Structural Behavior of Prestressed RC Dapped Beam with Openings Strengthened Using CFRP Sheets

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Abstract. This research examines the strengthening efficiency of prestressed concrete dapped end beam with opening under monotonic point load. The study concerns with the position of the opening relative to the dapped end, the shape of opening, as circle or square, in addition, the effect of CFRP strengthening around the opening. The experimental program consisted of testing nine scaled down prestressed concrete dapped end beam specimens with single opening near the dapped end. Beam specimens consisted of one control beam and the remaining eight beams classified into two groups. The first group contained four unstrengthened specimens, whereas the second group included beams with opening strengthened using CFRP sheets. A full wrapping configuration for the opening region was adopted in this research. The results presented the detrimental influence of the openings on the shear strength of the dapped beam and the additional strength achieved from strengthening. This study concludes that the shear strength of the prestressed dapped beam decreased by the presence of openings in the web with maximum reduction about 20% when the opening was located close the dapped end. Based on the test results, the strengthened beams recovered significant part of their original load carrying capacity. Generally, prestressed dapped beams regain a maximum of 92% of their strength when openings with different configurations and locations were strengthened with full CFRP wrap.

Keywords: Dapped beam; prestressed beam; opening; CFRP strengthening; reinforced concrete.

1. INTRODUCTION

For bridge girders and high-rise precast buildings, the dapped-end beam is a cost-effective engineering approach; it enables floors height in concrete structures and buildings to be as short as possible [1]. A dapped end beam is created by either recessing the corbels that are supporting it or notching the beam's stem at the bottom corners such that it sits by the beam's decreased section as support [2]. Precast concrete is now more frequently utilized around the world than concrete that is put in place. Due to the superior stability compared to that supported at its lower face, precast dapped-end beams have recently been used in buildings. Precast concrete may accelerate up construction, reduce costs, and increase product quality while also reducing construction time and facilitating work in inclement weather [3]. Amir Botros [4] studied ten of the dapped ends of prestressed concrete thin-stemmed members. They stated that the behavior is significantly different from the behavior of the end regions of conventionally supported beams. The dap increases tension in the end region, especially at the reentrant corner, which requires special reinforcing details. Wang [5] proposes that the nib must be at least 0.45h in height for structural facilities because the value of a dapped end beam depends on its ability to withstand shear stresses.

Openings in web of beams are usually encountered in practice. Typically, under-floor electrical and mechanical services must cross web beams. The fact that these pipes or ducts flow through holes reduces the amount of dead space and yields a more cost-effective design. However, the beams strength capacity is decreased by these openings. These openings could be circular, square, or rectangular in shape. In addition to the dimensions of the opening, the location of the opening on the beam's span has a significant impact on the properties of the structural beam. For prestressed beams the openings must be located outside the required strand embedment length and adequate shear reinforcement must be provided adjacent to the openings [6, 7, and 8]. In deep beams, web openings cause the shear flow to divide into one or two load pathways that go around the opening. Almost every tested beam fails as a result of concrete strut failure or diagonal cracking [9, 10]. Openings implemented in reinforced concrete beams weaken the overall behavior by reducing the ultimate load capacity as well as the reinforcement strain [11]. Generally, openings are divided into small or big depending on their size, with respect to the beam depth, some opinions express them big if the diameter or square side length is more than 0.4d. In comparison to beams with openings that lay at compression side, those with openings at tension side have less impact on a drop in the strength capacity. With regardless the vertical position, the horizontal position of openings has also an important impact taking into account the distance from the support, i.e., D-region, that has influence on ultimate of shear and bearing strength.

Strengthening by carbon fibers is a technique used in the last decades to compensate for the strength reduction of structural members from any cause especially when the signs of service cracks started appear. The openings usually are the weak regions influenced by static, time-dependent stresses or repeated loading; it also needs to strengthen after the strength degradation. Carbon Fiber reinforced polymer (CFRP) strips are commonly used in the strengthening of different concrete structures [12]. CFRP sheets offer excellent

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characteristics over other conventional strengthening materials. In addition to their excellent strength properties, they have high strength-to-weight ratio, good fatigue properties and durability resistance.

