

Strengthening of RC Beams Containing Large Opening at Flexure with CFRP laminates

S.C. Chin, N. Shafiq and M.F. Nuruddin

Abstract—This paper presents the study of strengthening R/C beams with large circular and square opening located at flexure zone by Carbon Fiber Reinforced Polymer (CFRP) laminates. A total of five beams were tested to failure under four point loading to investigate the structural behavior including crack patterns, failure mode, ultimate load and load deflection behaviour. Test results show that large opening at flexure reduces the beam capacity and stiffness; and increases cracking and deflection. A strengthening configuration was designed for each un-strengthened beams based on their respective crack patterns. CFRP laminates remarkably restore the beam capacity of beam with large circular opening at flexure location while 10% re-gain of beam capacity with square opening. The use of CFRP laminates with the designed strengthening configuration could significantly reduce excessive cracking and deflection and increase the ultimate capacity and stiffness of beam.

Keywords—CFRP, large opening, R/C beam, strengthening

I. INTRODUCTION

UTILITY pipes and ducts are necessary to accommodate essential services in a building. The types of services include air-conditioning, power supply, telephone line, computer network, sewerage and water supply. It has been practiced that pipes and ducts are usually hanged below the floor beams, and covered by a suspended ceiling for its aesthetic purpose. In order to reduce headroom and provide a more compact and economical design, it is now essential to pass these utility pipes and ducts through opening in a floor beam. Openings can be circular, square or rectangular in shape. It is found that circular opening is normally used for electricity cables, telephone lines and computer networks while square or rectangular openings are used for air-conditioning services [1].

Providing an opening in the web of a reinforced concrete beams resulted to many problems in the beam behavior including reduction in beam stiffness, cause excessive cracking and deflection and reduction in beam capacity. Furthermore, inclusion of openings leads to high stress concentration at the opening corners. The reduction of area in the total cross sectional dimension of a beam changes the simple beam behavior to a more complex one [2],[3].

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Strengthening of beams with openings primarily depends whether the building services are pre-planned or post-planned. In the case of pre-planned openings, the sizes and locations of openings are known in advance during the design stage. Thus, sufficient strength and serviceability of beams with opening can be ensured before construction. Although no specific guidelines or standards are provided in any of the major codes, the design engineer can extract the necessary information and guidelines reported in the literatures [1].

In order to restore the beam structural capacity due to openings, available literatures [4],[5] presented the role of diagonal bars as corner reinforcement while inclined reinforcement for strengthening around the opening was also reported [6]. Steel reinforcement provided at the upper and lower chords and diagonal reinforcement placed around the opening are considered as internal strengthening.

As in the case of post-planned, it involves drilling of openings in an existing structure in a newly constructed building. Problems may arise during the process of laying utility pipes and ducts. M&E engineers often request to provide or re-locate the position of opening to simplify the arrangement of pipes and ducts which has not been considered during the design stage. Simplifying the lengthy pipes and ducts cause a huge savings in terms of time, labor and cost especially in a multi-storey building. From the owner's point of view, placing an opening may represent some financial savings. Hence, structural engineers need to compromise with the M&E engineers and owner by providing an opening without ignoring the safety and serviceability of the structure. In an existing beam, strengthening externally around the opening is crucial with the use of external reinforcing material, such as steel plates or by fiber reinforced polymer (FRP) materials.

The most common type of FRP in the concrete industry is made with carbon, aramid or glass fibers. The FRPs are usually in the form of sheets, strips, wraps or laminates. These materials were applied by bonding it to the external surfaces of the beams with various configurations and layouts. Numerous experimental studies have shown that externally bonded FRP laminates could significantly increase a member's stiffness and load carrying capacity, enhance flexural and shear capacities, providing confinement and ductility to compression structural members and also controls the propagation of cracks [7],[8]. However, it was found that one of the disadvantages of external strengthening is the debonding of the externally bonded materials at their ends. This occurs due to the lack of anchorage and the stress concentration that controlled the failure of the strengthened

beams [9]. Various investigations [10]-[12] have used CFRP laminates as an effective external reinforcement for strengthening reinforced concrete beams. The effectiveness of externally bonded CFRP sheets in increasing the flexural strength of concrete beams was studied. The results indicated that flexural strength was increased up to 58% on concrete beams strengthened with anchored CFRP sheets [10]. An experimental study was presented to study the behaviour of reinforced concrete beams retrofitted or strengthened using CFRP sheets. The test results showed that CFRP sheets can significantly enhance the shear capacity of the beams and the failure mode of retrofitted beams varied depending on the scheme of CFRP sheets applied [11].

