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# EFFECT OF OPENING CHARACTERISTICS ON THE PERFORMANCE OF HIGH STRENGTH RC DAPPED-END BEAMS

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**Abstract**

In precast construction, dapped-end beam (D-EB) with openings serves as one of the elements that result in a more friendly environmental structure by reducing the height of the building. In this work, the behaviour of the dapped-end beams with openings have been studied experimentally. The effect of introducing the openings without any additional reinforcement was monitored. Nine D-EB*s* were included in the experimental work. Three locations for the opening have been tested, at zones of high, moderate and low bending moment. Three shapes of openings were considered, circular, with a diameter of 170 mm and 220 mm, square with a side of 150 mm and the rectangle with dimensions of 150 mm × 250 mm. Two sizes of circular opening within the zone of a moderate bending moment have been studied. It was found that a considerable enhancement in load capacity in the range of about 23 to 25% was gained when the straight main nib (extended end) reinforcement was replaced by bent reinforcement. In addition, the results showed that the best location of the opening was when it located within the regions of high positive bending moment. Furthermore, the absence of opening reinforcement resulted in unexpected failure modes.

Keywords: Dapped end beam, High strength concrete, Opening, Precast beam, Re-entrant corner, Self-compacting.

## 1. Introduction

The concept of using precast dapped-end beams (D-EBs) is commonly utilized in the precast construction industry. The advantages of using such members is to reduce the story height of buildings and enhance lateral stability [1]. this will make buildings construction more environmental friendly because that leads to saving in the construction materials and required energy for air conditioning. However, geometrical discontinuities due to including dapped-ends and openings in a beam reduce its stiffness and induce high-stress concentrations at re-entrant and opening. Consequently, the behaviour and failure mode of such beams become more complex and must be properly studied.

Based on available previous investigations, the failure of the D-EBs is expected to occur at the nib (extended end), the junction between of the nib and the main body, re-entrant corner, or bottom corner of the full-depth part of the dapped-end [2] as shown in Fig. 1. A number of researches have been conducted to investigate the behaviour of D-EBs. Mattock and Chan [3] proposed a rational and modified design procedure for D-EBs considering the dapped ends as an inverted corbel following the design proposal of Mattock [4]. They recommended that a group of closed stirrups should be provided near the full-depth beam and all reinforcements should be well anchored.

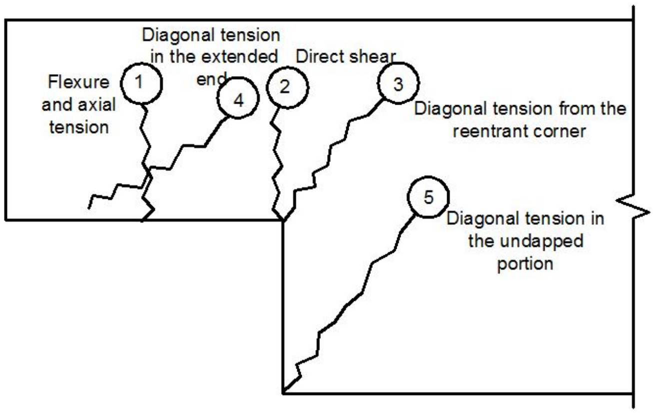



**Fig. 1. Failure modes for the dapped end beam [2].**

In 1983, Liem [5] suggested a new method to enhance the strength of the hanger region. Inclined hanger reinforcement was used to interrupt the diagonal cracks emanating from the re-entrant corner. It was concluded that a considerable enhancement in the capacity of dapped ends was obtained. Regarding the economical view, it was concluded that inclined reinforcement are ($\sqrt{2}$) times more than the horizontal reinforcement in terms of the amount of steel required. Mattock and Theryo [6] carried out experimental tests on D-EBs and concluded that the inclined hanger bars provide better cracking control than vertical hanger bars. Based on experimental tests, Lu et al. [7] concluded that enhancing the concrete compressive strength and increasing the amount of flexural reinforcement of the nib could be led to an improvement in the shear strength of D-EBs. As well as, the reduction in the ratio of shear span to nib depth could improve the shear strength of D-EBs. Peng [8] performed experimental tests to study the effect of detailing on the behaviour of D-EBs. The results showed that the details and anchorage of longitudinal and hanger reinforcement have an important effect on the ductility and shear strength of D-EBs. Mattock [9] developed a simplified strut-and-tie model (STM) to design D-EBs with the minimum required amount of reinforcement. Ahmad et al. [10] studied the influence of nib end depth on the response of the D-EBs. In 2014, Aswin, et al. [11] discussed effect of grade of concrete, dapped -end dimensions, (shear span/effective depth of dap) ratio, types and distance of hanger reinforcement, bent form of the longitudinal reinforcing bars, main dapped end and hanger reinforcement on the response of dapped ends. Results revealed that RC DE-B with non-vertical stirrups, bent longitudinal bars, the smaller spacing between stirrups yielded better performance. In 2015, Aswin, et al. [12] suggested using high strength concrete (HSC) within dapped end region only. They found that the use of HSC in such region may improve the ultimate load by 51.9% and increasing the amount of nib and main flexural reinforcing bars gave an enhancement in failure load by 62.2% and 46.7% respectively. Lu et al. (2015) suggested that by using HSC and low ratios of tensile reinforcement, the D-EBs exhibited ductile flexure failure. Desnerck et al. [13] investigated several reinforcement details of dapped ends. In 2018, Desnerck et al. [14] studied experimentally several variables that may affect the performance of such members, such as compressive strength and reinforcement layout.  It was found beyond studying different reinforcement deficiencies, the maximum drop in the capacity was about 40%.

