Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 9, No. 03, March, 2023

Behaviour of Steel I Beams with Web Openings

Jinan Laftah Abbas [1*]

[1] *Lecturer, Department of Civil Engineering, College of Engineering, University of Diyala, Diyala, Iraq.*

Received 07 November 2022; Revised 28 January 2023; Accepted 16 February 2023; Published 01 March 2023

Abstract

This paper aims to study the behavior of steel I beams with web openings. However, web openings might lead to a noteworthy reduction in the load-carrying capacity of beams, but can also be so supportive and essential from an economic point of view. An experimental investigation and nonlinear three-dimensional finite element analysis using the ABAQUS computer program were planned and conducted on six steel I-beams having the same dimensions, different diameter ratio spacing, and opening shapes such as circular, rectangular, and hexagonal. Experimental results showed that the ultimate load of a steel beam with web openings reduced with an increase in the area of the opening. A circular opening has a stronger shape than a rectangular opening because a rectangle has fast deflection and torsion angles, so it resists an applied load less than a circular opening. Also, the beam with hexagonal openings is better than that with rectangular openings because hexagonal openings are more resistant to deflection and deformation than rectangular openings. The finite element results, which are validated against the experimental results, show good accuracy with the experiment. Besides, a parametric study is presented here to study the influence of varying the shape of openings on the value of the failure load and midspan deflection. It can be noticed that the steel beam with a circular opening, which had been tested experimentally and modeled by the Abaqus program, is the best case and gives a higher failure load as compared to the diamond, octagonal, trapezoidal, transverse, and longitudinal ellipses. Thus, providing web openings reduces the weight and increases structural efficiency.

Keywords: Steel I Beams; Web Openings; Aspect Ratio; Openings Shape; Failure Load; Finite Element; Abaqus.

1. Introduction

Several attempts have been made by structural engineers since the 1940s to determine original ways to reduce the cost of steel construction. Open-web extended steel beams were first used in construction during World War II to reduce the cost of steel structures. Therefore, steel beams with web openings such as castellated as well as cellular beams have been widely used in recent times. As a result of the restrictions on the maximum allowable deflections and the high strength properties of steel structures, they cannot be permanently consumed to their full advantage. Thus, many new methods have been intended to increase the stiffness of steel members without any increase in the weight of the steel. It is predictable that the simplicity of integration of services, like electric cables, hydraulics, and ventilation pipes, within the structural depth of the beams will be the main advantage in the construction, and this will reduce the total height of the construction by decreasing the floor to ceiling height for each story level.

Many researchers have performed numerical and experimental investigations with the intention of studying the response of steel beams with different web openings. Some of them indicated that the existence of web openings in structural members might cause large disadvantages for the loading carrying capacity [1–3]. Chan & Redwood (1974) [4] have indicated an elastic distribution of stress for beams having large web openings of circular shape by the theory

* Corresponding author: jinanlaftah19@gmail.com; jinanlaftah19@uodiyala.edu.iq

http://dx.doi.org/10.28991/CEJ-2023-09-03-08

of elasticity as well as an analysis of curved beams. In order to evaluate the loading carrying capacity of steel beams having many web openings of circular shape using an explicit method, a design method based on the investigations of Olander (1953) [5] and Sahmel (1969) [6] that was established at the Steel Construction Institute in 1990 is used. The method was late integrated into Amendment A2 of Euro Code 3 (EN1993-1-3) [7].

A numerical study and laboratory tests on steel beams having rectangular as well as circular openings were carried out by Thevendran & Shanmugan (1991) [8], which have been investigated to show that the presence of web openings lessens the beams ultimate strength as well as their lateral buckling capacity. The created models were simply supported beams in addition to cantilever beams that were made from a plexiglass sheet. The buckling load of similar types of beams was obtained by the energy method. Lian & Shanmugan (2003) [9] stated that on plate girders curved in plan and having a centrally circular web opening, the mechanism of failure in the tests was similar to the failure detected in plate girders without web openings, except for the change of location of plastic hinges on the flange plates.

Later, Dinehart et al. (2004) [10] investigated the distribution of stress around the openings of cellular beams below load combinations. The chief aim of this study was to explain the critical position of a typical circular cell under load conditions. The effects of the shape of web openings in horizontally curved composite plate girders on their ultimate strength have been investigated by Basher et al. [11]. Numerical simulations were made for the purpose of providing data to develop a design model for the shear capacity of steel girders that contain web openings and were executed by Hagen & Larsen [12]. Radic et al. [13] performed a numerical analysis of castellated beams regarding two various procedures to calculate the elastic critical moment for lateral torsional buckling by comparison with Eurocode 3 procedures and FE results [14, 15].

A three-dimensional finite element analysis has been made on (408) cellular beams for obtaining the influence of the shape of the beam on the value of deflection. Panedpojaman & Thepchatri (2013) [16], in which it can be indicated that the stress distribution of the finite element (FE) model reveals the strut stress in the web-post contributes to increasing the deflection as well as the regular bending deflection. Rodrigues et al. (2014) [17] describe existing finite element representations that are calibrated in contrast to the numerical and experimental results. The accurate results allowed an extensive parametric analysis for beams having web openings to be performed, paying attention to the web opening profile size and its location, amongst others. The obtained results from this study exposed the necessity of using welded longitudinal stiffeners for increasing the ultimate load of the beams. Jichkar et al. (2014) [18] attained buckling load analysis in addition to deflection calculation of various beam sections with various loadings and support conditions with circular, square, and hexagonal web openings. The results obtained from this study showed that increasing the section of beam caused the buckling load to increase. In addition, the bucking load continues to reduce as web openings are provided within the section. Thus, increasing the number of web openings in the steel beam causes a decrease in the buckling load, although the beam deflection will also rise. A cellular beam applied to a concentrated load at midspan has a high moment carrying capacity as compared to a beam subjected to a uniformly distributed load.

In recent times, many investigations have been made in order to design and analyze cellular beams in addition to castellated beams [19]. Morkhade & Gupta (2015) [20] performed an experimental study in addition to the parametric study to indicate the performance of steel I beams having rectangular opening web openings. The effect of many parameters, such as aspect ratio, fillet radius, stiffener location about the openings, and the influence of locations of openings on the load capacity of the steel beams, were studied by using ANSYS v.12. The results indicated that the stiffeners and fillet radius also affected the stress distribution in the openings corner regions. When the openings are located within the middle two-thirds neutral zone of the span, the load carrying capacity of perforated beams is nearly equivalent to that of plain webbed beams. Manoharan et al. (2017) [21] expressed a comparative analysis of steel beams that have various cross sections. This study observes the influence of a circular opening having various sizes on steel beams. Both the deflection pattern and the maximum stress are studied analytically. ANSYS software has been used for this study. The analysis indicated that steel beams have no obvious influence on the deflection because of the opening near the support. Besides, increasing the size of openings leads to increased Von Mises and shear stresses.

The high strength of an H-shaped steel beam with circular openings was investigated in an experimental test obtained by Feng et al. [22], in which a comparison was made between the test results and the current design guidelines. It can be concluded that both the Chinese and Australian guidelines are conservative, while Eurocode 3 is non-conservative. Lately, several efforts have been made to provide design guidelines and analysis procedures to calculate the influence of perforated steel beams with web openings [23, 24]. A critical study of steel beams with web openings has been investigated, and it is observed that the web openings not only deteriorate the practical section, but also dismiss its continuity [25]. The behavior of buckling, bending, and torsion for steel I beams that have and do not have web opening is studied by using nonlinear finite element analysis using LUSAS software [26]. From this study, it can be concluded that the web openings of square shape have the highest efficiency of structural under buckling. Besides, the lower buckling load and moment contribute to higher structural efficiency. The stress analysis of beams with web openings by experimental study and finite element analysis has been investigated [27]. The final results illustrate the influence of a suitable radius of web opening on the torsional capacity of the section. It is detected that the torsional capacity at certain loading conditions and its angle of twist are analyzed. Several studies investigated the possibility that the presence of web openings may cause substantial disadvantages in terms of load carrying capacity [1, 28]. From this review, it can be inferred that there is a necessity to investigate the behavior of steel I beams with web openings. However, the web openings might cause a substantial reduction in the load-carrying capacity of beams depending on the adopted shape of the openings, their location, and their size, but they can furthermore be so supportive and essential from an economic point of view. Thus, this present research is concerned with the effect of the presence of web opening on the load carrying capacity as well as the web crippling strength of the steel sections.

2. Research Methodology

This study is an experimental work consisting of six steel I-beams with the same dimensions but with different spacing to diameter ratios, in addition to different opening shapes such as circular, rectangular, and hexagonal shapes. Apply a concentrated load to the middle of the model to find out which shapes have greater resistance, greater rigidity, and a lower possibility of failure to provide the highest possible level of safety to the structures. Figure 1 shows the schematic representation of the experimental program.