Over the years, the behavior of strengthened RC beams with openings was an area of extensive investigation. Abdalla [13] studied the effectiveness of using FRP sheets to stop local fractures around an opening. They found that the maximum capacity of reinforced concrete beams is decreased by about 75% if an opening with height of 0.6 of the beam depth in the shear zone is not strengthened. Using strengthening around small openings may recover the full capacity of the beam. Chin [14] Found a reduction in shear capacity due to the presence of openings at distance (d) from the support. Also, they study the behavior of the beam after strengthening around the opening by CFRP laminates concluding that the beam strength increased to approximately 54% of the original structural capacity of beams. Noorwirdawati [15] studied five reinforced concrete beams with opening strengthening by CFRP sheet. They conclude that the load carrying capacity of the beam has increased from 7.5% to 19.6% due to the addition of CFRP sheet as reinforcing material. For a CFRP-strengthened beam, the shear span or the area next to the center-wrapped area showed signs of cracking instead of the middle region; this was wrapped in CFRP sheets to the concrete using sheets of adhesive. Elansary [16] tested Six RC beams with openings near the supports. The beams crack patterns, deflections, and strains were contrasted with those of a reference solid RC beam devoid of an aperture. The shear strength and load deflection of the tested beams were measured experimentally and compared to those predicted by mathematical methods. According to the experimental findings, adding openings decreased RC beams' shear capacity by up to 35%. Additionally, it was shown that using CFRP sheets to reinforce the web opening increased the shear capacity of comparable beams by 21% to 28%. Salahaldin [17] presented experimental work for the restoration of the damaged RC hybrid beams with openings in the shear region. Based on the examination of the performed experimental tests of the repaired RC beams with openings, they concluded that damaged hybrid members could be repaired in a very effective manner using CFRP sheets, especially if the opening size is small.

The significant stress concentration that normally forms at the re-entrant corner of a dapped end connection must be taken into account while designing and describing the connection. The specifics of the reinforcing and the strength of the surrounding concrete determine the shear strength of this area. If there is an opening within or close to this region, the geometric resistance will be reduced by making the disturbed area D- region different depending on the openings position or shape. This research introduces a new case study in structural engineering by investigating the efficiency of strengthening openings in a prestressed dapped end beam when openings were introduced close to the dapped end. The main parameters taken into account were openings location with respect to the dapped end, opening shape and effect of strengthening.

2. RESEARCH METHODOLOGY

To achieve the goals intended from this study, nine prestressed RC dapped beams with openings in the web of the beams were designed and tested up to failure under monotonic point load to evaluate the structural behavior of these beams constructed with different openings shape and location near the dapped end. Focus on the effect of opening strengthening is introduced and highlighted in this study. All specimens were cast with the same dimensions, concrete compressive strength, and main and shear reinforcement. The variables considered included opening shape, opening location and strengthening using CFRP sheets. Details of the testing program adopted in this study to accommodate the different variables of this work are shown in Figure 1.

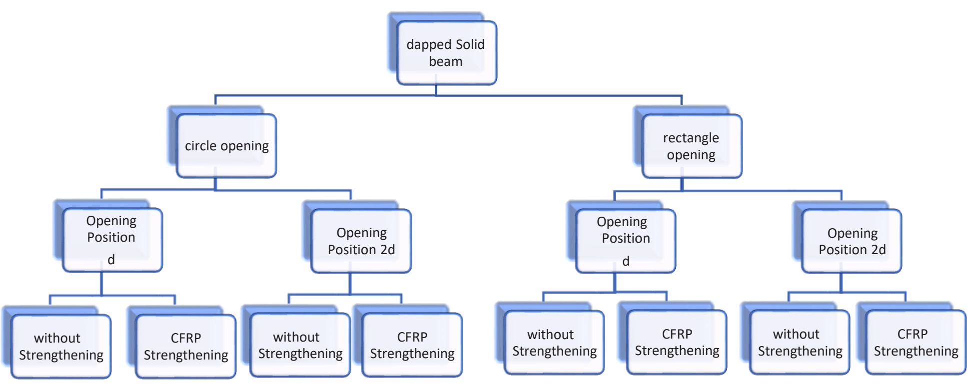

Figure 1: Parametric study of the tested specimens.

