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Nonlinear Modeling of Concrete Beam with Opening in Flexural Region

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Abstract. The use of openings in reinforced concrete beams is a common practice to accommodate utility ducts and pipes necessary for essential services like water supply, electricity, telecommunications, and computer networks. In existing buildings, drilling openings in beams may be required for serviceability; however, the ACI Code lacks clear criteria regarding deformation and cracking in this context and does not consider the nonlinear material behavior that occurs after cracking. To investigate these issues, a study utilized the nonlinear finite element modeling to analyze the behavior of reinforced concrete beams with such openings. The flexural behavior of steel-reinforced concrete beams, both with a single opening in the flexural zone and without openings, was analyzed using 2D Diana Finite Element Analysis. The Diana beam modeling utilizes height-to-width ratios of 30 cm by 20 cm and 30 cm by 30 cm. Furthermore, it includes openings of sizes 10 cm and 15 cm located in the flexural zone. The study examined initial cracking load, load-deflection curves, ultimate load, stress distribution, crack patterns, and failure modes. This comprehensive analysis offers valuable insights into the impact of openings on the structural performance of reinforced concrete beams under flexural loads.
This analysis confirms that beams with openings display larger crack widths and lower load-bearing capacity compared to control beams. This indicates a reduced structural integrity under identical loading conditions and highlights the significant impact of geometric modifications on beam performance.

Keywords: Modeling, Beam, Opening, Flexural & Diana.

1 Introduction

Concrete beam with openings is a structure made of concrete that has holes in it to let pipes and utilities like water, electricity, and communication lines pass through (Fig. 1) [1]. These holes can help reduce the weight of the beam without losing strength. However, these openings can create problems. If they are planned carefully with the right sizes and locations, the beam can remain strong. But sometimes, contractors may ask for more holes during construction, which can complicate things. While extra holes might save money, they can also risk the safety of the structure (Fig. 2).

Building codes require special support around these holes, which is hard to add after the beam is built. If holes are placed incorrectly, they can cause stress that leads to cracks, making the beam weaker and more likely to bend (Fig. 3). Recently, using computer simulations has become popular for checking structures with openings, resulting in many studies on concrete beams with these designs.

Figure 1 Concrete beams with openings

Figure 2 Construction mistakes

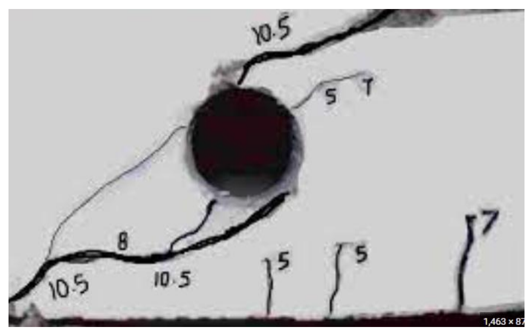


Figure 3 Cracks around opening

Galustanian *et al*. (2022) [3] found that openings in the tension zone did not significantly reduce beam strength, with a maximum failure load decrease of 14% compared to undrilled beams. However, shear-zone drilled openings caused severe reductions in strength and ductility, ranging from 30% to 62%, due to the lack of shear reinforcement. They also noted that finite element modeling effectively predicted the structural behavior of reinforced concrete beams with openings.

Tabassum *et al*. (2023) [4] tested seven beams with rectangular openings, finding that center openings reduced load capacity by 12.94% in tension and 26.47% in compression, while shear-zone openings decreased it by 5.26% in tension and 13.53% in compression. Diagonal cracks occurred due to stress concentration. Reinforcing openings with corner supports proved more effective, and shear-zone openings offered higher load capacity than center openings. Proper placement of openings can improve the cost-benefit ratio without compromising strength.

Sayed (2019) [5] examined the effect of multiple circular web openings on the shear strengths of reinforced concrete beams using FE simulation. A 3D finite element model was developed for this analysis. The study revealed that the diameter of the openings significantly influences beam behavior more than the shear span length. Additionally, the size of the openings had a greater impact on beam performance compared to the number of openings.

Sathiyapriya *et al*. (2021) [6] used finite element modeling with ANSYS to study the effect of openings on concrete beam strength. They found that if the opening diameter is less than 0.3 times the beam depth, the beam behaves normally, but the opening's location is important. When the diameter exceeds 0.3, shear cracks develop, reducing load capacity. As the diameter increases, failure mode shifts from bending to shear. The deflection values varied by about 5%-10% compared to experimental results, confirming that ANSYS can effectively predict the behavior of reinforced concrete beams with openings.