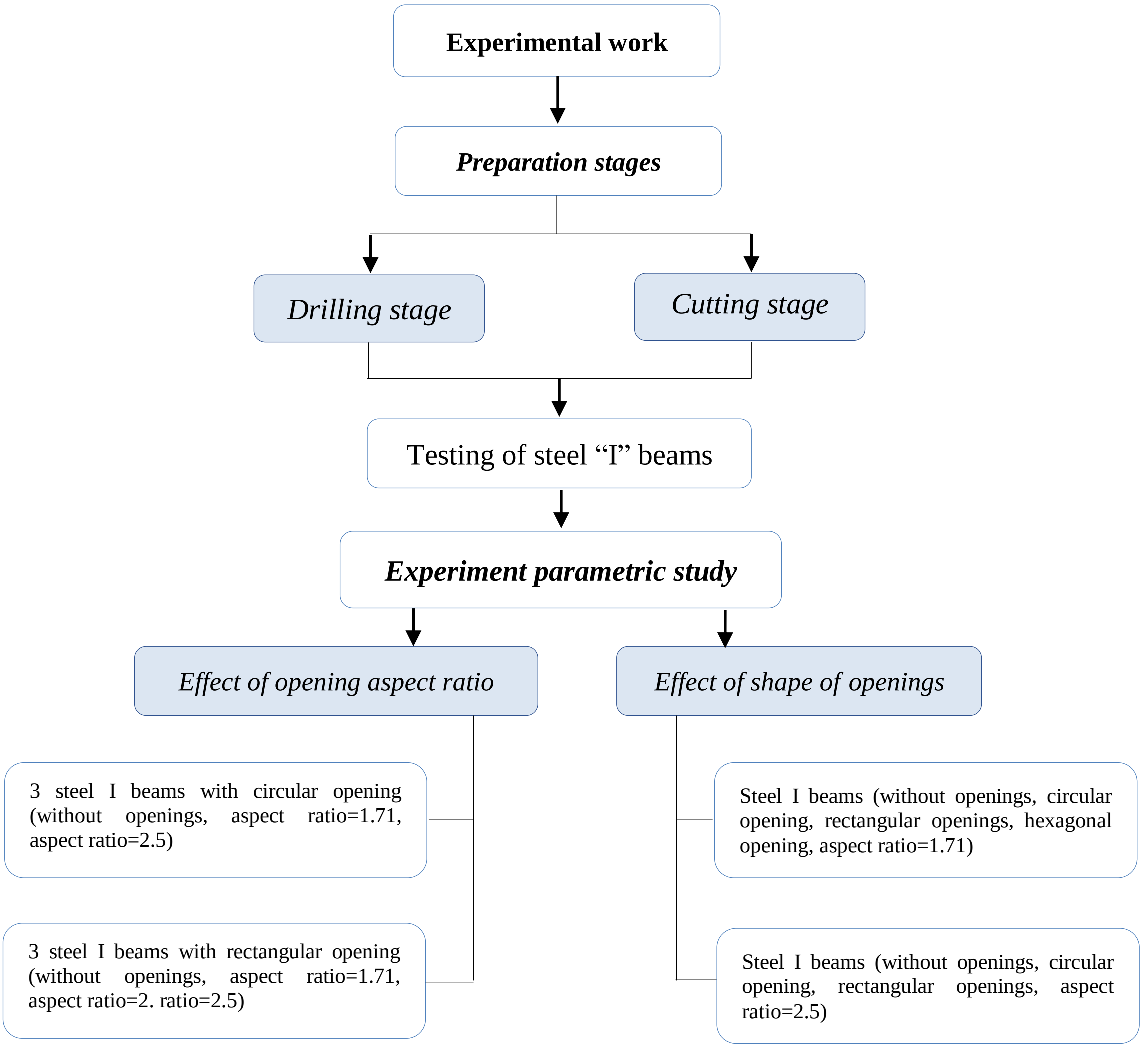


Figure 1. Schematic representation of the experimental program

2.1. Specimens Details

Six steel I-beams all have the same dimensions in length. The first one was without opening, which is regarded as the reference beam. Two of them had circular openings with the same diameter but different spacing to diameter ratios. In addition, two beams had rectangular opening shapes but different spacing and diameter ratios; the last one had a hexagonal shape. All specimens had the same area of opening. The specimens were 1400 mm long, the web was 107 mm wide, and its thickness was 5 mm. The width of the flange was 63 mm, and its thickness was 6.5 mm. Figures 2 and 3 show the longitudinal and cross sections of steel I beams, respectively. Details of all specimens can be found in brief in Table 1.

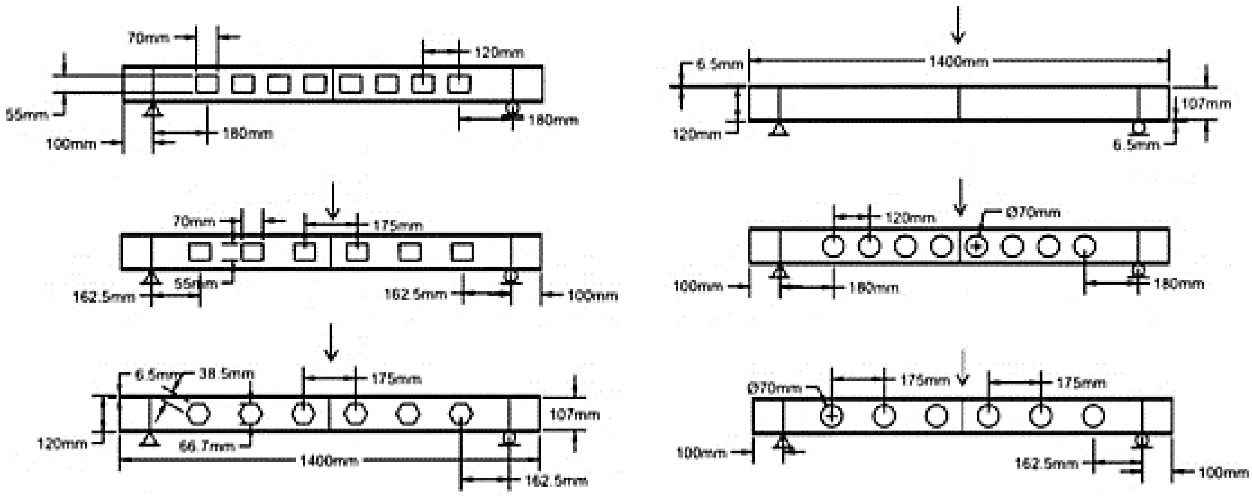


Figure 2. Details of all steel I Beams

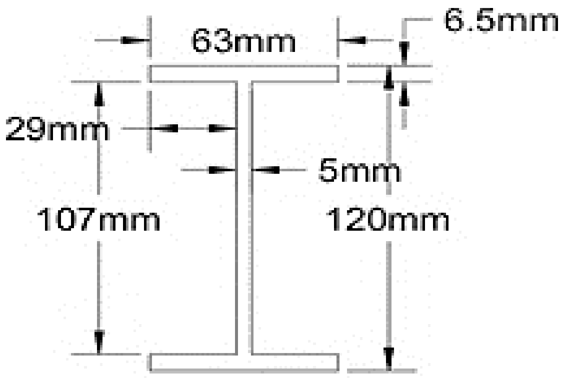


Figure 3. Cross section of steel I Beams

Table 1. Details of all steel I Beams

Specimen	Length	Openings shape	The diameter	Distance between the centers of the openings
S 1	1400 mm	without openings	Without diameter	Without openings
S2	1400 mm	circular	Ø 70 mm	120 mm
S3	1400 mm	circular	Ø 70 mm	175 mm
S4	1400 mm	rectangular	70 × 55 mm	120 mm
S5	1400 mm	rectangular	70 × 55 mm	175 mm
S6	1400 mm	hexagonal	-	175mm

2.2. Material Properties

Tensile test coupons, which were cut from the web and flange plates of the section segments, were tested for determining the material properties essential for the numerical modeling of the steel beams having web openings. Only four coupons were cut out for all of the test specimens for the material testing laboratory, two from the web plate and two from the flange plate, because all the tested specimens are made from the same section at the material testing laboratory, as shown in Figure 4. The stress-strain relationship for both the flange and the web can be shown in Figure 5. The test results, such as the yield stress, ultimate stress, and modulus of elasticity (E) attained from the coupons test, are shown in Table 2.

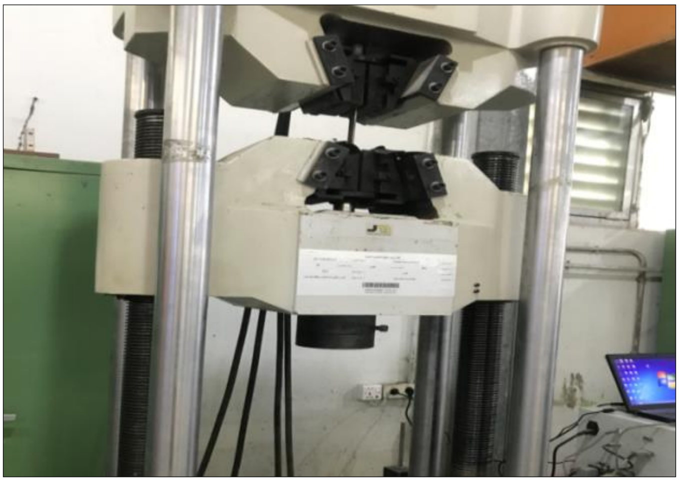
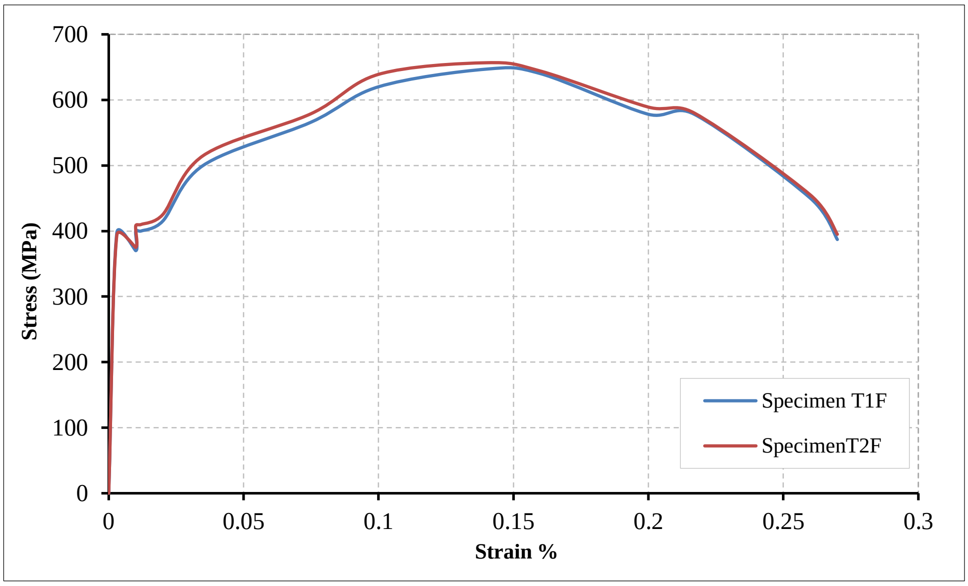
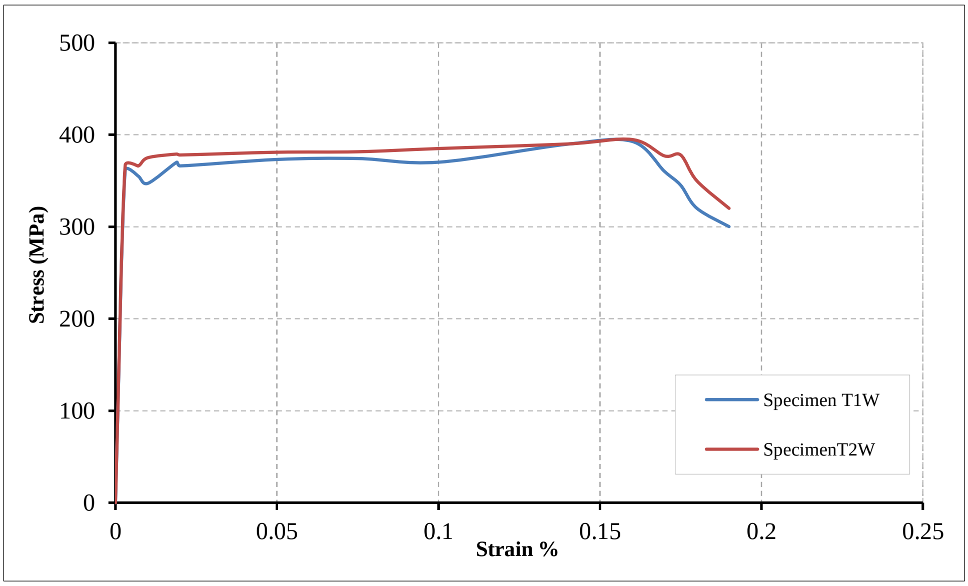