3. DESIGN OF TEST SPECIMENS

PCI Handbook recommended procedure of calculation applicable to calculate the structural behavior of prestressed dapped end beam. In this method, there are 5 anticipated failure types, as shown in Figure 2, and the most significant of which are the re-entrant crack shear failure and flexure shear at nib region. Numerical calculation was made by this method and the 2007 PCI Design Provisions [14] for computing the strength of the member in these regions with respect to the model proposed in this study. The characteristics of this method are mentioned in the various codes and reinforced concrete text books. The anticipated mode of failure is the flexural failure at the extended end or by diagonal tension at reentrant corner that can be calculated by the equations below;

$$\mathrm{As} = \frac{1}{\varnothing \mathrm{fy}}\left[\mathrm{Vu}\left(\frac{\mathrm{a}}{\mathrm{d}}\right) + \mathrm{Nu}\left(\frac{\mathrm{h}}{\mathrm{d}}\right)\right] \tag{1}$$

$$\mathrm{Ash} = \frac{\mathrm{Vu}}{\varnothing \mathrm{fy}} \tag{2}$$

Where; as: area of horizontal dapped steel mm^2. Ash: area of vertical stirrup at full depth beam section near the end mm^2. a: distance between support and steel hanger, Nu: horizontal force if any, Vu: shear force.

Depending on the proposed design procedure of the PCI Handbook Design Provision the final beam design details are show in Figure 3 with the assumption of simply supported boundary condition for the tested specimens. The anticipated magnitude of the ultimate shear force Vu at failure from the proposed design details and reinforcement shown in Figure 3 is about 105 kN predicted from the calculations and design recommendations. Assuming the acting load is to be applied at one-third of the span length away from the dapped end indicating a maximum load equal 157 kN to achieve failure in the tested beam specimens when no openings exit in the web of these beams.

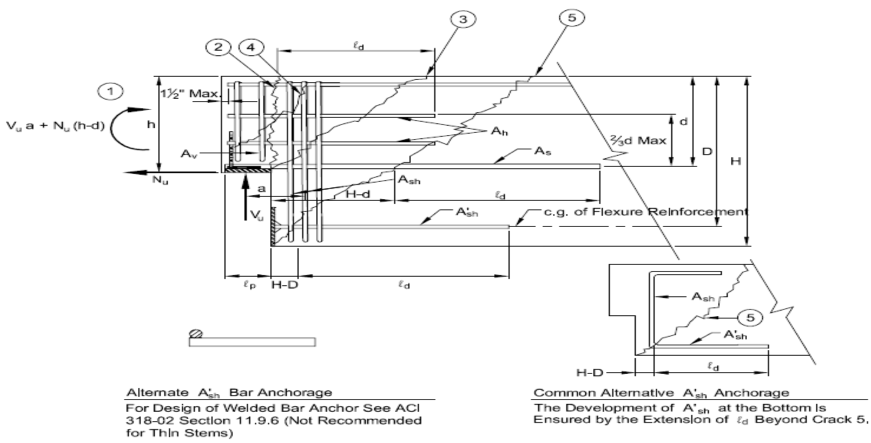

Figure 2: Modes of failure of the Dapped End beam (PCI Design Handbook, 2007).

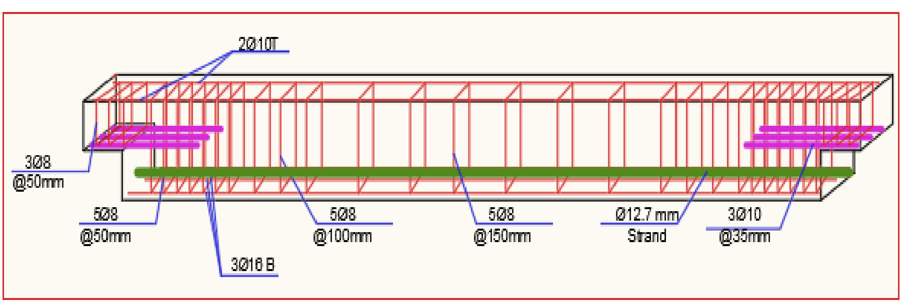

Figure 3: Details and steel reinforcement of dapped end beam specimen.