Latha and Naveen (2017) [7] found that a circular opening with a diameter less than 44% of the beam depth (without special reinforcement) allows the beam to behave like one without openings, failing in flexure at mid-span. Maximum compressive stress occurs at the top. In contrast, an opening diameter greater than 44% reduces ultimate load capacity by at least 34.29%, shifting failure mode to shear at the opening. Maximum compressive stress is in the opening region, with tensile stress in the reinforcement reaching yield before ultimate failure.

3. Description of 2D Nonlinear Finite Element Model

The reinforced concrete beam, measuring 4500 mm in length, features height-to-width ratios of 30 cm by 20 cm and 30 cm by 30 cm. It includes openings sized at 10 cm and 15 cm, strategically located in the flexural zone (Table 1). The beam was modeled as a two-dimensional system and analyzed using a DIANA nonlinear finite element (NLFE) approach [8] (Fig. 4), significantly reducing both computational time and memory requirements.

In all NLFE analyses, the concrete body was represented using the 2D plane stress element CQ18M, a quadrilateral element with nine nodes, capable of simulating plastic deformation, cracking, and crushing behavior. The steel reinforcement bars were modeled as truss elements (L2TRU) embedded within the surrounding concrete. This approach considered only axial elongation, excluding bending and shear deformations. A finite element mesh size of 25 mm x 25 mm was selected (Fig. 4), yielding superior results compared to other mesh sizes.

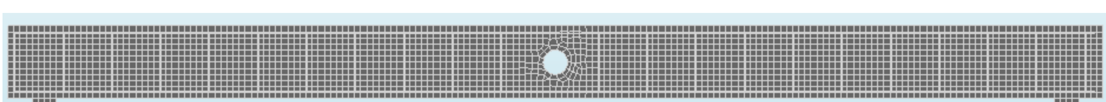


Figure 4 Beam with opening in flexural zone

Table 1 Beams Dimensions & Opening Details

Group	Beam designation	Span (cm)	Height (cm)	Width (cm)	H/W	No. of opening	Opening dimeter (cm)	Zone
								Flexural
A	**C(1.5)**	450	30	20	1.5			
	F1-10(1.5)					1	10	F
	F1-15(1.5)						15	
	C(1)			30	1			
	F1-10(1)					1	10	F
	F1-15(1)						15	

4. Analysis Process for NLFE Model

In the nonlinear analysis, loads were applied to the finite element model by directly increasing the external force until failure. Initially, a uniform load increment was used to estimate the approximate failure load. As the failure load was approached, smaller increments were employed for a more precise analysis of the structural behavior near failure. All load steps converged within the tolerance limits, requiring the same number of iterations (30). The Newton-Raphson method was utilized to update stiffness and compute the nonlinear response. This method was particularly effective, as it updates the stiffness matrix at each iteration, accurately capturing the beam's nonlinear behavior, including cracking and stress redistribution. Its iterative approach ensures reliable convergence in fewer steps for problems with significant nonlinearity.

5. Presentation of Results from 2D NLFE Model

5.1 Initial Cracking Load

Table 2 presents the results of the initial cracking loads for control beams designated as C(1) and C(1.5), which are free of openings and have height-to-width ratios of 30 by 20 cm and 30 by 30 cm, respectively, as detailed in Table 2. Additionally, it includes beams designated as F, which have openings in the flexural zone, with opening sizes of 10 cm and 15 cm. In group A, initial cracks in all beams were observed in the mid-span region (Fig. 5 & 6). Beams C(1.5), F1-10(1.5), and F1-15(1.5) exhibited a notable decrease in initial cracking loads compared to C(1). The control beam C(1.5) had a cracking load of 5 KN, reflecting a 30% reduction from C(1). Beams F1-10(1.5) and F1-15(1.5) showed further reductions, with cracking loads of 4.61 KN and 4.18 KN, respectively.