In order to maintain the saving in the story height, it is necessary to pass service ducts and pipes in the floor beams through transverse openings. Many researches have been performed to study the effect of inclusion transverse openings on the structural behaviour of RC beams [15]. Shakir [16] concluded that the location and size of rectangular openings in (RC) beams have a great influence on the shear strength and failure load. Latha and Kumar [17] reported that the effect of circular openings on the collapse load of RC beams becomes more obvious when the diameter of openings exceeds 44% of beam depth. Osman et al. [18] demonstrated that RC beams exhibited early failure if the opening located across the line connecting between the supports and loading points.

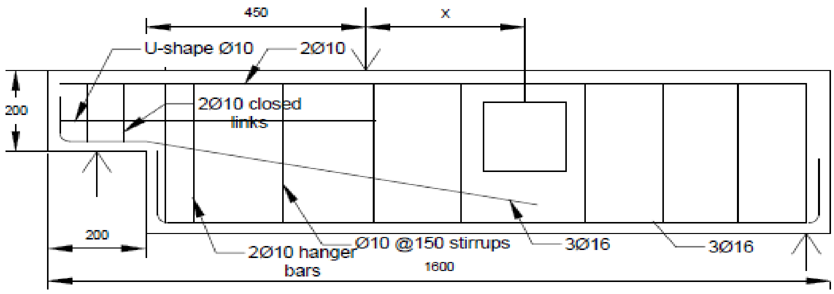
Although Chen et al. [19] tested four small-scale D-EBs with openings to evaluate the applicability of the STM modelling for this type of irregular members. Nevertheless, there is no available research on the effect of openings on the behaviour of D-EBs have been performed.

The inclusion of both dapped ends and openings in beams converts the simple beam behaviour to a more complicated one and makes it difficult to predict the failure mode. Previous researchers focused their attention on either D-EBs without openings or non-dapped end beams with openings. It was significant to investigate experimentally the effect of inclusion of both openings and dapped-ends on the structural behaviour and failure mode of RC beams. This work can be the first step to study more advanced structures such as verendeel trusses with dapped ends, which satisfy various advantages such as weight reduction, easy fabrication, more stability, less overall heights of structures and passages of services. The effects of openings shape, location, and size on the D-EBs response were studied. The results of this study provide a good reference for studies to be achieved in the future about the behaviour of D-EBs with an opening.

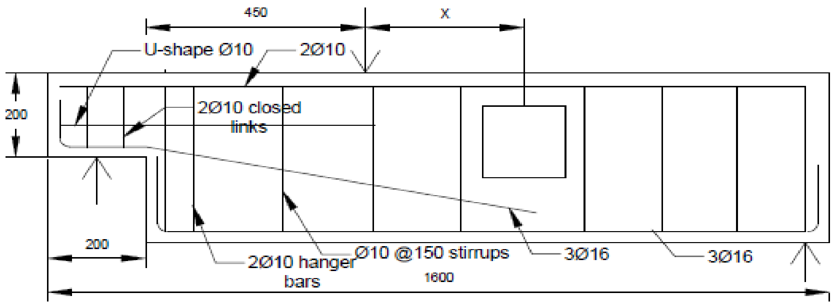
## 2. Experimental program

Eight simply supported RC D-EBs with openings in addition to one without opening (the control specimen) were constructed and tested up to failure. The design of steel reinforcement of all D-EBs was in accordance with the requirements of the PCI Design Handbook [2]. Each dapped end beam specimen had a total length of 1600 mm, full depth of 400 mm and a width of 200 mm, having one opening in a specified location. The dapped-end length and height were 200 mm × 200 mm. The investigated parameters were opening shape, location, and size. The characteristics of the openings are identified in Table 1 and the details of the control and a typical beam with opening are shown in Fig. 2.

High strength self-consolidating concrete was used in all test specimens. The high strength self-consolidating concrete was produced using mix proportions, as listed under constituent materials of the concrete mix (kg per 1 $m^3$) [20]: Cement: 470 (1); Water: 155; Gravel: 800 (1.7); Sand 880 (1.78); Limestone; 100 (0.21); Gilnum (L): 7.5 and W/C: 33%, in which, was obtained beyond three trail mixes according to ACI 237R-07 [20]. The values in parentheses represent a mix ratio. The adopted mix proportions yielded an average of compressive strength of 80 MPa and splitting tensile strength of 4.0 MPa. The compressive strength was determined from the cube test of 150 mm × 150 mm and splitting tensile strength was determined from testing cylinders of 100 mm × 200 mm [21]. The yield stress and ultimate strength for steel used are shown in Table 2. The reinforcement arrangements for the tested beams are shown in Fig. 2. The supports are represented using thick steel plates and smooth shafts. Rubbers plate were used to ensure a uniform distribution of reactions.