4. EXPERIMENTAL PROGRAM

The experimental program consists of testing nine prestressed RC dapped beams with dimensions of 3 meters long and a cross-section of 300 mm depth and 150 mm width, and the dapped end is 150x150 mm. Beams were reinforced with ϕ12.7 mm low relaxation 7 wires strand and steel reinforcement contained 3 rebars ϕ16 mm at bottom face, 2ϕ10 mm at the top face, and ϕ8 mm stirrups distributed at 50 mm in the nib region and distributed as 7ϕ8 mm @50 mm. The other stirrups were 5ϕ8 mm spaced @100 mm and the remaining stirrups in the middle span were 5ϕ8 mm spaced @150 mm as shown in Figure 3. Also, the study is concerned with the type of opening. In the current study two types or shapes for the openings with size of 30% of beam depth were investigated; a circular of 100 mm diameter and a square with 100 mm opening. As for the position of the opening, two locations with respect to the dapped end were considered in this study, the first one was 250 mm as (d) length and the second one was 500 mm as (2d) length from the dapped end. These openings are vertically aligned at the center of the beam or at mid depth of the beam. Details of the tested beam specimens with their designation are listed in Table 1. Strain gauges for the concrete and reinforcement were installed at one end of the beam. To guarantee shear failure at that end and simulate one-third span loading case the load was applied at 1 meter from the support. The static load was gradually applied until failure. Figure (4) below shows testing setup.

Figure 4: Testing setup.

Table 1: Details of the tested beam specimens.

Specimen	Opening shape	Opening location	Strengthening
PSSOLID, Reference	Non	Non	1
PSCOd	circular	d	Non
PSCOd-FRP	circular	d	yes
PSSqOd	square	d	Non
PSSqOd-FRP	square	d	yes
PSCO2d	circular	2d	Non
PSCO2d-FRP	circular	2d	yes
PSSqO2d	square	2d	Non
PSSqO2d-FRP	square	2d	yes

5. TESTS RESULTS

The nine specimens of prestressed dapped end beams consisted of a reference beam without opening in addition to eight strengthened/unstrengthened prestressed with openings. The solid reference beam (PSSOLID) failed at the dapped region due to re-entrant corner shear crack followed by concrete crushing at the top face near the dapped end as shown in Figure 5. On the other hand, the failure for the non-strengthened beams with openings was due shear crack in the opening's region, whereas the mode of failure for other beams with strengthened openings was similar to that for the reference one as shown in Figures 6 and 7. The study shows that cracks appeared earlier at the re-entrant region and below the concentrated load in addition to opening region, then the cracks widened progressively along the route between the concentrated load and nearer support crossing the opening. When failure occurred at the opening, it was a shear failure, whereas, it was a secondary compressive failure in the dapped zone.

The failure load and first crack load are presented and compiled in Table 2. Results presented in this table indicated that openings reduces dapped beam strength, while indicating increase in the specimen's strength for strengthened samples using CFRP sheets. Generally, all beam samples were less strength than the solid reference one. For specimens with openings near the support at (d) distance failed by ultimate load capacity less than by 20 % of the reference dapped beam. This is due to opening lay at the highly stressed and disturbed region (D) of the dapped end. While the strengthened beam by CFRP sheets around the opening, their strength has increased by 10% as compared to unstrengthened beams. The CFRP strengthening reduces the opening effect significantly and work as additional stirrups around the opening, also the CFRP sheet prevents the cracks to grow towards the opening.