Figure 4. Tensile testing machine



(a) Flange



(b) Web

Figure 5. Stress strain relationship for (a) Flange; (b) Web

Table 2. Material properties of the tested specimens

Specimen	Actual width (mm)	Actual thickness (mm)	σ_y (MPa)	σ_u(MPa)	E (MPa)
		Flange			
T1F	20	6.5	397.2	646.9	0.81 x 10^5
T2F	20	6.5	393.6	651.7	1.03 x 10^5
	Overall Average Values		395.4	649.3	0.92 x 10^5
		Web			
T1W	20	5	376.9	392.6	1.73 x 10^5
T2W	20	5	366.5	394.8	1.87 x 10^5
	Overall Average Values		371.7	378.7	1.8 x 10^5

2.3. Preparation Stages

Firstly, the models were cut at the same lengths as mentioned previously; the length of each beam was 1400 mm, as shown in Figures 6-a and 6-b. Next, the models were drilled according to their dimensions. This stage is regarded as one of the most difficult and complex stages, due to the accuracy required in measuring the holes and adjusting the distances between the holes, but the work was done with high accuracy, and the models were drilled according to the dimensions and shapes mentioned earlier. Figure 7 clarifies the work during the drilling process. Finally, the painting stage was carried out to determine the dentation sites of the specimens during the examination and where the gaseous pigments were used in the painting process.

(a) Before cutting

(b) After cutting

Figure 6. Preparation stage for specimens

Figure 7. Drilling stages for specimens

2.4. Testing Machine

The hydraulic testing machine has been manufactured in Italy. All steel beams will be tested by using the 600 KN universal testing machine subjected to a two-point bending test system under a simple supported condition.

3. Results and Discussions

The test was executed on six steel I beams with different aspect ratios and shapes of openings. The experimental results displayed that the concentration of stress nearby the corners and regions of the openings is critical. Therefore, these corners should be curved to eliminate or minimize the stress concentration. Besides, it has been detected from the experiments that there is a decrease in the stiffness and the ultimate load of the beam due to an increase in the area of openings along with their location. The failure occurs along the web diagonal, as the maximum stress is situated along the buckling. The plastic hinge is formed near the web's vertical centerline. The dissimilarity of vertical deflection at midspan versus applied load for all tested beams until failure can be shown in Figures 8 to 13.