**(a) Control beam.**




**(b) Beams with openings.**

**Fig. 2. Dimensions and reinforcement details of the dapped end beam.**

**Table 1. Designations of specimens and characteristics of openings.**

| Beam designation | *x**(mm) | Opening size** (mm) |
|---|---|---|
| **D00** | ------- | Solid |
| **DS1** | 165 | 150×150 |
| **DS2** | 375 | 150×150 |
| **DS3** | 485 | 150×150 |
| **DC1** | 165 | 170 |
| **DC2** | 375 | 170 |
| **DC3** | 485 | 170 |
| **D2CL** | 375 | 220 |
| **DR2** | 375 | 150×250 |

*measured from the loading point to the centre of opening
**rectangular opening *H*×*W*; for circular opening *D*

**Table 2 Mechanical properties of steel reinforcement.**

| Bar diameter (mm) | Yield stress (MPa) | Ultimate strength (MPa) |
|---|---|---|
| 10 | 670 | 810 |
| 16 | 615 | 710 |

## 3. Discussion and Results

### 3.1. Load deflection curves results

Figure 3 shows the load-deflection curves of the specimens D00, DC1 and DS1. It can be noticed that the three specimens yielded the same behaviour throughout most of the loading stages, and a diagonal crack developed from the re-entrant corner. But, at the load level of 310 kN, the rate of widening in the diagonal crack was increased for specimen D00, leading to sudden failure and producing the least load capacity of 325 kN. This may be attributed to improvement in the behaviour caused by the inclined nib bars [5].

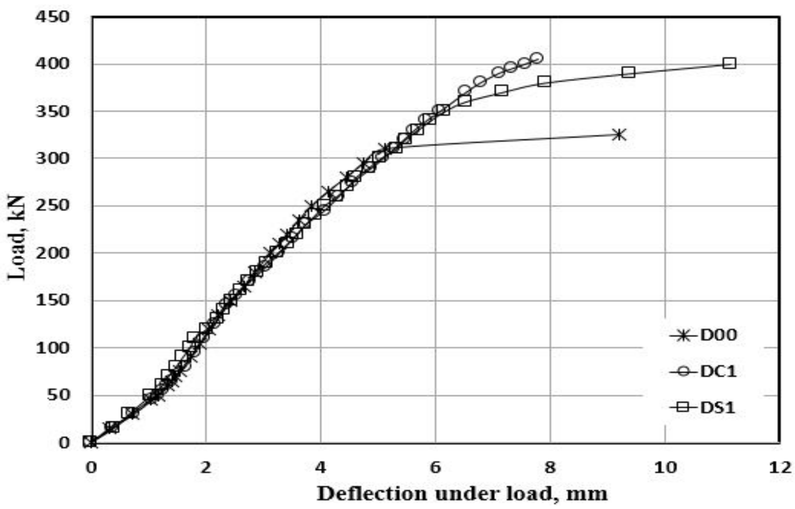



**Fig. 3. Load-deflection curves for specimens D00, DC1 and DS1.**

In addition, it is clear that the two dapped ends yielded the same performance up to the final loading stages and same load capacity in spite of the difference in the shape of the openings. This gives the impression that when the opening was located within the high moment region (does not interrupt the diagonal crack failure), it played a minor role in determining the capacity and that is the best location to introduce openings.

This can be interpreted as locating the opening within the zone of the maximum moment near the neutral axis did not cause flexure failure because the compression block above the opening, (of compressive strength 78 MPa) was efficient to equilibrate the tension force induced in the main steel reinforcement.

Thus, there is no significant reduction in the moment capacity. The detailing of the dapped ends was dominant and since the same details were adopted then the negligible difference was obtained. The diagonal shear crack developed from the point load passed out of the opening.

For specimens DC2 and DS2, in which, the test results are shown in Fig. 4, the opening location was shifted away from the point of load application. This gives more possibility that the opening may lie on the path of the expected crack that may be developed diagonally from the point of application to the bottom face of the beam.

For the square opening, the diagonal crack was developed more rapidly than for circular shape resulted in a relatively weak response. This may be attributed to the concentration of the stresses at corners. Thus, two parameters interacted or two types of cracks develop, which are cracking with the dapped ends and the diagonal cracks as a deep beam.

For DC3 and DS3 specimens, the openings were shifted more toward the non-dapped end. Thus, the effect of the diagonal crack emanating from the re-entrant corner diminished and a new diagonal crack from the non-dapped end support towards the opening was more effective.