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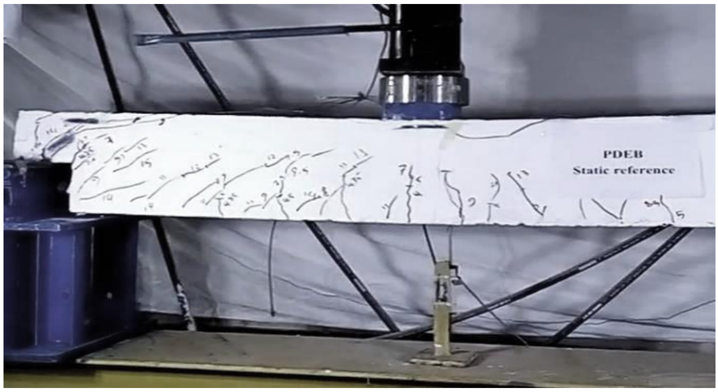

Figure 5: Reference dapped beam at Failure stage.

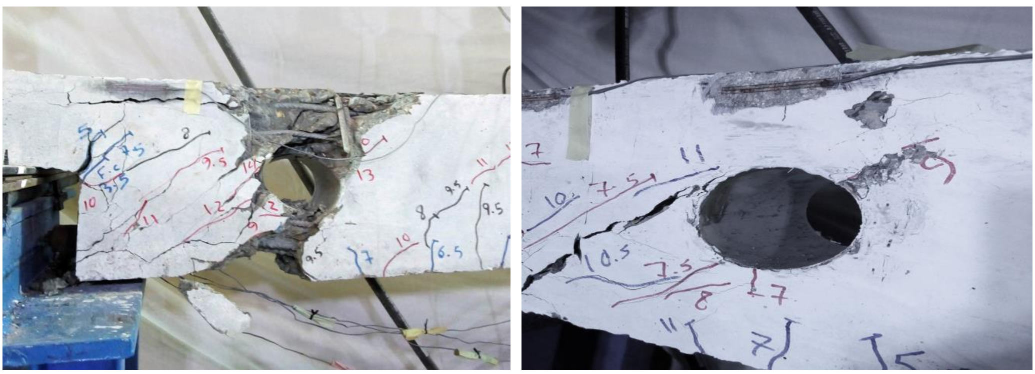

Figure 6: Dapped beam with unstrengthened opening at Failure stage.

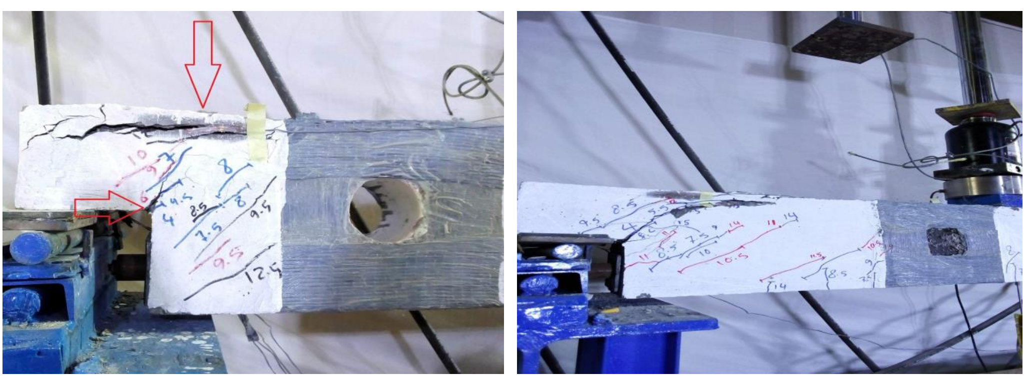

Figure 7: Dapped beam with strengthened opening at Failure stage.

The other four beams with distant opening from the support, shown in Figure 8, results showed that openings have minor effect on the dapped beam strength. Results showed that shear strength of dapped beams were reduced by about 10% of the reference beam. Consequently, the CFRP strengthening has minor rule. An increase in the strengthened samples of about 5% is observed as compared to unstrengthened onse. In all strengthened beams ductile behavior is less observed. Near failure, steel reinforcement yielded progressively and the strains increased proportional to the loading until the concrete cracks. With increasing loading cracks widened, beam curvature increased causing more steel yielding till the concrete above the nib has crushed. The prestressed strand work with steel plates at the ends as a confinement technique that reduce the cracks and fractures in moderate stage. Generally, the prestressing of concrete has enhanced confinement which in turn, increased shear strength in the region around the opening.

