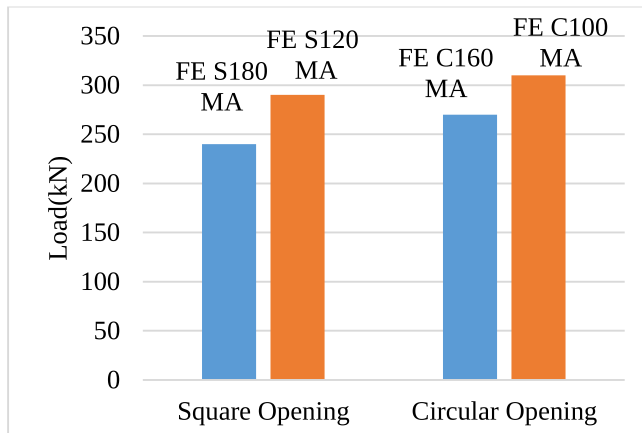


Figure 11: Effect of opening size and shape

6.3 EFFECT OF STRENGTHENING METHOD

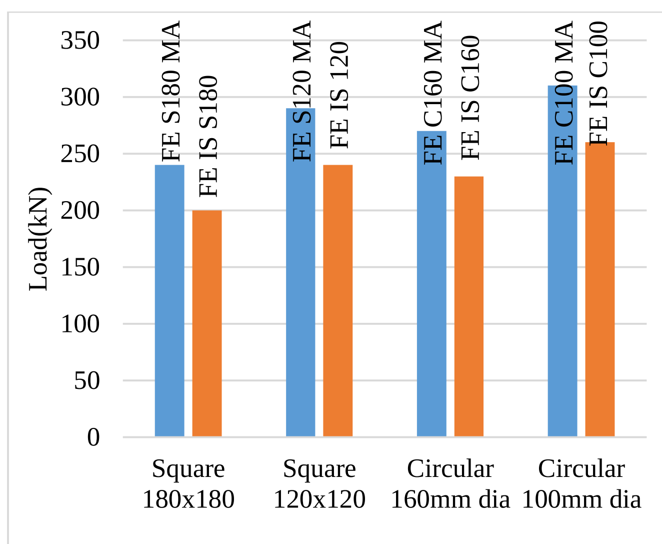


Figure 12: Effect of strengthening method

From the finite element results, it is clear that the load carrying capacity is more when the models are strengthened externally and with mechanical anchors to avoid the de-bonding failure. Figure.12 shows the effect of strengthening method.

7. CONCLUSION

This paper presents a study on external shear strengthening and internal shear strengthening of RC deep beams with openings. Different location, sizes and shapes of openings made in the web were investigated. Based on the numerical results and discussions, the following conclusions could be drawn,

- The externally bonded GFRP was remarkably effective to increase the ultimate load and strength of the RC deep beams with both the square and circular openings.
- Mechanical anchors significantly increases the ultimate load carrying capacity of the FRP strengthened RC deep beams. The finite element models of same configuration and with & without mechanical anchors were compared to investigate the effectiveness of anchoring systems. Anchoring systems was effective in preventing the de bonding failure. The strengthened RC deep beams without mechanical anchors failed by de bonding of FRP from the concrete surface. When de bonding took place, the GFRP sheets tended to rip off concrete surface. This initiated a large disturbance to the FE simulation and a major difficulty to the solution algorithm. This in turn caused the FE simulation to terminate due to a divergence. Divergence in the FE solution coincided with a considerably large deflection exceeding the displacement limitation of the ANSYS software.
- The increase in the opening size, regardless of the shape, led to the reduction in beam's shear strength. For both strengthened and unstrengthen beams the strength decrease was observed.
- Equivalent stress was decreased when the models are strengthened externally and internally.
- Introducing reinforcement bars around both the square and circular openings may increase the ultimate strength of the beam. But the load carrying capacity is more when the models are strengthened externally and with mechanical anchors to avoid the de-bonding failure.

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