However, very little research efforts were found in the literature was directed towards the study of strengthening of beams with the presence of openings. Mansur et. al. [13] investigated the use of FRP plates for strengthening reinforced concrete T-beams with small circular opening. Abdalla et.al. [14] studied on shear strengthening of reinforced concrete beams with rectangular opening using FRP sheets. Maaddawy and Sherif [15] investigated on the usage of FRP sheets for shear strengthening of reinforced concrete deep beams with square openings while Pimantas [16] reported on strengthening of reinforced concrete beams with circular and square opening by externally installed FRP rods.

In this paper, a detailed experimental program was conducted. The main objectives of the experimental investigation were: (i) to study the behavior of reinforced concrete beams with large circular and square opening of un-strengthened beam at flexure zone; (ii) to estimate the loss of structural capacity of beams with opening compared to solid control beam; and (iii) to study the effective strengthening configuration using carbon fiber reinforced polymer (CFRP) laminates to strengthen large opening at flexure location.

II. EXPERIMENTAL PROGRAM

In the experimental program, a total of five reinforced concrete beams were tested to failure under four point loading to investigate the structural behavior including crack patterns, ultimate load, failure mode, and load deflection. The opening region was strengthened by CFRP laminates to re-gain the loss of structural capacity.

A. Test Specimen

A schematic diagram of the test specimen showing the reinforcement details is shown in Fig. 1. The test specimen was 2000 mm long with a rectangular cross section of 120 x 300 mm. The effective depth to the main reinforcement was 280 mm while the effective span of the beam was 1800 mm. The tension steel reinforcement consisted of two diameter 12 mm deformed steel bars each having a nominal cross section area of $A = 113 \text{ mm}^2$. The compression steel reinforcement consisted of two diameter 10 mm deformed steel bars with $A = 79 \text{ mm}^2$ for each bars. The stirrups consisted of diameter 6 mm smooth bars with $A = 28 \text{ mm}^2$ each spaced at 300 mm center to center.

In this study, large circular and square shape of opening was considered. The size for square opening was 210 x 210 mm whereas the opening size for circular opening was 230 mm in diameter. The ratio of circular and square opening area to the beam's effective depth was 0.82 and 0.75, respectively whereby researchers classified them as large opening [16],[17]. The beams were cast in a horizontal position using plywood formwork. The large circular opening was created by a circular polyvinyl chloride (PVC) pipe inserted in the beam before casting of concrete. While large square opening was formed by inserting a box fabricated from plywood. In this study, the large opening was created at mid-span of the beam.

A total of five RC beams were cast. The beams consisted of a solid control beam without opening, two beams with large circular and square opening without strengthening and remaining two beams with large circular and square opening for strengthening using CFRP laminates. The beam specimens are listed in Table I.

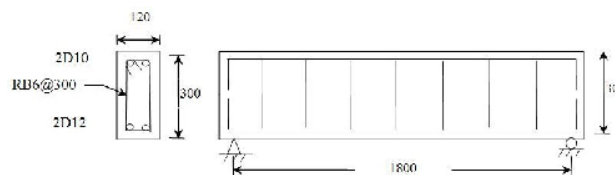


Fig. 1 Beam reinforcement details (Units in mm)

B. Material Characteristics

The concrete used in the experimental study was ready-mixed concrete designed for 28 days compressive strength of 35 MPa. The water cement ratio was 0.54. The coarse aggregate was 20 mm granite crushed aggregate. Fine sand as fine aggregate was used. The longitudinal steel reinforcement was deformed steel bars with nominal yield strength of 460 MPa. The web reinforcement was mild steel with nominal