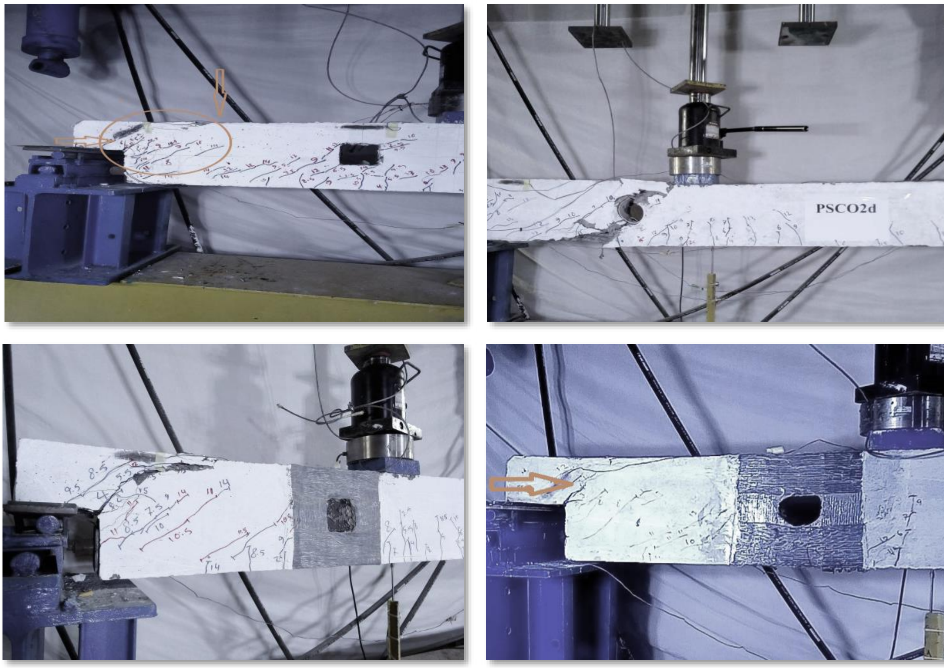

Figure 8: Prestressed dapped end beam with distant openings.

Comparison for the test results for the nine prestressed RC dappled end beams are shown in Table 2 below, along with comparison to the values for the solid dapped end beam. Percentage of the load carrying capacity to the reference solid beam also shown in the table in addition to the maximum deflection.

Table 2: Ultimate load, cracking load and maximum deflection of tested beams.

sample	First crack load (kN)	Failure load (kN)	Failure load ratio to PSSOLID	Deflection (mm)
PSSOLID, Reference	4.5	165	1	21.21
PSCOd	3.5	131.45	0.796	20.78
PSCOd-FRP	3	144.12	0.877	16.34
PSSqOd	3	130.66	0.769	20.69
PSSqOd-FRP	4	137.91	0.835	13.36
PSCO2d	4	141.11	0.855	17.27
PSCO2d-FRP	4	144.02	0.872	16.64
PSSqO2d	3.5	153.02	0.927	19.12
PSSqO2d-FRP	3.5	151.54	0.918	20.11

The results show the maximum deflection increased with presence of opening, while it reduced for strengthening beams. Figure 9 to Figure 12 below showed the load-deflection curves for all tested samples.

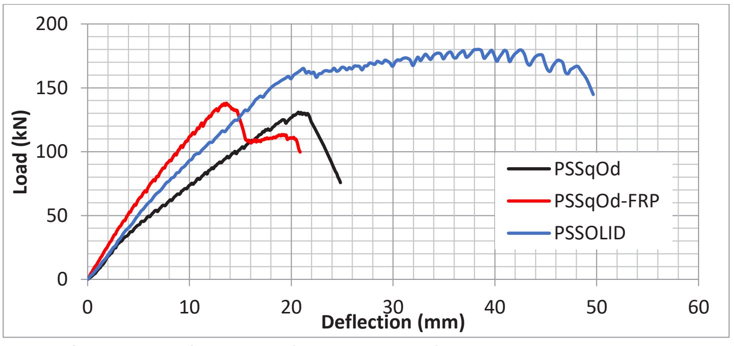

Figure 9: Comparison for load-deflection curves for square opening at (d) distance.