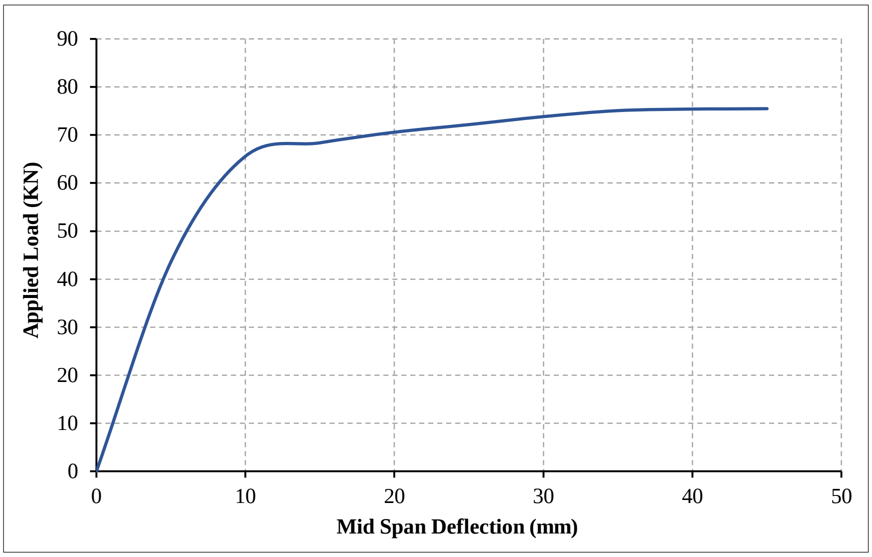


Figure 8. Load versus mid span deflection for beam S1

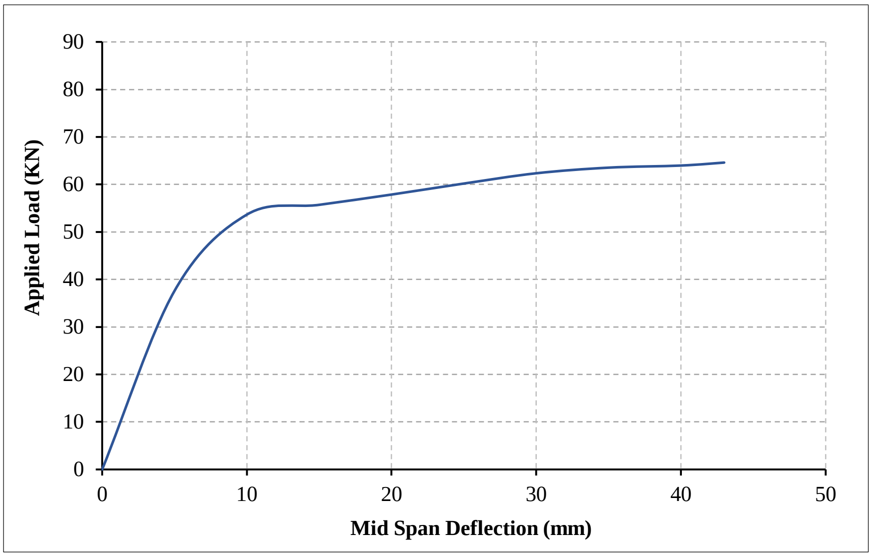


Figure 9. Load versus mid span deflection for beam S2

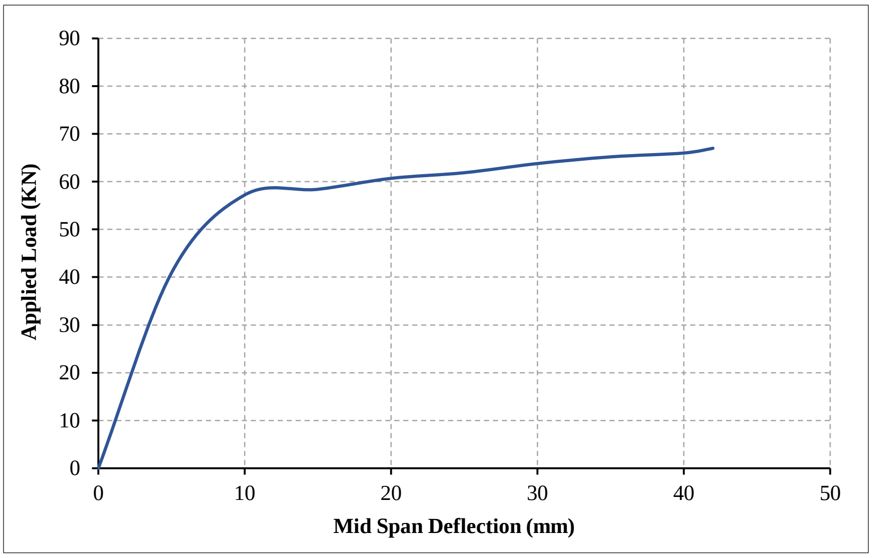


Figure 10. Load versus mid span deflection for beam S3

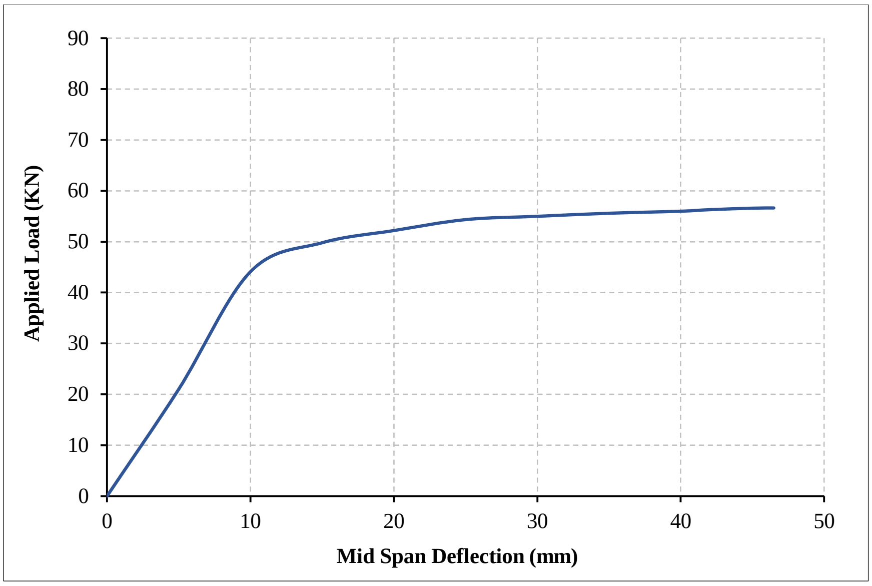


Figure 11. Load versus mid span deflection for beam S4

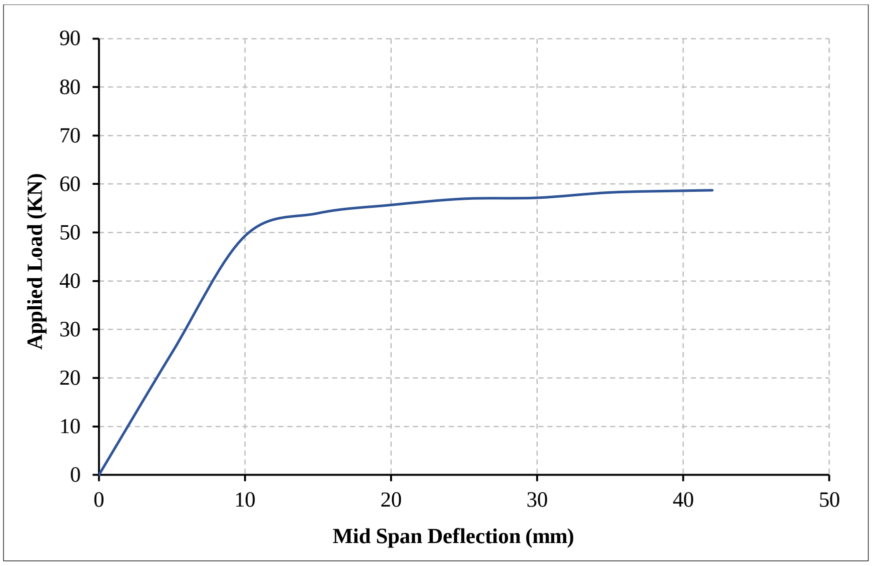


Figure 12. Load v versus mid span deflection for beam S5

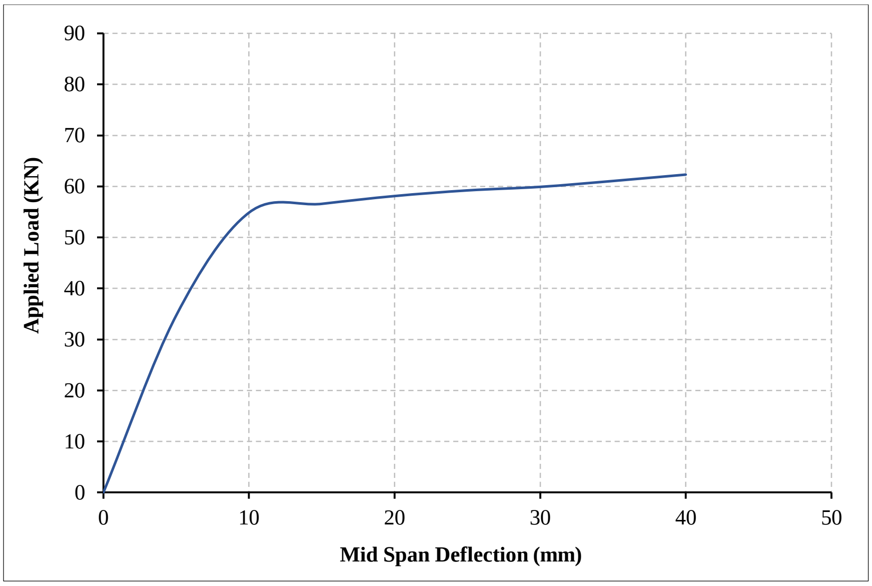


Figure 13. Load versus mid span deflection for beam S6

4. General Behaviour of Beams

Several parameters are studied in this experimental test, such as the aspect ratio of openings, which is defined as the ratio of opening length to its depth (L/D), as well as the shape of openings, in order to study the effect of these parameters on the peak load of all steel beams and the value of the corresponding deflection.

4.1. Effect of Aspect Ratio

The failure modes of steel I beams with circular openings can be shown in Figure 14. By making a comparison between steel beams with a circular opening and having an aspect ratio that varied from 1.71 to 2.5. It can be observed that the ultimate load and stiffness of a steel beam with web openings are reduced by a rise in the opening area (i.e., a decrease in the S/Do ratio). Peak load increased by about 3.72% as the aspect ratio increased from 1.71 to 2.5. This difference is due to the effect of the load due to the number of openings; the higher the number of openings, the less resistance there will be to the applied load, and it will lead to faster deformation as well as faster failure. Besides the steel beam with no opening, this structure has the maximum peak load (see Figure 15).

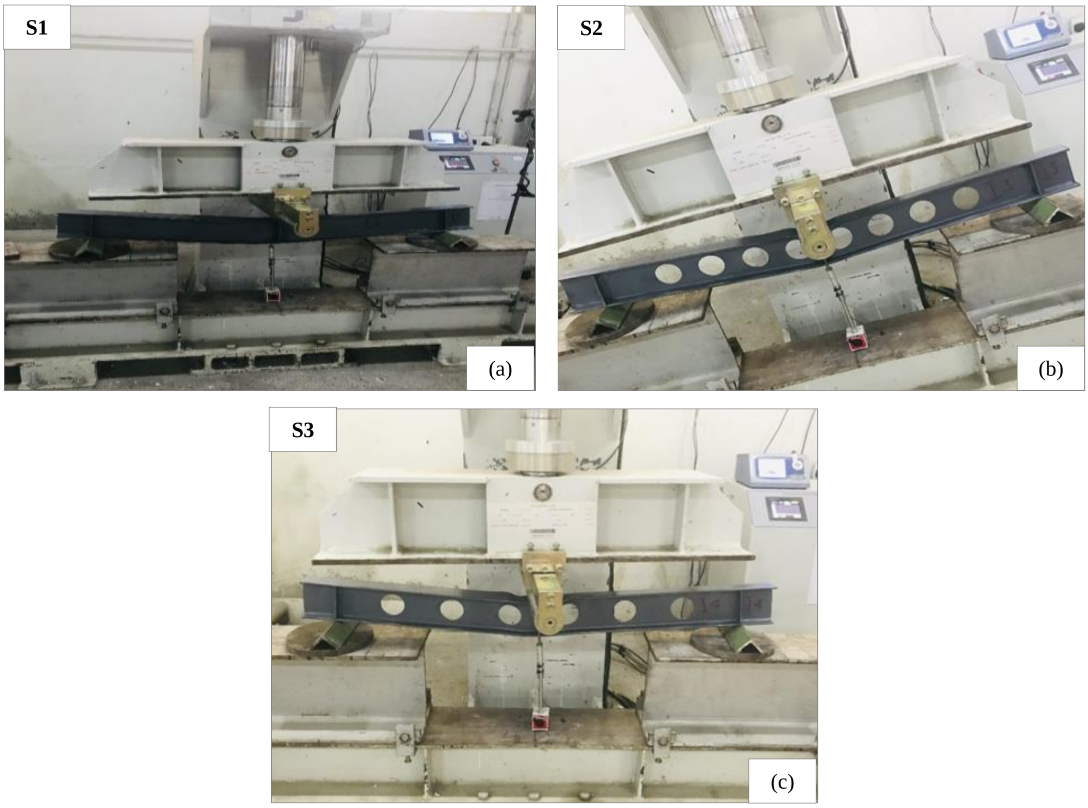


Figure 14. Failure mode for steel beams with circular openings and various aspect ratio (a) without opening; (b) aspect ratio=1.71; (c) aspect ratio=2.5

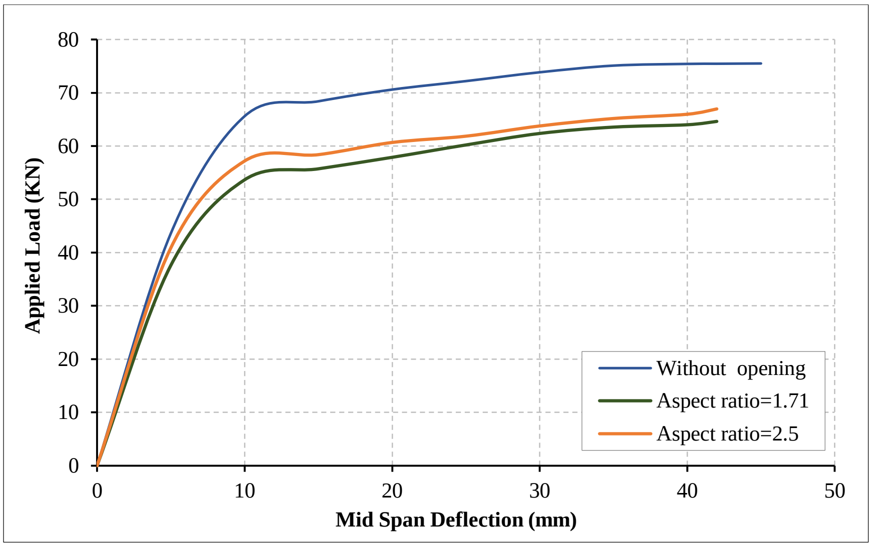


Figure 15. Load versus mid span deflection for steel beams with circular openings and various aspect ratio

The failure mode of steel beams having a rectangular opening shape and also with different aspect ratios (1.71 and 2.5) can be shown in Figure 16. A comparison is being made between these beams in Figure 17. It can be inferred from this comparison that there was an increase in peak load by about 3.71% as the aspect ratio increased from 1.71 to 2.5.