TABLE I
 BEAM SPECIMENS

Beam Specimens	Opening	Conditions
Control beam, CB	-	-
C-con-f	Circular	Without Strengthening
S-con-f	Square	Without Strengthening
C-cfrp-f	Circular	Strengthening with CFRP laminates
S-cfrp-f	Square	Strengthening with CFRP laminates

yield strength of 275 MPa. The CFRP laminates were unidirectional with a width of 100 mm and a thickness of 1.4 mm. The nominal tensile strength and tensile modulus of elasticity of CFRP laminates were 2200 MPa and 170 GPa, respectively. CFRP laminates were applied after the beams were cast. To ensure a suitable surface preparation for bonding, the beam surface were brushed and cleaned before the application of CFRP laminates. The laminates were bonded to the specimens with an epoxy resin, Sikadur 30. The thickness of a cured CFRP laminates bonded to the specimen is typically 3 mm.

C. Test Setup

The beam specimens were tested until failure under four point loading with static load using a Universal Testing Machine (UTM) of 500 kN. The test setup is shown in Fig. 2. A spreader beam was used to transfer the load to the test specimen through two loading points at 500 mm apart. The beam deflection was monitored by a number of linear variable displacement transducers (LVDTs) placed at the bottom soffit of the beam. The crack development and propagation were marked and the mode of failure was recorded.



Fig. 2 Test setup

D. CFRP Strengthening Systems

Based on the crack patterns of the tested un-strengthened beams with opening, a strengthening configuration was designed for each beams and applied around the opening. The strengthening configurations are shown in Fig. 3. RC beam with circular opening at flexure, "C-cfrp-f" was externally strengthened with CFRP laminates which placed at (i) above and below the opening with fibers oriented in a direction parallel to the longitudinal axis of the beam, (ii) diagonally adjacent to the opening and (iii) at tension and compression zone of the beam. The strengthening configuration of "C-cfrp-f" is shown in Fig. 3(i). For beam with square opening at flexure "S-cfrp-f", the CFRP laminates were bonded (i) inside the four surfaces of the opening and (ii) at tension zone (bottom of beam) as shown in Fig. 3(ii).

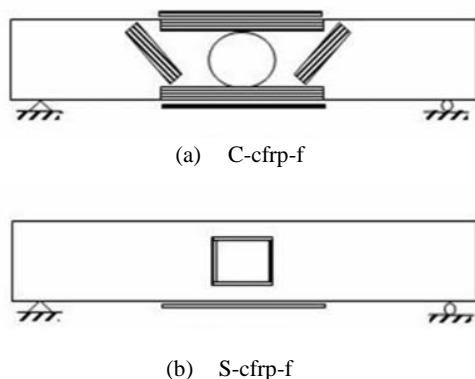


Fig. 3 Strengthening configurations with CFRP laminates

III. RESULTS AND DISCUSSION

Results and observation of beams during the experiment were recorded and detailed discussions are presented. The results of a solid control beam are compared to beams with strengthened and un-strengthened openings.

A. Control Beam

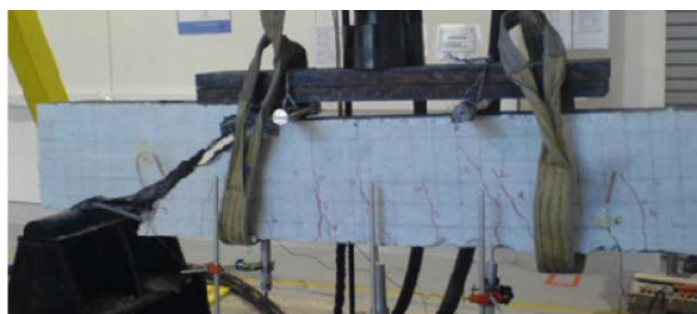
The control beam without opening, CB failed in shear mode as designed. In the experiment, crack lines appeared at the tension zone and penetrated vertically up to the neutral axis of the beam. It was observed that the flexural cracks increased in numbers followed by the formation of diagonal cracks. The crack width increased before failure, bringing an abrupt brittle failure at the shear zone. Large diagonal cracks formed from the point of the applied load to the support as the bottom reinforcements yielded with a failure load of 115.67 kN. Fig. 4a shows the crack pattern and failure mode of the control beam.