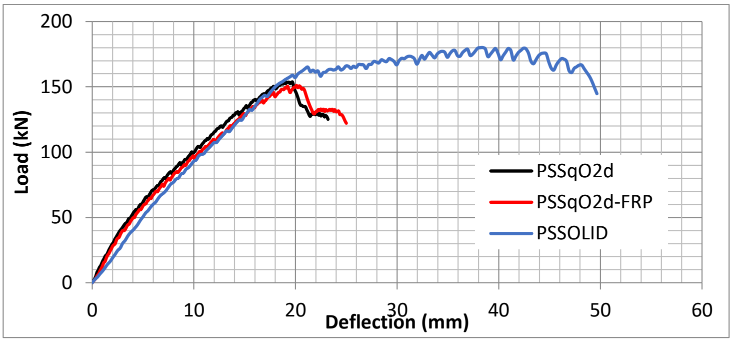

Figure 10: Comparison for load-deflection curves for square opening at (2d) distance.

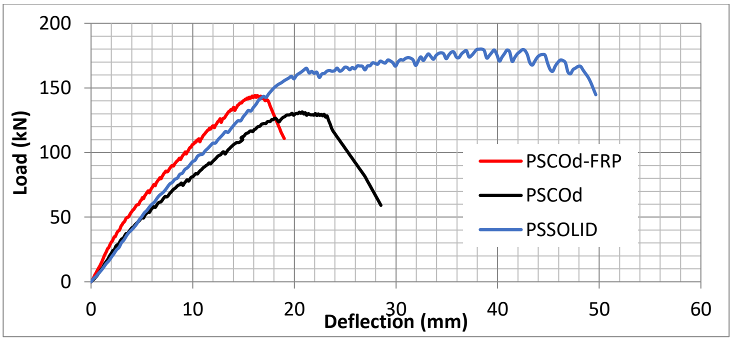

Figure 11: Comparison for load-deflection curves for circular opening at (d) distance.

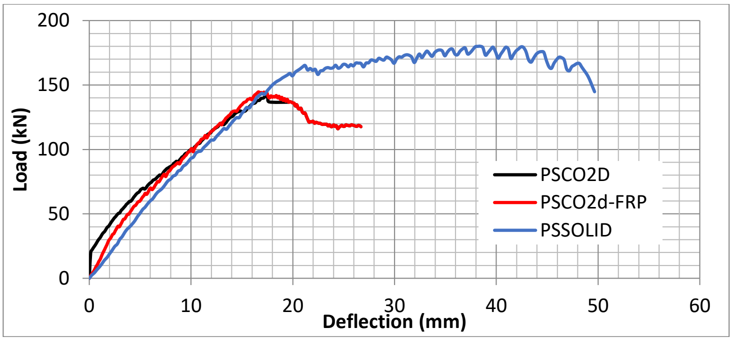

Figure 12: Comparison for load-deflection curves for circular opening at (2d) distance.

6. STRUCTURAL BEHAVIOR COMPARISON

The research investigates the effects of some parameters on dapped end beam behavior. Comparisons can be introduced between the variables for this study as shown below.

6.1 Opening Shape Effect

Results presented in above figures indicated that openings significantly reduce shear strength of the dapped beams. More than 20% reduction in the ultimate load capacity is observed due to web openings near dapped end. An ultimate load capacity of about 80% and 77% as compared to the reference beam is recorded due to circular and square openings, respectively. This result showed that dapped beams behavior is more susceptible to square openings effect than circular ones.

6.2 CFRP Strengthening Effect

Results presented in Table 2 and Figures 9 to 12 revealed that CFRP strengthening is most effective for openings close to the dapped end and it is less effective for distant openings. Generally, an enhancement of about 8% is achieved due to CFRP strengthening for openings close to the dapped end, whereas negligible effect is shown for distant openings. This result is obviously presented and highlighted in Figure 13 in which comparison for the effect of CFRP strengthening is presented.