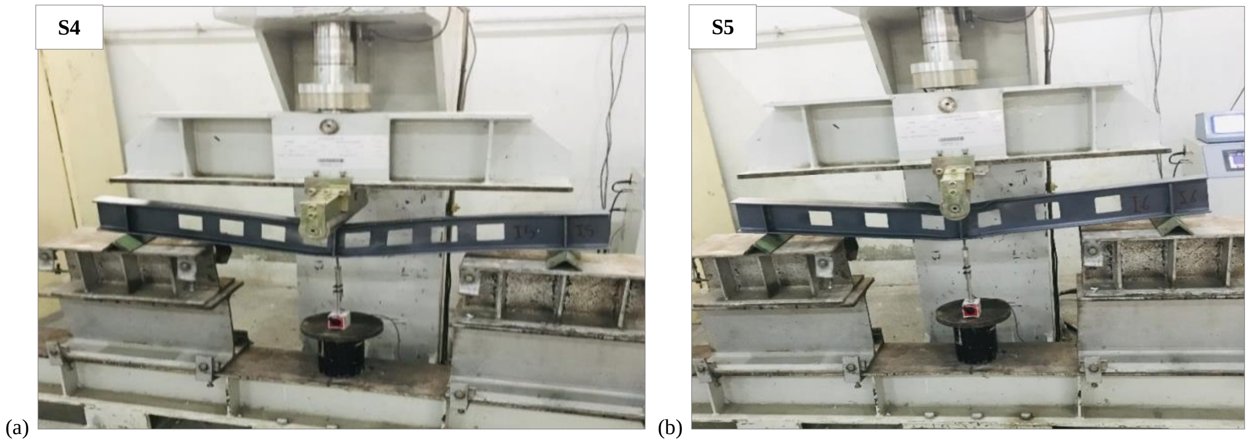


Figure 16. Failure mode for steel I beams having rectangular openings as well as various aspect ratio(a) Aspect ratio=1.71(b) Aspect ratio=2.5]

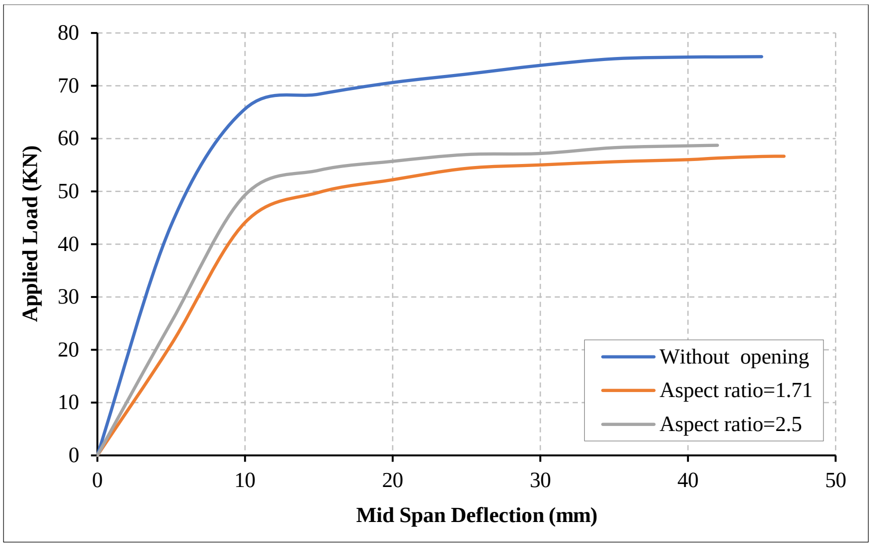
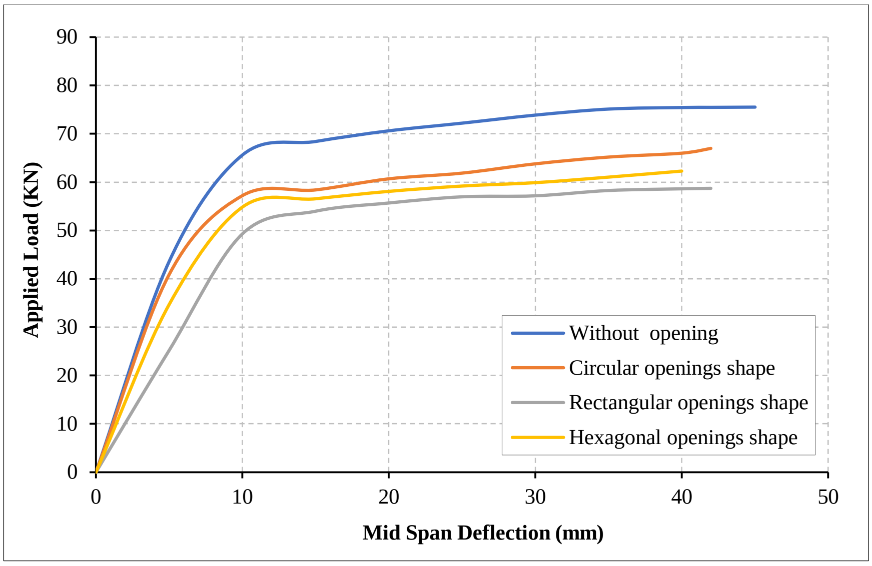


Figure 17. Load versus mid span deflection for steel beams with rectangular openings and various aspect ratio

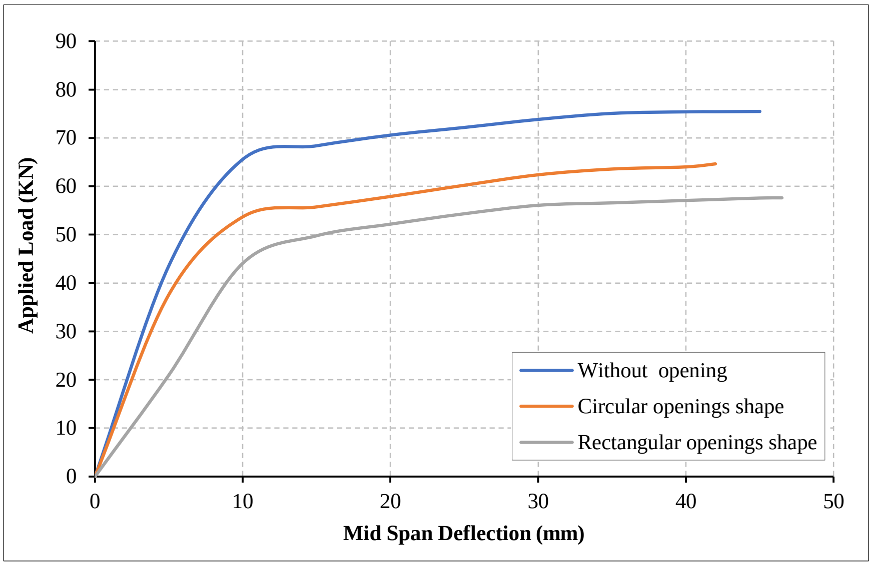
When examining and plotting the curve, it can be found that the steel beam with round openings is more resistant to failure and more rigid to bear the load imposed in the center than the beams with rectangular openings. The reason for this is the shape of the opening. A circular aperture has a stronger shape than a rectangular aperture because a rectangle has fast deflection and torsion angles, so its resistance to an applied load is lower than a circular aperture.

4.2. Effect of Shape of Openings

Figure 18 shows another comparison between beams with the same diameter and the same number of openings but with different opening shapes (circular, rectangular, as well as hexagonal opening shapes). It can be seen from this comparison that the steel beam with round openings had a better bearing capacity than the beam with hexagonal openings and the beam with rectangular openings. In addition, the circular shape opening is very effective, so it displays less stress concentrations as well as being easy to fabricate. In the case of a steel beam with aspect ratio 1.71, it can be observed that the beam with circular openings is better than the beam with rectangular openings, as shown in Figure 18, as the rectangular opening shape was established to be very critical because of the high stress concentration in the corner regions. In addition, it can be indicated that the beam with hexagonal openings is better than the beam with rectangular openings because hexagonal openings are more resistant to deflection and deformation than rectangular openings, as shown in Figure 18-a. The decreasing rate in peak load was about 12.38% as the shape of the opening changed from hexagonal to rectangular. Besides, the decreasing rate in peak load was about 7% as the shape of the opening transferred from circular to hexagonal and about 12.39% as the shape of the opening for the case of steel beams having rectangular openings for steel I beams having an aspect ratio equal to 2.5, as shown in Figure 18-b. The failure mode of a hexagonal beam can be shown in Figure 19.



(a)



(b)

Figure 18. Load vs mid span deflection for steel beams with different openings shape and with aspect ratio equal to (a) 1.71 (b) 2.5

Figure 19. Failure mode for steel beams with hexagonal openings shape

5. Finite Element Modelling

Nonlinear three-dimensional finite element analysis is used in the current study to estimate the behaviour of a steel I beam with a web opening by using the ABAQUS computer program. The results obtained from this analysis are associated with experimental results, and the comparison presented good accuracy results. A three dimensional solid element (C3D8R), which is well-defined by eight nodes as well as an isotropic material property. Each node has three degrees of freedom; translation in the nodes x, y, and z is used for modeling all of the steel beam and the stiffener. A steel beam model is made by gathering many part instances, such as the steel I beam, stiffeners, and the steel plate used to apply load to the steel beam. The assembled model has independent part instances as well as a global coordinate system. The opening is extruded through a web of steel I beams. All part instances are positioned within the assembly with respect to the global origin by translation and/or rotation. The contact between the steel beam and the steel plate as well as stiffeners is characterized by tie constraint, which considers the surface of the steel beam as the master surface and the surface of stiffeners and steel plates attached to the steel beam as the slave surface. This is used to connect two separated surfaces together so that there is no relative motion between them. The surface-to-surface relationship represents the bonds between the master and the slave in the region of contact constraints. After that, the support and the load are applied. Support is applied in the 'Initial' step with a rotation/displacement boundary condition. The load is applied in "Step 1' as a concentrated load on the upper area of the steel plate, as presented in Figure 20. Next, the model is separated into small elements by selecting the size of the element mesh in the part instances. In other words, the finite element analysis needs to use essential model meshing, as seen in Figure 20. Then, the job is formed, which permits succumbed for the analysis. The analysis results are stored in *.odb file. The information about the results, in addition to the several model shapes as undeformed and deformed shapes, is attained from the output database by the visualization module. Both of these history output requests, in addition to field output requests, can be achieved at a nodal point, in elements, or else in a wholly model, depending on the exact output request that can be plotted in the Abaqus viewport by exporting data and plotting tools to Microsoft Excel via the Excel utility option.