Overall, the presence of 10 cm and 15 cm openings in the flexural zone significantly affected initial cracking loads and deflections. Control beams consistently had higher cracking loads than those with openings, particularly where larger (15 cm) openings reduced load-bearing capacity

Table 2 Initial cracking loads for beams with and without openings

Group	Beam Designation	Initial cracking load (KN)	Deflection at first Crack (mm)	Reduction in load (%)
A	**C (1)**	7.10	1.51	0
	F1-10(1)	7.01	1.52	0
	F1-15(1)	6.52	1.44	8
	C (1.5)	5.00	1.53	30
	F1-10(1.5)	4.92	1.51	31
	F1-15(1.5)	4.61	1.48	35

Figure 5 Beam C(1.5) at load of 5 kN

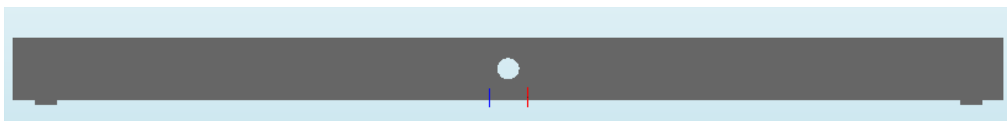


Figure 6 Beam F1-10(1.5) at load of 4.9 kN

5.2 Load-deflection Curves

The results indicate that all beams exhibited similar behavior in the elastic region up to the yield point (Fig. 7). However, significant differences in performance emerged after this point, particularly related to the size of the openings. The control beam C(1), with a height of 30 cm and a width of 30 cm, demonstrated the highest load-bearing capacity. In contrast, the beams with openings, although maintaining the same width, had varying heights that influenced their performance, with the 30 cm width beams consistently outperforming those with a width of 20 cm.

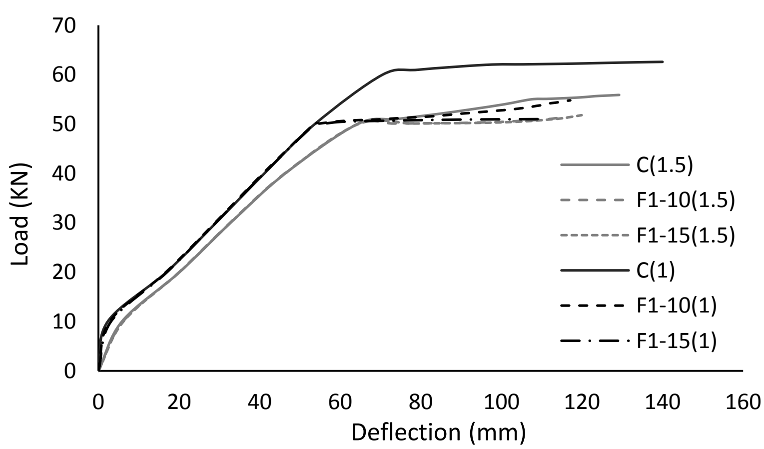


Figure 7 Load-deflection curves for beams with and without openings

The analysis showed that the size of the openings significantly affected beam strength. The 10 cm opening caused a moderate reduction in load capacity, while the 15 cm opening led to a more substantial decline, indicating that larger openings compromise structural integrity more than smaller ones.

5.3 Ultimate Load

Table 3 presents the ultimate loads, deflections, and load capacity reductions for beams in group A. The control beam C(1) had the highest load at 62.5 kN and a deflection of 132.5 mm. The control beam C(1.5) followed with 55.9 kN and 129.08 mm. The beam with a 10 cm opening (F1-10(1)) showed a 14% reduction, reaching 53.8 kN and a deflection of 113.59 mm. The 15 cm opening beam (F1-15(1.5)) had an ultimate load of 52.5 kN and a 16% reduction, with a deflection of 126.64 mm.

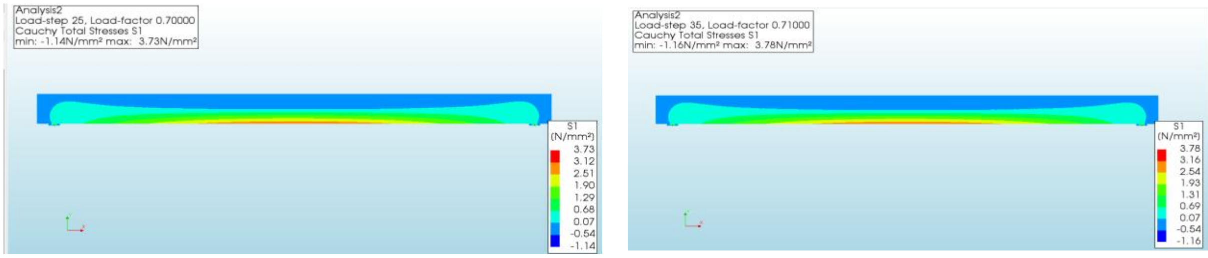
These results indicate that larger openings significantly weaken load-bearing capacity, while beams with a width of 30 cm perform better than those with 20 cm, demonstrating that increased width enhances strength, even with openings.