B. Un-strengthened beams

1. Crack pattern

When a large circular opening was made in the web of a beam and no strengthening was conducted, the failure mode of the beam, "C-con-f" was in flexure, as shown in Fig. 4b. It was observed that the crack lines appeared below the opening and at the tension zone of the beam. The flexural crack width were widen before failure. The beam failed by a sudden crushing of concrete at the top chord of the opening due to yielding of top reinforcement with major flexural cracks at mid-span.

While in beam with large square opening at mid-span, "S-con-f", cracks were seen initiated at four corners of the square opening. As seen in Fig. 4c, crack lines appeared at the opening corner at the bottom chord propagated towards the bottom of the beam whilst cracks from the opening corner at top chord extended to the point of applied load. Flexural cracks were seen at the tension zone and these crack lines were then penetrated vertically passing the neutral axis of the beam. The crack width enlarged before failure. The beam failed in flexure due to yielding of top steel reinforcement above the opening leading to crushing of concrete cover.



(a) Control beam, CB



(b) C-con-f



(c) S-con-f

Fig. 4 Crack patterns and failure mode of un-strengthened beams with large opening at flexure

2. Ultimate Load

The ultimate load and failure mode of the tested beams were summarized in TABLE II. From the table, the maximum load of beam “C-con-f” was 96.57 kN while beam “S-con-f” was 78.14 kN. Comparing to the solid control beam without opening, the reduction of beam capacity in beam “C-con-f”, and beam “S-con-f” was 17% and 32%, respectively. Large square opening poses a larger reduction in the flexural strength compared to large circular opening.

TABLE II
 SUMMARY OF TEST RESULTS

Beam Specimens	Ultimate Load, P_u (kN)	Failure Mode
Control beam, CB	115.67	Shear
C-con-f	96.57	Flexure at opening
S-con-f	78.14	Flexure at opening
C-cfrp-f	164.4	Shear at opening
S-cfrp-s	86.07	Flexure at opening

3. Load Deflection Behaviour

The load deflection behavior of CB, “C-con-f” and “S-con-f” are compared and illustrated in Fig. 5. Referring to the figure, the presence of large circular and square opening in RC beam at flexure causes a reduction in beam stiffness, 9% and 19%, respectively less than the stiffness of the control beam. In deflection, RC beam containing a large circular opening causes an increase in deflection approximately 30% more than the control beam whereas the deflection of beam with square opening was 10% less than the control beam. The decreased in beam strength and stiffness is mainly caused by the sharp opening corners of the square opening which subjected to high stress concentration and also due to reduction of the opening cross sectional area at the mid-span region. The inclusion of opening at flexure disturbs the natural load path of the crack pattern causes cracks to appear at the tension region around the opening.

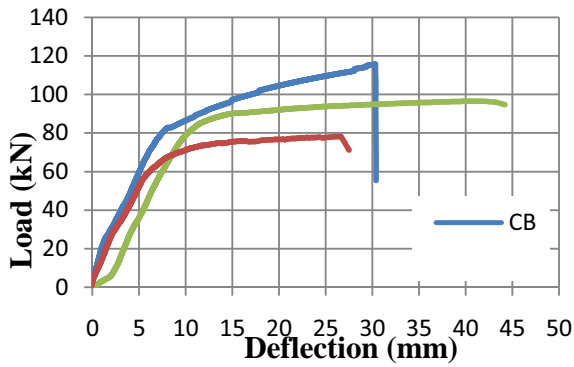


Fig. 5 Load deflection behaviour of un-strengthened beams with large opening at flexure