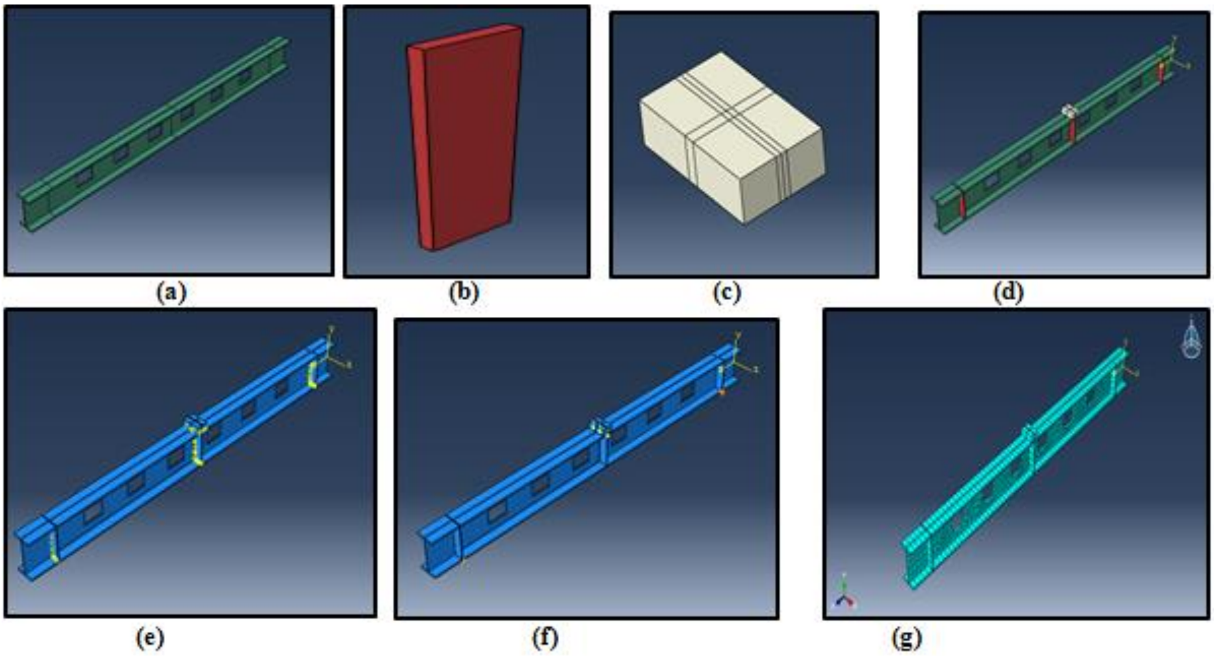


Figure 20. Representation of steel I beams with web openings (a) steel beam (b) stiffeners (c) load support (d) assembling of part instances (e) steel beams with tie constraint (f) steel beam with load and boundary condition (g) mesh formation of steel beam

6. Validation of Steel Beams

A comparison is made between the FE results and the experimental results. The models were planned by using the Abaqus computer program to validate and represent steel I beams of experimental work. The Abaqus program was also used to indicate the effect of changing the shape of the web opening on the variants of vertical deflection at midspan versus the applied load for all beams until failure. In addition, the results obtained from the FE analysis of models are consistent with the failure modes of composite walls detected through experiment, which failed due to flexural mechanisms, local buckling of steel beams, and rupture of welded joints. The deformation shapes of these steel I beams can be seen in Figures 21 to 32.

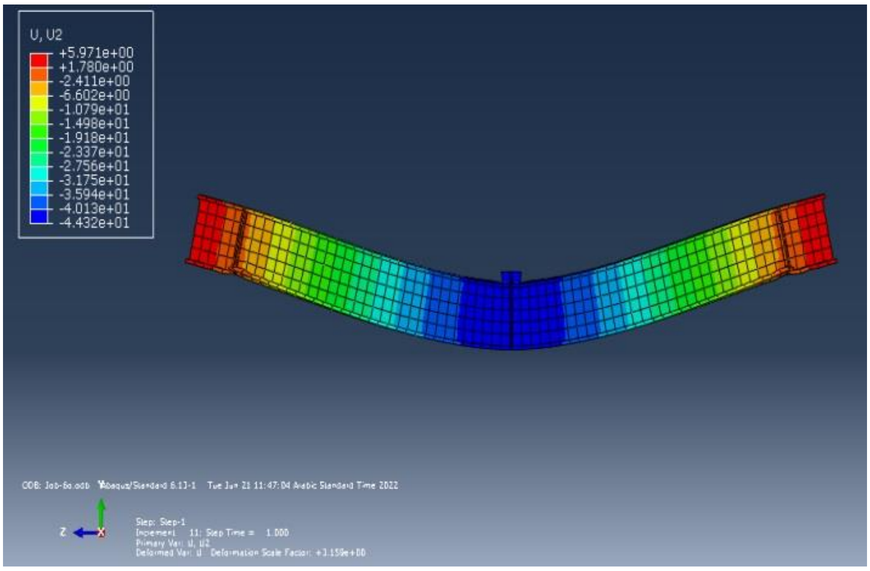


Figure 21. Deformation of steel I beam S1 without opening

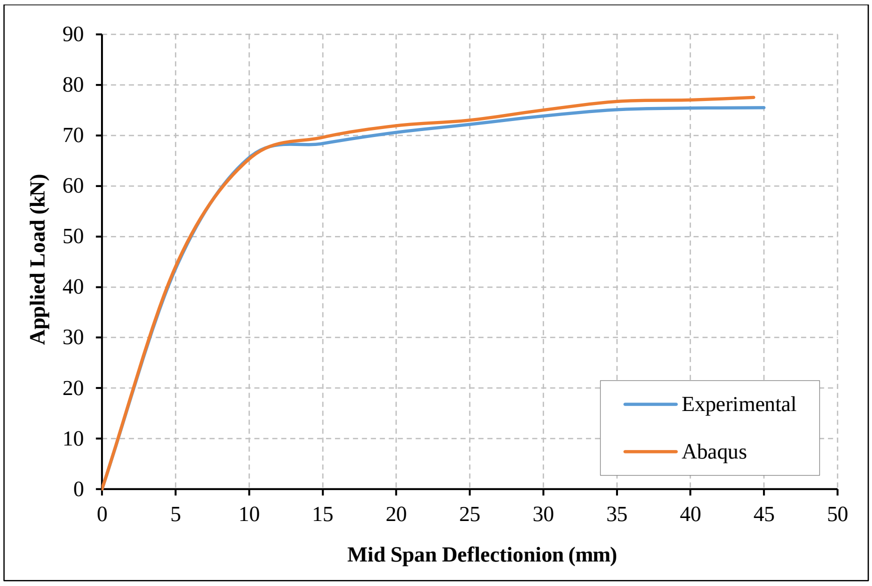


Figure 22. Load versus mid span deflection for model S1 without opening

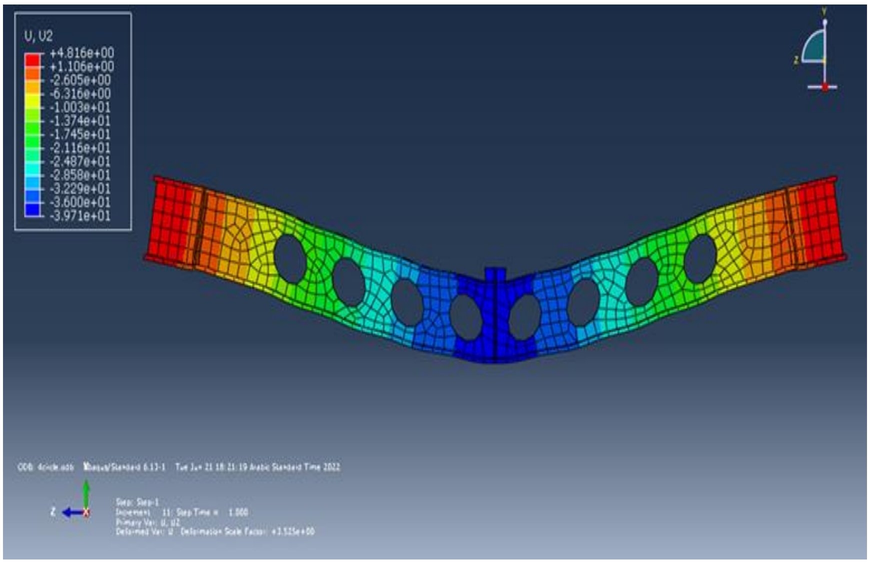


Figure 23. Deformation of steel I beam with circular openings and aspect ratio=1.71 (Model S2)

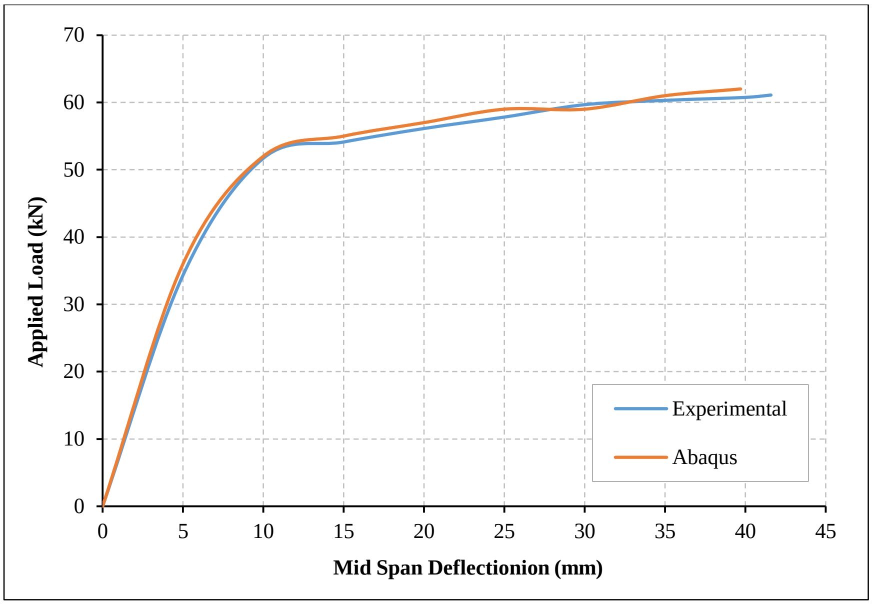


Figure 24. Load versus mid span deflection for model S2

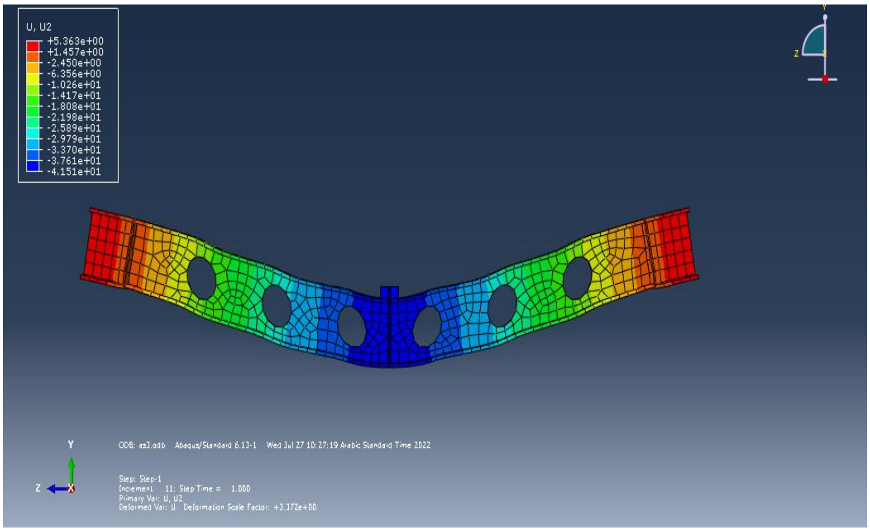


Figure 25. Deformation of steel I beam with circular openings and aspect ratio=2.5 (Model S3)