Table 3 Ultimate loads for beams with and without openings

Group	Beam Designation	Ultimate load (KN)	Deflection (mm)	Reduction in load (%)
A	**C(1)**	62.5	132.50	**0**
	F1-10(1)	53.8	113.59	**14**
	F1-15(1)	53.0	102.30	**15**
	C(1.5)	55.9	129.08	**11**
	F1-10(1.5)	52.7	148.23	**16**
	F1-15(1.5)	52.5	126.64	**16**

5.4 Stress Distribution

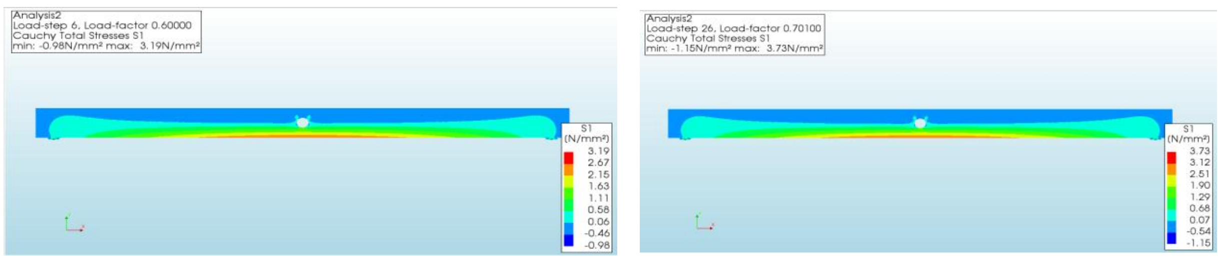
Figures 8 and 9 illustrate the tensile stresses in the control beam C(1) and the beam F1-10(1) with an opening, before and after initial crack. The maximum tensile stress observed is 3 MPa, indicating the concrete's capacity to withstand tensile forces. Before cracking (Figures 8a & 9a), tensile stresses were distributed evenly, remaining within acceptable limits, showing the beam could bear the load without cracks. After the initial crack (Figures 8b & 9b), there was a notable increase in tensile stresses, especially at mid-span, indicating a loss of tensile strength. Analyzing these stresses helps assess beam performance under loads, reveals stress distribution, identifies weak points, and predicts potential crack locations, facilitating preventive measures against structural failure.



a) Before initial crack at load 7KN

b) Immediately after initial crack at load 7.1 KN

Figure 8 Tensile stresses in beam C (1**)**

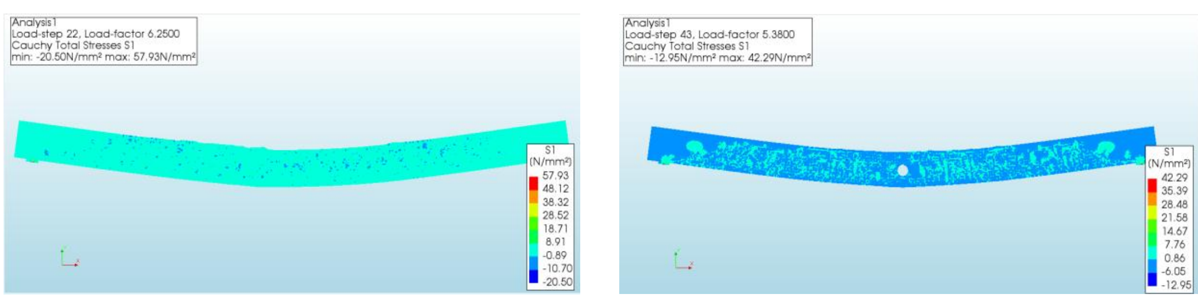


a) Before initial crack at load 6 KN

b) Immediately after initial crack at load 7.01 KN

Figure 9 Tensile stresses in beam F1-10(1**)**

Figure 10 shows that compressive stresses were nearly zero at the point of failure at mid-span, indicating the specimen could not withstand compressive forces as the applied load exceeded the concrete's capacity. Conversely, before failure, no tensile stresses were recorded. This behavior was consistent across all beams in Group A.



a) beam C (1) at 62.5 KN

b) beam F1-10(1) at 53.8 KN

Figure 10 Compressive Stresses in beams at ultimate load

5.5 Crack Width

Control beams C(1) and C(1.5) demonstrate superior structural performance compared to beams with openings, which compromise load resistance and lead to greater crack widths. At a load of 40 KN (Fig. 11), crack widths for the control beams are around 1 mm, indicating strong load-bearing capacity and minimal damage. In contrast, the F beams show crack widths of approximately 2 mm, reflecting reduced performance due to the openings.