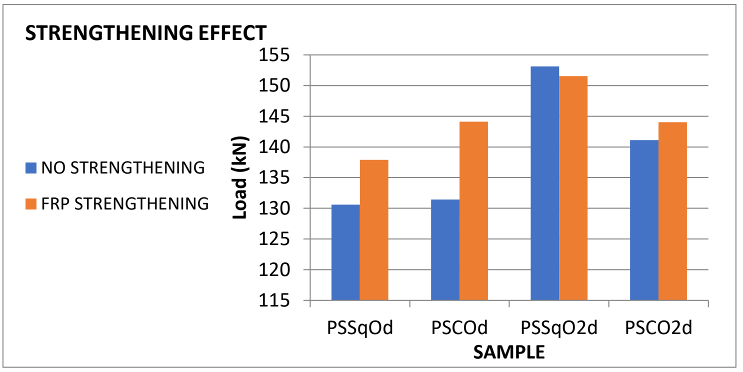

Figure 13: Comparison for strengthening effect at ultimate loads.

6.3 Opening Location Effect

Results compiled in Table 2 and shown in Figures 14 and 15 revealed that opening location significantly affect dapped beam behavior. It is indicated that openings close to the dapped end greatly affect ultimate and cracking strength, whereas lesser effect is observed for distant openings. A reduction in the ultimate shear strength about 20 to 23% is indicated for openings close to the dapped end, as for distant openings a reduction about 7 to 13% is recorded.

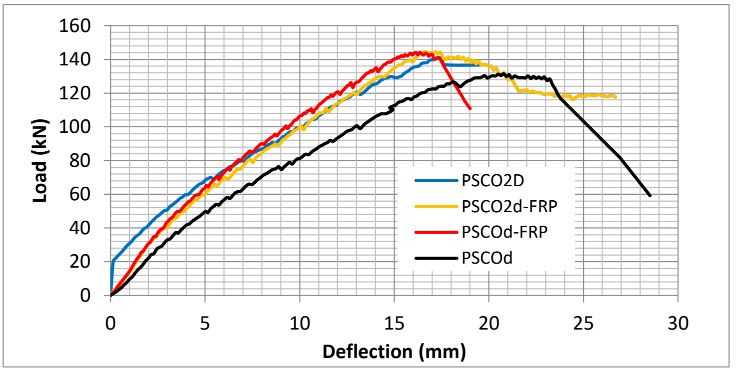

Figure 14: Effect of opening location and strengthening due to circular openings.

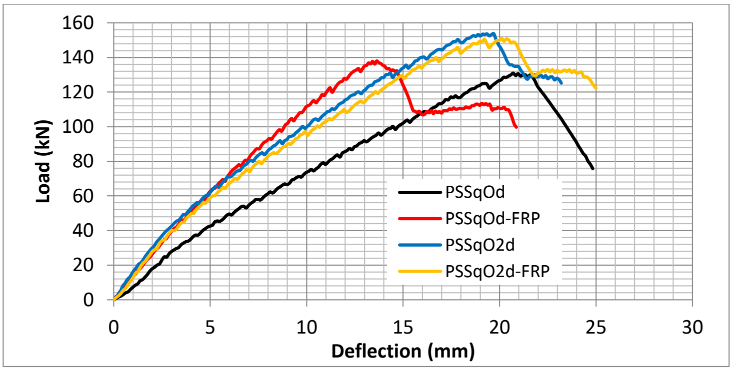

Figure 15: Effect of opening location and strengthening due to square openings.

7. CONCLUSIONS

The following conclusions are drawn from this study.

- Openings located at a distance (d) from the dapped end reduced the ultimate shear strength capacity by about (20-23) % for square and circular opening respectively.
- This study concludes that dapped beams ultimate strength is not greatly affected by the presence of openings at a distance (2d) from the support, so the strengthening was not valuable.

- Strengthening the opening by CFRP sheets restores the strength lost due to openings upto 92% of the load carrying capacity for near opening.
- The crucial mode of failure was the diagonal tension failure at the re-entrant corner, which is caused by the re-entrant corner crack due to simultaneous yielding of the horizontal and vertical steel reinforcement followed by concrete compression failure at the concrete top face near the nib.
- Shear failure was dominant due to the reduction of concrete section at the opening region.

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