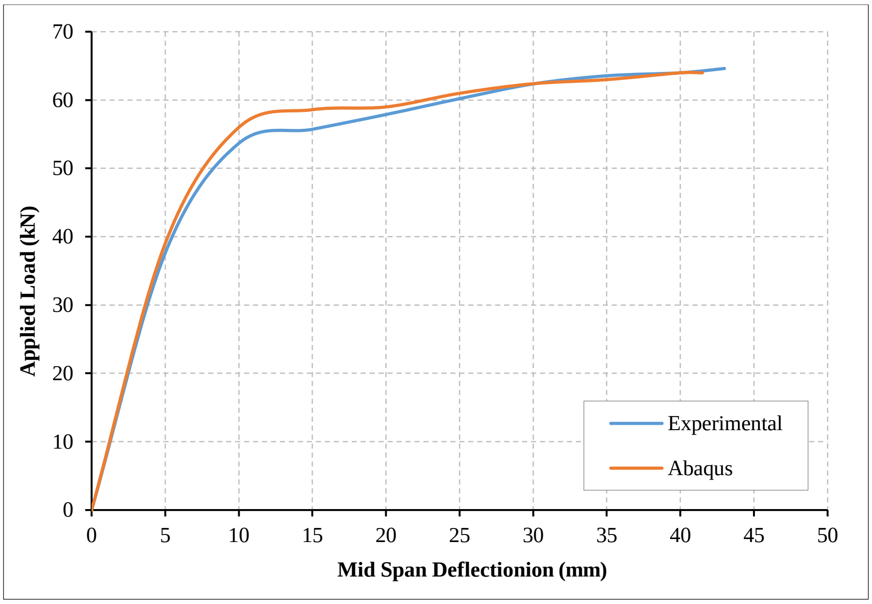


Figure 26. Load versus mid span deflection for model S3

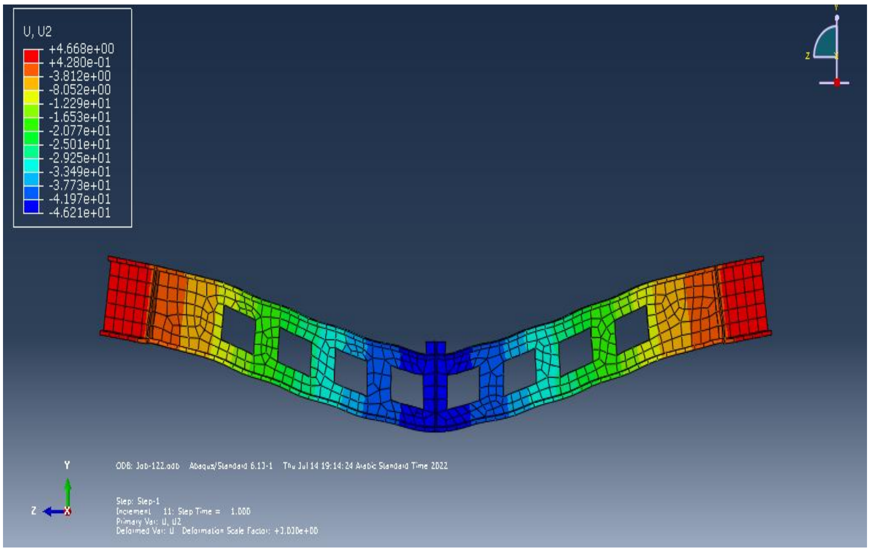


Figure 27. Deformation of steel I beam with rectangular openings and aspect ratio =1.71 (Model S4)

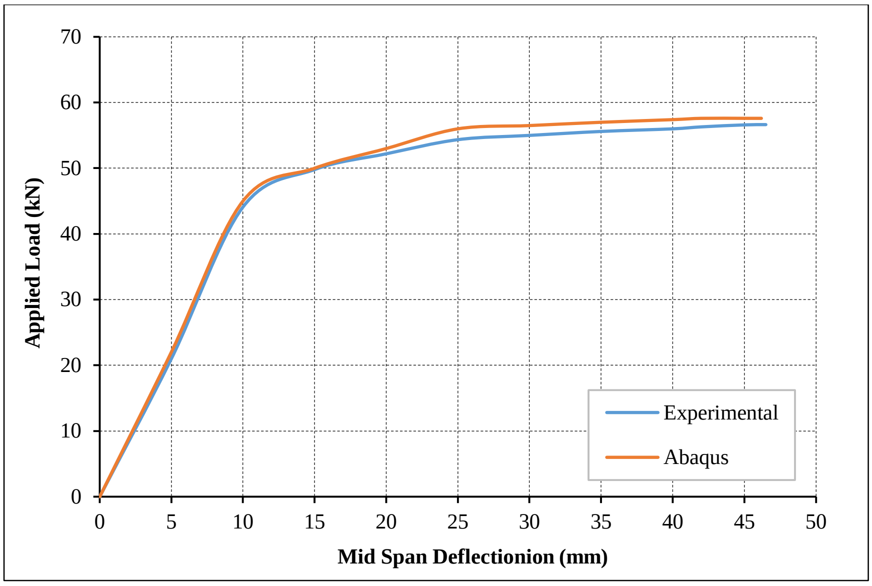


Figure 28. Load versus mid span deflection for model S4

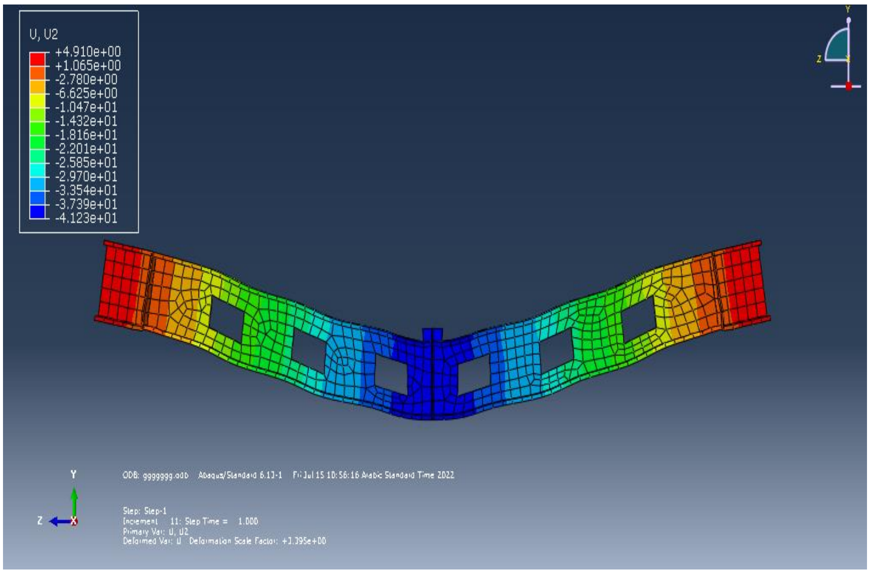


Figure 29. Deformation of steel I beam with rectangular openings and aspect ratio=2.5 (Model S5)

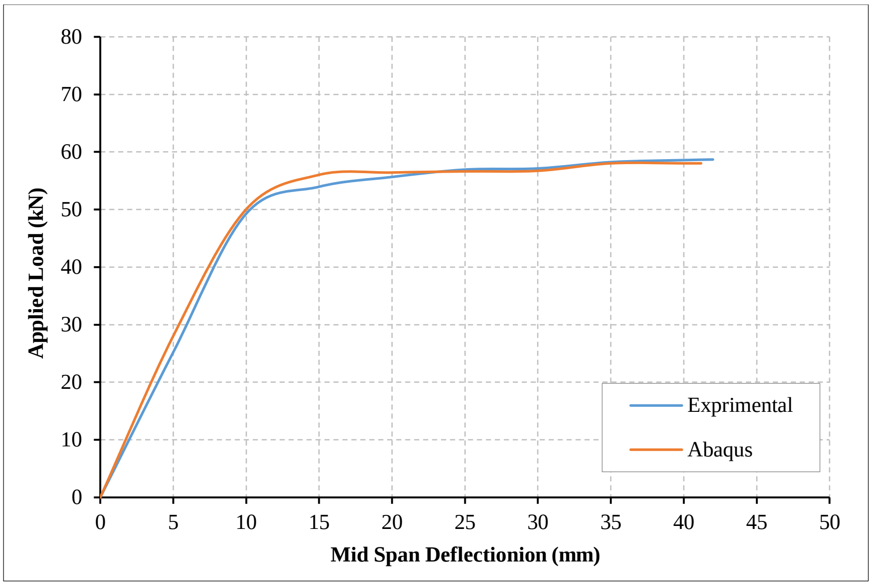


Figure 30. Load versus mid span deflection for model S5

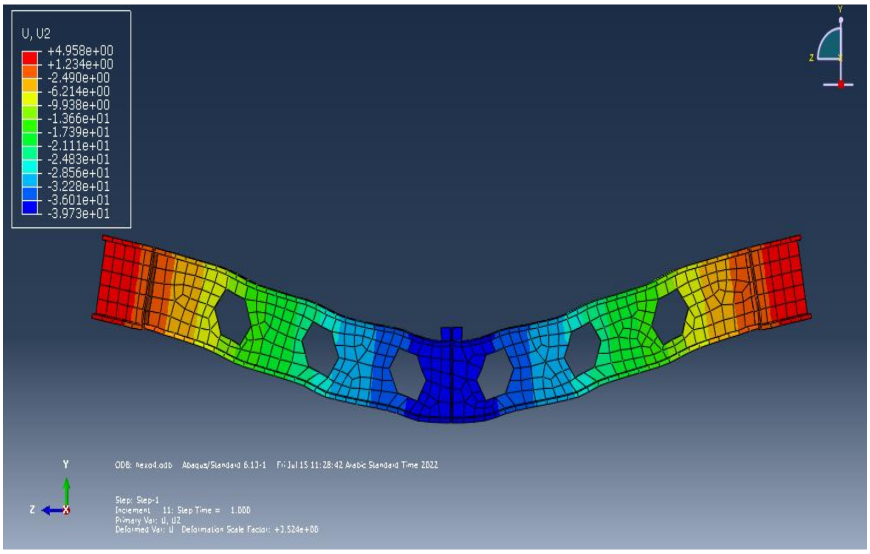


Figure 31. Deformation of steel I beam with hexagonal openings shape aspect ratio=2.5 (Model S6)