This analysis confirms that beams with openings have larger crack widths than control beams, highlighting their diminished structural integrity under the same loading conditions and emphasizing the significant impact of geometric modifications on beam performance.

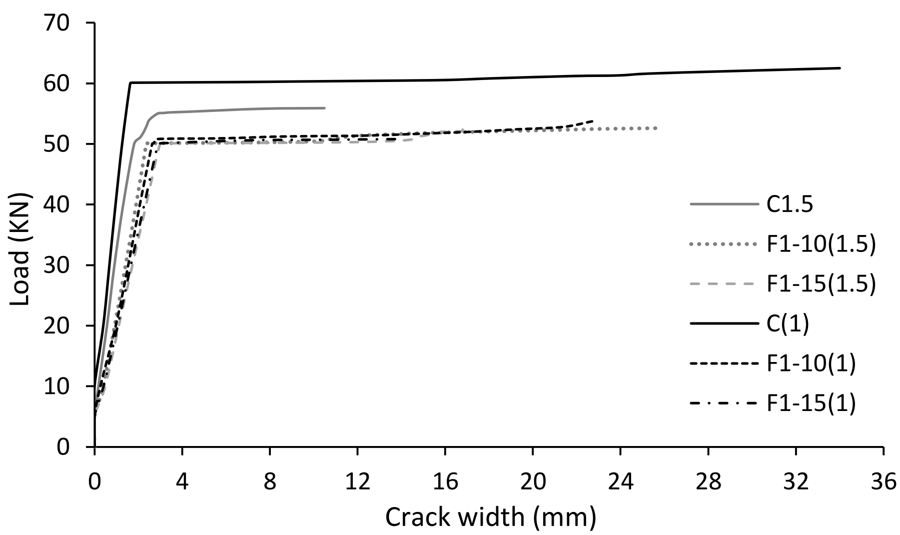


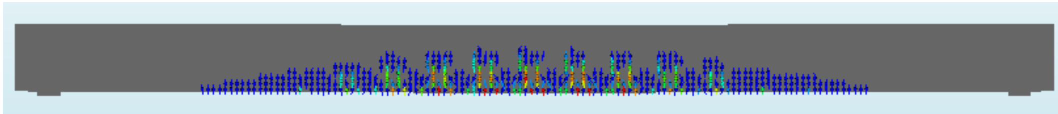
Figure 11 Crack widths for beams in Group A

5.6 Crack Pattern

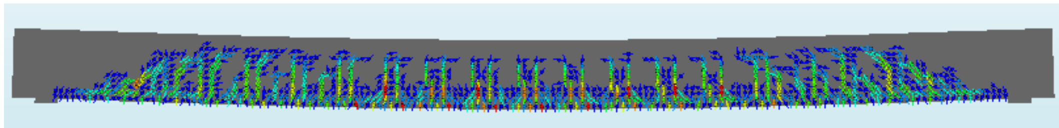
In all tested beams, cracks formed when the applied moment reached the cracking moment. The vertical flexural cracks, perpendicular to the steel reinforcement, resulted from pure bending (i.e., zero shear), with no cracks observed outside the constant moment zone. As the load increased, cracks propagated toward the load points on the compressive face. With further loading, crack length increased throughout the beam's depth, extending upward and spreading along the beam length toward the supports (Fig. 12).

5.7 Failure Modes

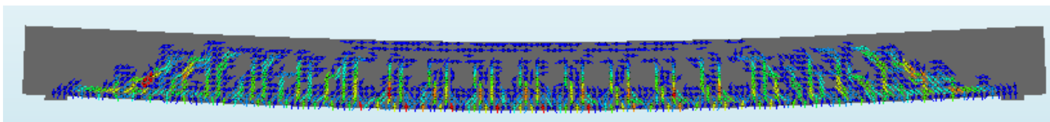
A flexural failure was observed in all beams, both with and without openings, at ultimate loads, as shown in Figure 13. The beams exhibited flexural failure followed by compression failure at the top. These flexural failures occurred in the pure bending zone (i.e., zero shear), indicated by significant deflection at mid-span.