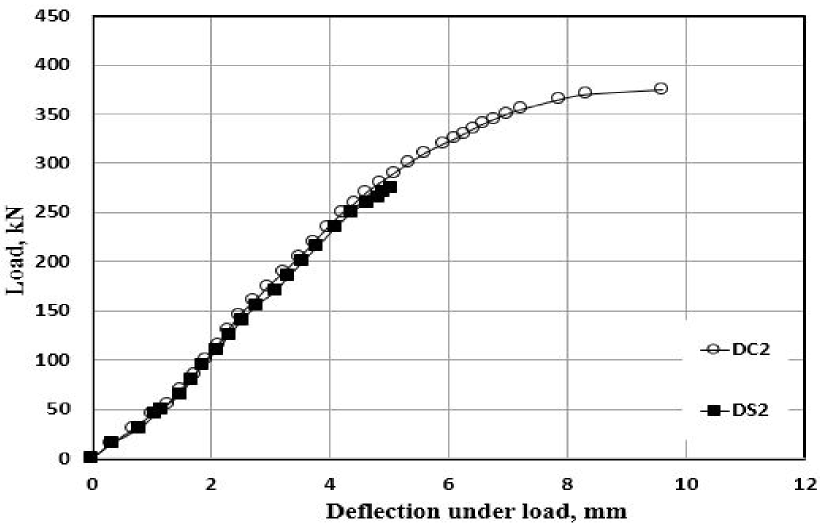



**Fig. 4. Load-deflection curves for specimens DC2 and DS2.**

The results are shown in Fig. 5. A noticeable difference can be seen between the two specimens all over the stages of loading, which may be attributed to the difference in stages and location of formation of the initial cracks. It was found that changing the shape of the opening from circular to a square when located at high shear zone, resulted in an increase of the ultimate load by about 21% and max. deflection by about 18%. Thus, it is recommended to use a suitable reinforcement against shear if it is possible (or strengthening) for the top and bottom chords of the opening when it is located out of the zone of the maximum moment. Then, more loads may be accommodated and the failure occurs within the dapped end region in a gradual manner. This has been considered in next work and comparison have been made between the performance of the D-EBs with reinforced or non-reinforced openings in the top and bottom chords.

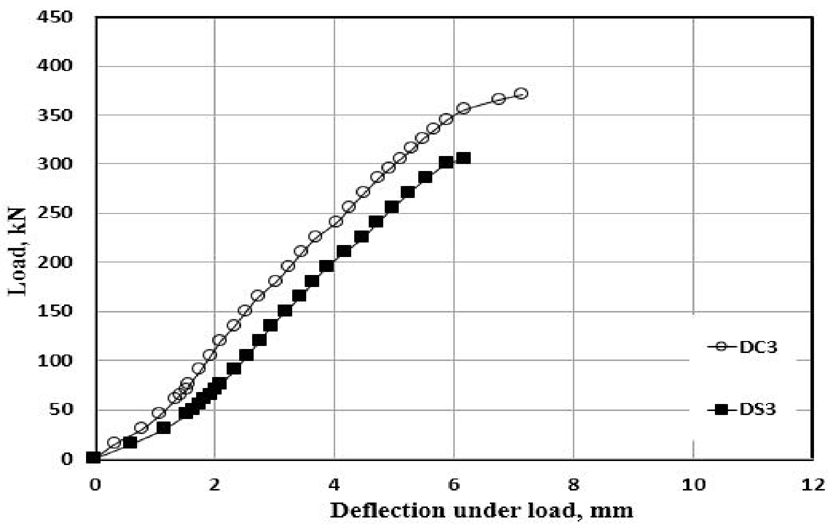



**Fig. 5. Load-deflection curves for specimens DC3 and DS3.**

Figure 6 shows the effect of opening size on the load-deflection curve. It can be seen that at a load level of 290 kN (failure load of DC2L), the deflections were 6 mm and 5 mm for specimens DC2L and DC2. But because that specimen DC2L failed earl, which is higher opening diameter 13% relative to DC2 led to a reduction in capacity and deflection at the failure of about 22% and 40% respectively.

Figure 7 shows the load-deflection curve of specimen DR2 against that of specimen DS2. It is noted that the failure load of specimen DR2 was greater than that of specimen DS2. That can be explained by the cracking path directed toward the corners of the opening, which played a major role in the failure modes of both these two specimens, was larger and it was interrupted by more shear reinforcement in specimen DR2.

In the same time, it is clear that the response of DR2 was softer than that of DS2 that can be due to the opening size is larger in the specimen DR2. Furthermore, at the interval of loading 300-322 kN of DR2, some instability in response can be seen revealing that severe local failure occurred subsequently in two points around the opening leading to a sudden failure of the specimen at the load of 322 kN.