C. Strengthened beams

1. Crack pattern

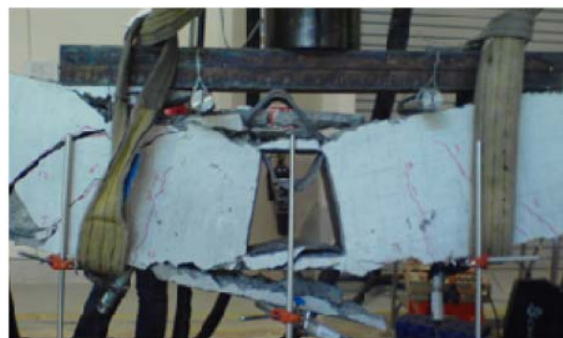
Beam “C-cfrp-f” was strengthened by CFRP laminates with the strengthening configuration as illustrated in Fig. 2b(i). During the experiment, flexural cracks appeared at the tension zone away from the area restricted by CFRP laminates. It was observed that diagonal cracks appeared at the right span with increasing crack width before failure. Fig. 6a shows the failure mode of the beam. It was a sudden shear failure due to the formation of diagonal crack with yielding of bottom

reinforcement and crushing of concrete near the support. The width of the diagonal crack was approximately 15 mm.

While in beam “S-cfrp-f”, the square opening was strengthened with the designed CFRP strengthening scheme as shown in Fig. 2b(ii). During the beam testing, it was observed that flexural cracks appeared away from the area resisted by CFRP laminates. These cracks grew in numbers and penetrated to the beam neutral axis and eventually a diagonal crack appeared near to the support. The diagonal crack propagated to the point of the applied load and increased in crack width before failure. As shown in Fig. 6b, the failure mode of the beam was in flexure. Cracks appeared at the edge of the CFRP laminates (bottom of beam) and peeling of concrete cover with CFRP laminates was observed. In addition, cracks formed at area of applied load were seen penetrated to the corner of the opening at the top chord and caused a sudden crushing of concrete due to yielding of main longitudinal bar above the opening. The CFRP laminates at the top and bottom surface inside the opening was bend and de-laminated from the surface of the opening due to the tension-compression forces of the beam from the applied load.



(a) C-cfrp-f



(b) S-cfrp-f

Fig. 6 Crack patterns and failure mode of strengthened large opening at flexure

2. Ultimate Load

The ultimate load of strengthened beam with large circular and square opening at flexure was recorded and listed in TABLE II. The ultimate load of “C-cfrp-f” was 164.4 kN. When compared to the ultimate load of control beam, 115.67 kN, an excessive strength of 42% was noticed. Compared to the un-strengthened beam “C-con-f” with the ultimate load of 96.57 kN, the strengthened beam manage to re-gain the total capacity with an over strengthening of 70% with the designed strengthening scheme. Meanwhile, the ultimate load of square opening strengthened with CFRP laminates with this strengthening scheme, “S-cfrp-f” was 86.07 kN. The re-gain of beam capacity is only 10% of the capacity of un-strengthened beam with square opening at flexure, “S-con-f”.

3. Load Deflection Behaviour

The load deflection behaviour of strengthened beam with large circular and square opening at flexure “C-cfrp-f” and “S-cfrp-f”, respectively is plotted in Fig. 7. Both the beams exhibited a similar trend of stiffness as the control beam. Compared to beam “S-cfrp-f”, beam “C-cfrp-f” offer a more ductile behavior at the post-yielding stage.

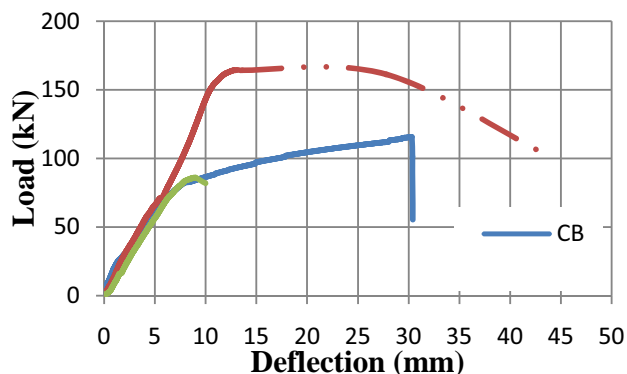


Fig. 7 Load deflection behaviour of strengthened beams with large opening at flexure

D. Strengthened beams versus Un-strengthened beams

Fig. 8 shows the load deflection behaviour of un-strengthened and strengthened beams with large circular and square opening at flexure, “C-con-f” and “C-cfrp-f”. With the application of CFRP laminates, it has significantly increased the beam stiffness to 33% more than the un-strengthened beam with large circular opening whereas no significant improvement in beam deflection was observed. As for strengthened beam with large square opening at flexure “S-cfrp-f”, CFRP laminates increased the beam stiffness to 17% more than the un-strengthened beam “S-con-f” and significantly reduced the beam deflection about 61%, as shown in Fig. 9.