a) Cracks at 10 KN

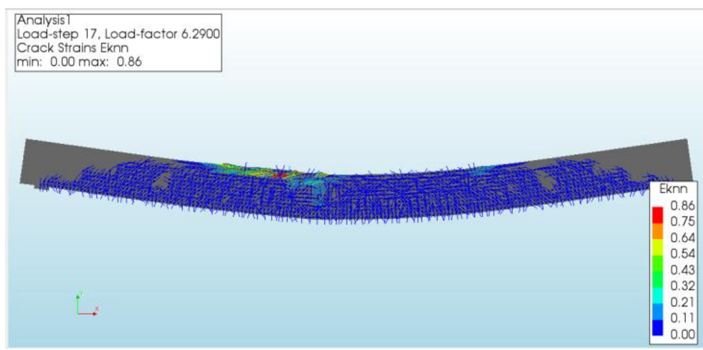


c) Cracks at 40KN

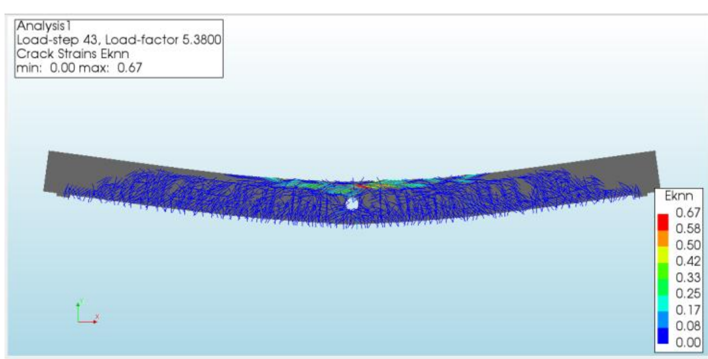


d) Cracks at 50 KN

Figure 12 Crack Patterns for Beam C(1.5)



a) Beam C(1) at its ultimate load of 62.5 kN



b) Beam F1-10(1) at its ultimate load of 53.8 kN

Figure 13 Failure mode for beams

5.8 Conclusions

The presence of 10 cm and 15 cm openings significantly reduces the cracking loads and deflections of beams. Beams without openings demonstrate higher cracking loads compared to those with openings, especially the 15 cm opening, which most adversely affects load-bearing capacity. Additionally, beams with a width of 30 cm have greater capacity than those with 20 cm, emphasizing that increased width enhances strength. Furthermore, beams with openings display larger crack widths and reduced structural integrity, leading to flexural failures at ultimate loads, characterized by substantial mid-span deflection and compression failure at the top.

Using DIANA software for analyzing steel-reinforced beams both with and without openings under uniform load is effective and can yield reliable predictions across the entire load range. This includes parameters such as initial cracking load, load-deflection curves, ultimate load, stress distribution, crack width, and mode of failure. The software demonstrates its capability to model the behavior of beams accurately, making it a valuable tool for engineers in structural analysis.

References

1. Samny, M., Ezz-ELdeen, H., & Elsepahy, M., (2018). Experimental and analytical study of strengthening reinforced concrete beams with openings. International journal of applied engineering research, 13(7), 4934-4950.
2. Mansur, M. (2006). Design of reinforced concrete beams with web openings. In Proceedings of the 6th Asia-Pacific Structural Engineering and Construction Conference (APSEC 2006), September 5-6, 2006, Kuala Lumpur, Malaysia (pp.104-121).
3. Galustanian, N., El-Sisi, A., Amer, A., Elshamy, E., & Hassan, H. (2023). Review of the structural performance of beams and beam–column joints with openings. Civil Eng, 4(4), 1233-1242.
4. Tabassum, N., Hassan, T., Ali, S. & Ehsan, K., (2023). Experimental Study of the effect of rectangular openings in reinforced concrete beams , 7th International Conference on Engineering Research, Innovation and Education School of Applied sciences & Technology, SUST, SUST, Sylhet. pp: 1 -9.
5. Sayed, A., (2019). Numerical study using FE simulation on rectangular beams with vertical circular web openings in the shear zones. Eng. Structure, 198, 109471.
6. Sathiyapriya, D., Suganya, D. & Sattainathan A., (2021). Study on flexural behavior of reinforced concrete beam with effective openings. International Conference on Physics and Energy. pp 1- 9.
7. Latha, M. and Naveen, K., (2017). Behavior of reinforced concrete beam with opening, International Journal of Civil Engineering and Technology (IJCIET).8(7):581-593.
8. DIANA Finite Element Analysis, (2005). User's Manual Release 9. TNO DIANA BV. Delft, the Netherlands