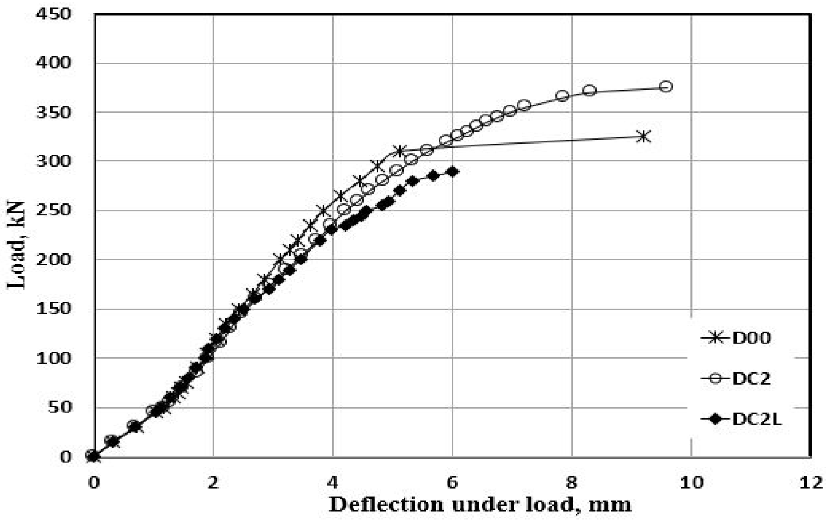



**Fig. 6. Load deflection curves for specimens DC2 and DC2L against D00.**

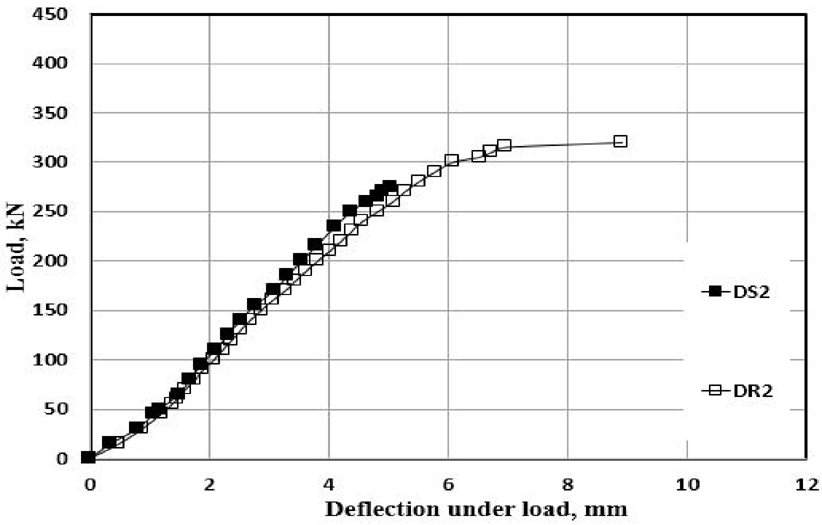



**Fig. 7. Load-deflection curves for specimen DR2 against DS2.**

## 2.1. Crack patterns and failure load

Figures 8 to 10 show the crack patterns of specimens D00, DC1 and DS1. It can be observed that the load capacity of the solid beam D00 is smaller than the capacities for the specimens DS1 and DC1. This may be attributed to the bent in the main nib reinforcement, which was needed to accommodate the openings. This may result in an enhancement in performance of the dapped end rather than to be straight as in the conventional form. The improvement in behaviour may be attributed to the fact that the bending of nib reinforcement may produce three different effects. It may produce better integrity between the upper part of the beam (including the dapped end) and the lower part leading to higher resistance to cracking penetration and propagation. Furthermore, the bent makes the bars within the dapped end to act as frames. Thus, more resistance to bending will be gained. In addition, the bent bars result in some enhancement in the hanger zone as reported previously by Leim [5]. In general, for the three specimens, the diagonal shear cracking was dominant. Figures 9 and 10 state that the diagonal cracking developed mostly, out of the opening zone. Thus, making the opening to be inactive.

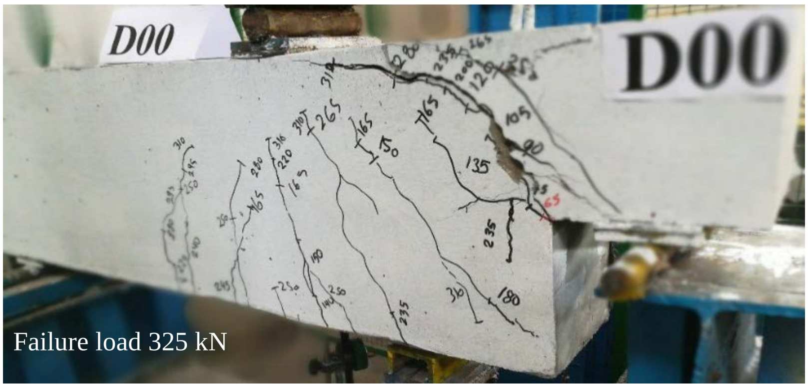



**Fig. 8. Crack pattern for specimen D00.**


**Fig. 9. Crack pattern for specimen DC1.**

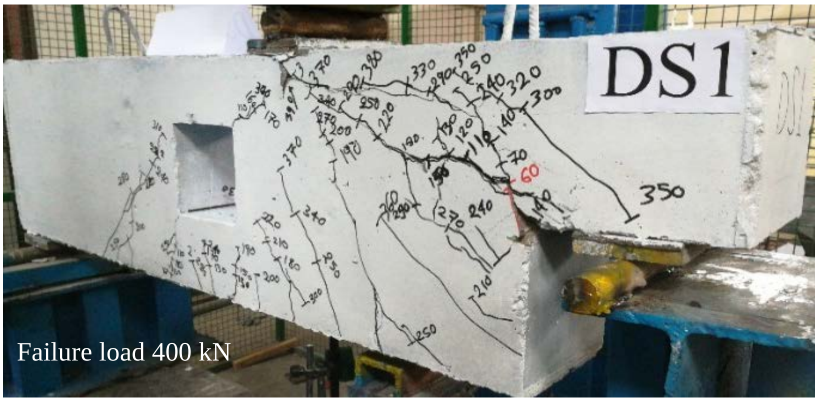



**Fig. 10. Crack pattern for specimen DS1.**

Regarding the angle of cracking, it can be seen that this angle is smaller for the beams DS1 and DC1 if compared with the solid beam. This supports the opinion that the bents in the main nib bars led in accommodating more bending moment and shear than the straight bars. Thus, the effect of flexure was more obvious in the solid beam thereby producing larger initiation angle of the crack. It can be seen that the mode of failure for the solid beam and the specimens DS1 and DC1 are identical although of the existence of the openings. This may be explained as that locating opening within the high moment region makes the induced cracks within opening zone spread towards the applied load to follow steep angle (approximately 45°), which is interrupted by the stirrups of the beam on both sides of the opening. This may restrict crack propagation around the opening significantly and reduces the effect of the opening and the specimen behaves as a solid one. This is obvious in the negligible difference in the capacity of 1.25% between specimens DS1 and DC1.