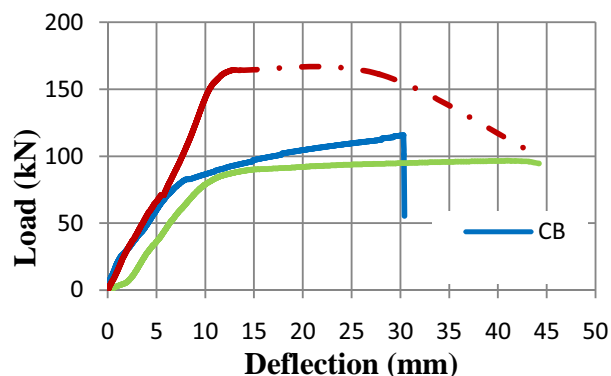


Fig. 8 Load deflection behaviour of un-strengthened and strengthened large circular opening at flexure

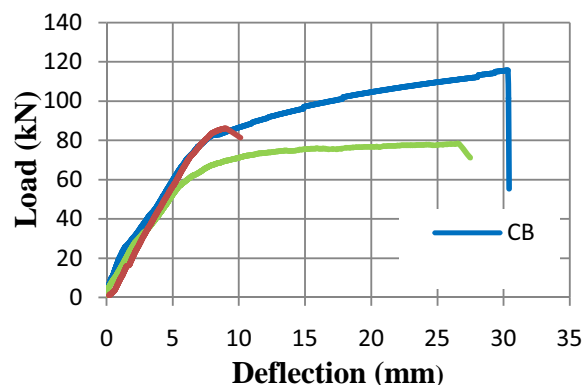


Fig. 9 Load deflection behaviour of un-strengthened and strengthened large square opening at flexure

E. Discussions

In terms of opening shape, beam with large square opening tend to exhibit a lower capacity than large circular opening. This may be due to large stress concentration at four corners of the large square opening whereby cracks are initiated. The increase in ultimate capacity of the strengthened beam “C-cfrp-f” is apparently cause by the presence of diagonal CFRP laminates near the large circular opening that interrupt the natural path of crack propagation, thus requiring a higher energy to redirect the path of crack through un-reinforced space [16]. As in the case of strengthened beam with large square opening “S-cfrp-f”, the flexural cracks are able to find the un-reinforced path which is not restrain by CFRP laminates, thus giving a lower ultimate capacity. In order to provide an effective strengthening configuration by minimizing the excessive strengthening in beam “C-cfrp-f” and maximizing the ultimate capacity in beam “S-cfrp-f”, various strengthening configuration are modelled in a non-linear finite element program, *ATENA*. The study with the finite element analyses will be discussed in the latter paper.

IV. CONCLUSION

Based on results and discussion, the following conclusions are made:

1. In un-strengthened beams with large opening at flexure location, excessive flexural cracks were found at the tension zone around the openings. The failure mode was in flexure. The inclusion of large square opening in RC beam significantly decreases the beam strength and stiffness, 48% and 19% respectively. However, in terms of deflection, large circular opening at flexure greatly increases the beam deflection to 30% more than the solid control beam.

2. The strengthening configuration of CFRP laminates around large openings at flexure significantly decreased the cracks formed around the opening and greatly reduced the beam deflection approximately 61% as in the case of square opening. No significant reduction in beam deflection with large circular opening was observed. Strengthening of beam containing a large circular opening at mid-span with CFRP laminates remarkably restore the beam original structural capacity. In contrast, an increase of 10% in flexural strength was observed in beam with large square opening. The stiffness of the beam having large circular and square opening increased 33% and 17% respectively, than the un-strengthened beams.

3. In summary, the application of CFRP laminates according to the strengthening configuration presented in this study could reduce excessive cracking and beam deflection, and increases the ultimate capacity and stiffness of the beam.

4. Generally, the shape of large square opening gives a higher reduction in structural capacity compared to large circular opening as the sharp corner of the opening are subjected to higher stress concentration.

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