Figure 11 shows the cracking pattern for specimen DC2. Comparing specimens DC1 with DC2, it can be seen that for beam DC2 the opening is shifted out of high moment region towards the far support. This results in more diagonal cracks to develop across the opening and reducing the far support stiffness thereby increasing dapped end reaction. Subsequently, the stresses concentrated within the re-entrant corner and caused the beam to fail at a lower load than DC1.

Comparing specimens DC2 with DC3, in which, the pattern is shown in Fig. 12, it can be seen that the crack patterns are identical for all stages of loading. It is clear that the cracking emanating from the circular opening followed a diagonal path and it was restricted from widening by the stirrups. However, for specimen DC3, due to the vicinity of opening from the left support, some cracking developed diagonally toward this support. Thereby dapped end could counteract more curvature than the dapped end of beam DC2. Hence, cracks that developed from the opening to the loading point and the support produced a weak zone at the opening, which acts as a plastic hinge. This made the beam to deflect as two segments and caused spalling near the loading point, which led to the formation of a sudden crack with the area above the opening. This crack resulted in a drastic drop in shear strength. Thus, the mode of failure changed at the last stage of loading to be as a diagonal shear failure through the opening. It can be concluded that disregarding opening details in the design may lead to an unexpected failure mode.

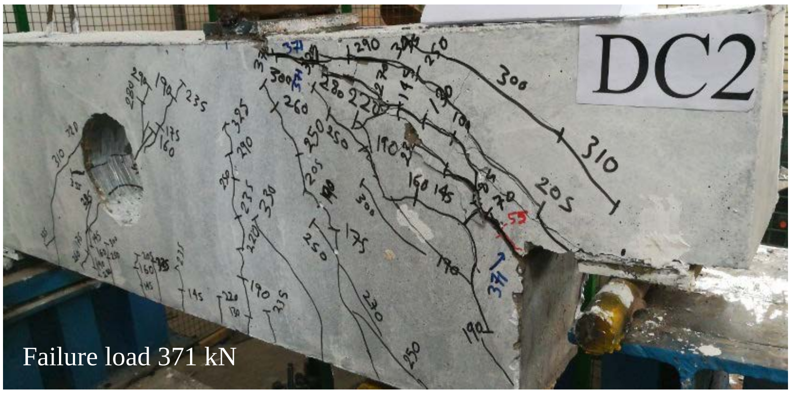



**Fig. 11. Crack pattern for specimen DC2.**


**Fig. 12. Crack pattern for specimen DC3.**

For specimen DS2, the crack pattern is shown in Fig. 13. Comparing DS1 with DS2, it can be seen that in DS2, the opening is shifted to the non-dapped end within the shear zone. Cracks emanated at the opposite corners of opening in the direction of the line passing from loading point toward left support. The test was terminated by diagonal shear failure through the opening.

Comparing DS2 with DC2, it is obvious that all the cracking pattern, the mode of failure and failure load were different. The first crack initiated in the square opening for DS2 at load 80 kN and at 160kN for the circular one (DC2). This is because of the concentration of stresses at the corners of the square opening and uniformity of stress distribution around the circular opening. This difference results in a weak opening zone in specimen DS2. Subsequently, failure for specimen DS2 is characterized by a diagonal shear crack passing through the opening. While for the specimen DC2, the opening zone resists more shear stress.

This ensures that the shape of opening play a major role when it is located at the regions where the shear is more effective than the bending moment (between the non-dapped end support and the zone of the maximum moment).

It can be seen that specimen DS3, in which, cracking pattern is shown in Fig. 14, resisted more load than specimen DS2. This may be attributed to the fact that DS3 includes more stirrups interrupting the crack initiated from the top corner and developed towards the point load. With loading progress, cracks propagated at the dapped end and from the bottom corners of opening towards the support. This resulted in more curvature. Subsequently, a spalling of the top layer of concrete has taken place. As a result of the difference in the number of stirrups, the failure of DS3 was delayed.

Figure 15 shows the cracking pattern for the specimen DC2L. It can be seen that the mode of failure is similar to that of specimen DC3. This may be attributed to the reduction in the top and lower chords of the opening, which results in more weakness in the opening zone rather than the dapped end zone as in specimen DC2. Therefore, it can be concluded that locating openings with larger size within the zone of small shear may result in similar behaviour as for smaller openings located within zones of high shear.

Table 3 shows the cracking load, load capacity and failure mode for the tested specimens.


**Fig. 13. Crack pattern for specimen DS2.**


**Fig. 14. Crack pattern for specimen DS3.**


**Fig. 15. Crack pattern for specimen DC2L.**

Figure 16 shows the crack pattern for specimen DR2. It is clear that the failure mode of this specimen is a diagonal shear failure through the opening. The improved capacity may due to the shifted stirrups to both sides of the opening leading to a higher shear resistance than DS2. Remembering that the top chord failed before the bottom due to the crashing. The failure occurred at two stages of loading. The first occurred at top chord within load level of 300 kN followed by collapse at 322 kN. Thus, it is recommended to substitute the stirrups within the opening location by stirrups on both sides of the opening.

**Table 3. Failure load and mode of failure for the tested specimens.**

| Beam designation | Initial cracking load (kN) | Failure load (kN) | Failure mode |
|---|---|---|---|
| **D00** | 65 | 325 | Diagonal cracking at re-entrant corner |
| **DS1** | 60 | 400 | Diagonal cracking at re-entrant corner with crushing |
| **DS2** | 50 | 275 | Gradual diagonal cracking through opening |
| **DS3** | 75 | 305 | Sudden diagonal cracking through opening |
| **DC1** | 65 | 405 | Diagonal cracking at re-entrant corner with crushing |
| **DC2** | 55 | 371 | Diagonal cracking at re-entrant corner with crushing |
| **DC3** | 75 | 370 | Sudden diagonal cracking through opening |
| **DC2L** | 50 | 290 | Gradual diagonal cracking through opening |
| **DR2** | 55 | 322 | Sudden diagonal cracking through opening with crushing |


**Fig. 16. Crack pattern for specimen DR2.**

Figure 17 shows the effect of the opening located on the DE-Bs capacity. It can be clearly noticed that the specimen DS1 and DC1 recorded the highest capacity compared with other cases and the failure occurred at the dapped ends rather than the opening. Therefore, introducing the opening has the lowest effect. The reason for that may due to locating the opening in the maximum moment region and this discussion previously presented. It can also be noticed that when the opening displaced to the second position ($x$ =375 mm) therefore, there is a possibility that the expected strut may be interrupted by the opening. This resulted in a drop in capacity of about 31% and 8% in case of D-EBs with square and circular opening respectively compared with the case of D-EBs with the opening located at high bending moment zone. The ultimate capacity slightly increased for DS3. This may be attributed to the longer crack path, which requires higher energy to be developed.

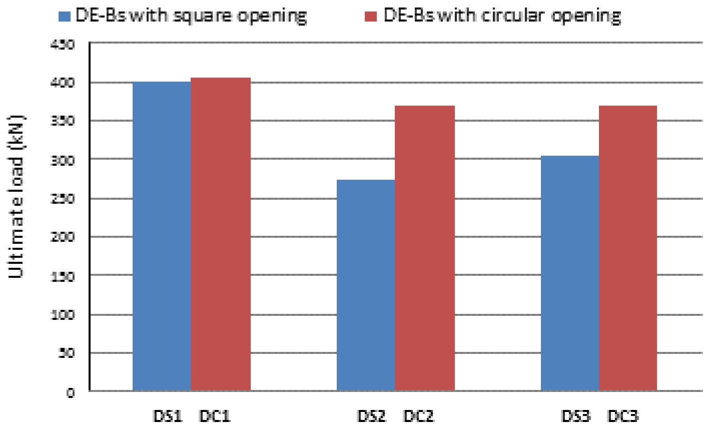



**Fig. 17. Effect of the opening location on load capacity of the dapped end beams.**

## 4. Conclusions

Based on experimental study achieved on high strength D-EBs self-consolidating concrete the following flinging can be drawn

- The presence of bent in the main nib reinforcement near the dapped end has a significant effect on the behaviour and ultimate load of the D-EB. Despite the presence of opening within high bending moment zone, the ultimate load was increased in the range of about 23 to 25% when the straight main nib reinforcement was replaced by bent reinforcement.
- The effect of opening on the behaviour of D-EB is insignificant when it was located in the region where the bending moment was dominated. Consequently, there was no pronounced effect on the shape of the opening on the ultimate load, which decreased by about 1% when the square opening was used instead of a circular one.
- The influence of opening became more important and the failure mode changed from a diagonal crack at the re-entered corner to crack through the opening as the opening was moved toward the shear-dominated region.
- For the moderate opening size of $D/H$ = 0.425, the effect of the circular openings on the ultimate load of D-EB was lesser than that of the squared openings of the same equivalent area. The ultimate load was decreased in the range of about 26% when openings shape changed from square to circular.
- For a large opening size of $D/H$ = 0.50, the circular opening has a more negative influence on the ultimate load of the D-EB than the rectangular opening of the same equivalent area. The ultimate load increased by about 11 % when the circular opening was changed to rectangular.

- The length of cracking paths, which penetrate diagonally through the opening, along the line connecting load and the non-dapped end support governed the failure load of the D-EB with an opening in the shear-dominated region.
- The number and location of the stirrups that intersected the cracking paths had a great influence on the behaviour and failure load of the D-EB with the opening in the shear-dominated region.
- It is recommended to use suitable reinforcement (or strengthening) within the chords of the opening in D-EB in the shear-dominated region to prevent drastic failure at later stages of loading.

## Nomenclatures

| | |
|---|---|
| *D* | Diameter of opening, mm |
| *D00* | Solid specimen |
| *DS1* | Specimen with square opening at *x* = 165 mm |
| *DS2* | Specimen with square opening at *x* = 375 mm |
| *DS3* | Specimen with square opening *x* = 485 mm |
| *DC1* | Specimen with circular opening at *x* = 165 mm |
| *DC2* | Specimen with circular opening at *x* = 375 mm |
| *DC3* | Specimen with circular opening at *x* = 485 mm |
| *DC2L* | Specimen with large circular opening at *x* = 375 mm |
| *DR2* | Specimen with rectangular opening at *x* = 375 mm |
| *L* | Length of opening, mm |
| *W* | Width of opening, mm |
| *x* | Distance from the re-entrant edge to the centre of opening, mm |

### Abbreviations

| | |
|---|---|
| ACI | American Concrete Institute |
| D-EBs | Dapped End Beams |
| HSC | High Strength Concrete |
| PCI | Precast/Prestressed Concrete Institute |
| RC | Reinforced Concrete |
| STM | Strut and Tie Model |

## References

1. Lu, W.-Y.; Chen, T.-C.; and Lin, I.-J. (2015). Shear strength of reinforced concrete dapped-end beams with shear span-to-depth ratios larger than unity. *Journal of Marine Science and Technology*, 23(4), 431-442.
2. Martin, L.D.; and Perry, C.J. (2004). *PCI design handbook: Precast and prestressed concrete* ($6^{th}$ ed). Chicago, Illinois, United States of America: Prestressed Concrete Institute.
3. Mattock, A.H.; and Chan, T.C. (1979). Design and behavior of dapped end beams. *PCI Journal*, 24(6), 28-45.
4. Mattock, A.H. (1976). Design proposals for reinforced concrete corbels. *PCI Journal*, 21(3), 18-42.
5. Liem, S.K. (1983). *Maximum shear strength of dapped-end or corbel*. Master Thesis. Concordia University, Montreal, Canada.

6. Mattock, A.H.; and Theryo, T.S. (1986). Strength of precast prestressed concrete members with dapped ends. *PCI Journal*, 31(5), 58-75.
7. Lu, W.-Y.; Lin, I.-J.; Hwang, S.-J.; and Lin, Y.-H. (2003). Shear strength of high-strength concrete dapped-end beams. *Journal of the Chinese Institute of Engineers*, 26(5), 671-680.
8. Peng, T. (2009). *Influence of detailing on response of dapped-end beams*. Master Thesis. Department of Civil Engineering and Applied Mechanics, McGill University, Montreal, Canada.
9. Mattock, A.H. (2012). Strut-and-tie models for dapped-end beams. *Concrete International*, 34(2), 35-40.
10. Ahmad, S.; Elahi, A.; Hafeez, J.; Fawad, M.; and Ahsan, Z. (2013). Evaluation of the shear strength of dapped ended beam. *Life Science Journal*, 10(3), 1038-1044.
11. Aswin, M.; Syed, Z.I.; Wee, T.; and Liew, M.S. (2014). Prediction of failure loads of RC dapped-end beams. *Proceedings of the 2nd International Conference on Civil, Offshore and Environmental Engineering*. Kuala Lumpur, Malaysia, 6 pages.
12. Aswin M.; Mohammed, B.S.; Liew, M.S.; and Syed, Z.I. (2015). Root cause of reinforced concrete dapped-end beams failure. *International Journal of Applied Engineering Research*, 10(22), 42927-42933.
13. Desnerck, P.; Lees, J.M.; and Morley, C.T. (2016). Impact of the reinforcement layout on the load capacity of reinforced concrete half-joints. *Engineering Structures*, 127, 227-239.
14. Desnerck, P.; Lees, J.M.; and Morley, C.T. (2018). Strut-and-tie models for deteriorated reinforced concrete half-joints. *Engineering Structures*, 161, 41-54.
15. Osman, B.H.; Wu, E.; Ji, B.; and Abdelgader, A.M.S. (2016). A state of the art review on reinforced concrete beams with openings retrofitted with FRP. *International Journal of Advanced Structural Engineering*, 8(3), 253-267.
16. Shakir, Q.M. (2016). Non-linear analysis of high strength reinforced concrete beams with large openings. *Jordan Journal of Civil Engineering*, 10(4), 451-461.
17. Latha, M.S.; and Kumar, B.M.N. (2017). Behavior of reinforced concrete beam with opening. *International Journal of Civil Engineering and Technology (IJCIET)*, 8(7), 581-593.
18. Osman, B.H.; Wu, E.; Ji, B.; and Abdulhameed, S.S. (2017). Shear behavior of reinforced concrete (RC) beams with circular web openings without additional shear reinforcement. *KSCE Journal of Civil Engineering*, 21(1), 296-306.
19. Chen, B.S.; Hagenberger, M.J.; and Breen, J.E. (2002). Evaluation of strut-and-tie modeling applied to dapped beam with opening. *ACI Structural Journal*, 99(4), 445-450.
20. American Concrete Institute (ACI). (2007). Self-consolidating concrete. *ACI 237R-07 Committee Report*.
21. ASTM International. (2017). Standard test method for splitting tensile strength for cylindrical concrete specimens. *ASTM C496/C496M-17,* ASTM International, West Conshohocken.