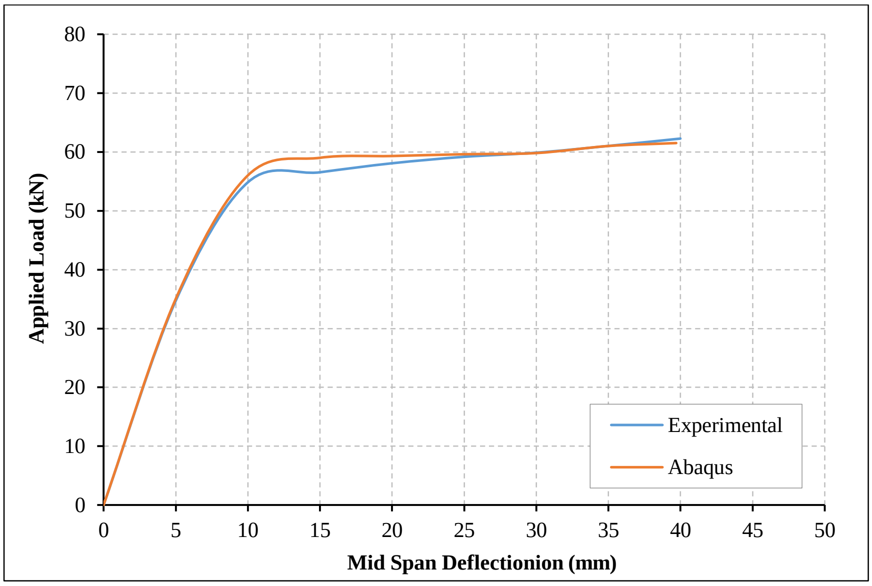


Figure 32. Load versus mid span deflection for model S6

Besides, both the experimental as well as the numerical results for the failure load and the corresponding mid-span deflection for the compared steel I beams are summarized in Table 3.

Table 3. Details of all steel I Beams

Specimens name	Experimental results		Numerical results		Error%	
	Peak load (kN)	Vertical deflection (mm)	Peak load (kN)	Vertical deflection (mm)	Peak load (KN)	Vertical deflection (mm)
S1	75.5	45	77.5	44.3	2.64	1.56
S2	61.07	41.6	62	39.7	1.522	4.56
S3	64.62	45	64	41.5	0.95	7.78
S4	56.64	46.5	57.6	46.2	1.69	0.64
S5	58.7	42	58	41.2	1.19	1.9
S6	62.3	40	61.5	39.7	1.28	0.75

7. Parametric Study

The parametric study presented here consists of analyzing six steel I-beams with various shapes of web openings, which have been modeled using the ABAQUS computer program to study the effect of varying the shape of openings on the value of the failure load and mid-span deflection. The dimensions and material properties of the steel I beam in the parametric analysis are described analytically in Table 4.

Table 4. The dimensions and materials properties of the steel I beam in the parametric analysis

Specimen	Length (mm)	Openings shape	Distance between the centers of the openings (mm)
P1	1400	Diamond	175
P2	1400	Octagonal	175
P3	1400	Trapezoid (T1)	175
P4	1400	Trapezoid (T2)	175
P5	1400	Transvers ellipse	175
P6	1400	Longitudinal ellipse	175

All openings have the same area. The deformation shapes of all steel I beams used in this parametric study can be seen in Figures 33 to 38.

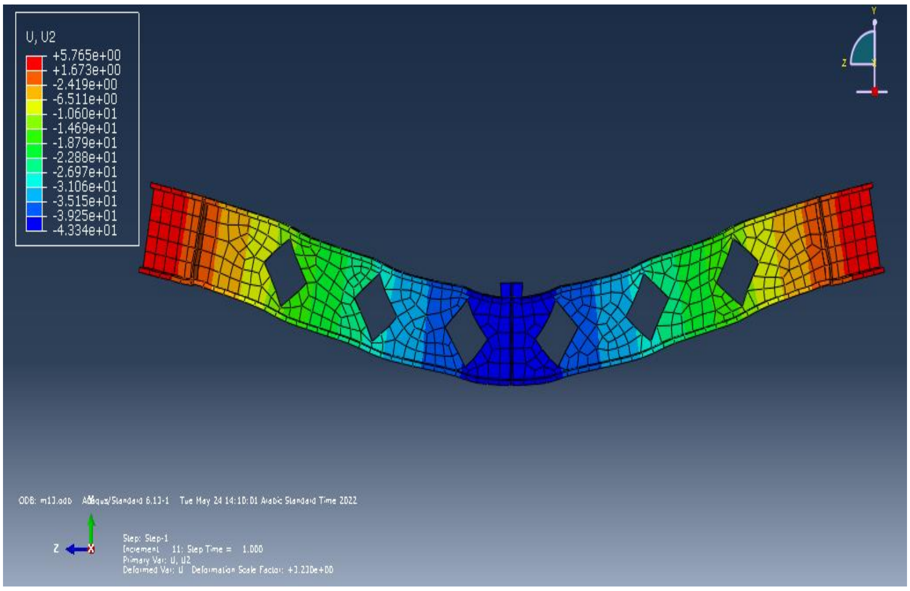


Figure 33. Deformation of steel I beam with diamond openings shape having aspect ratio=2.5

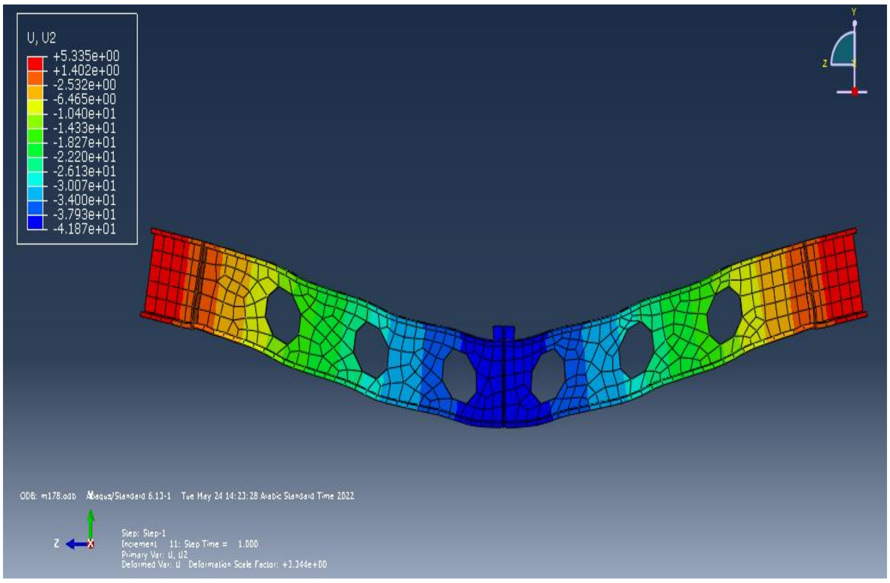


Figure 34. Deformation of steel I beam with octagonal openings shape having aspect ratio=2.5

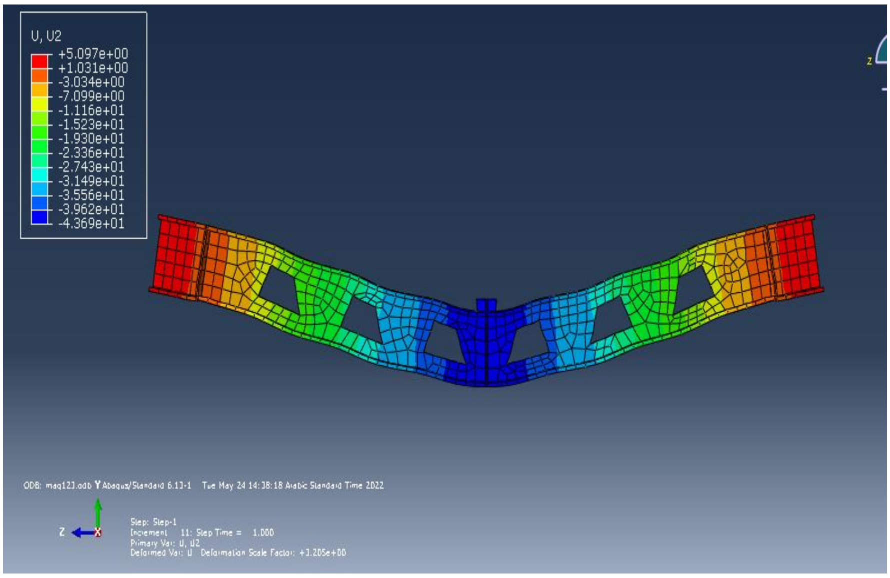


Figure 35. Deformation of steel I beam with trapezoid (T1) openings shape having aspect ratio=2.5

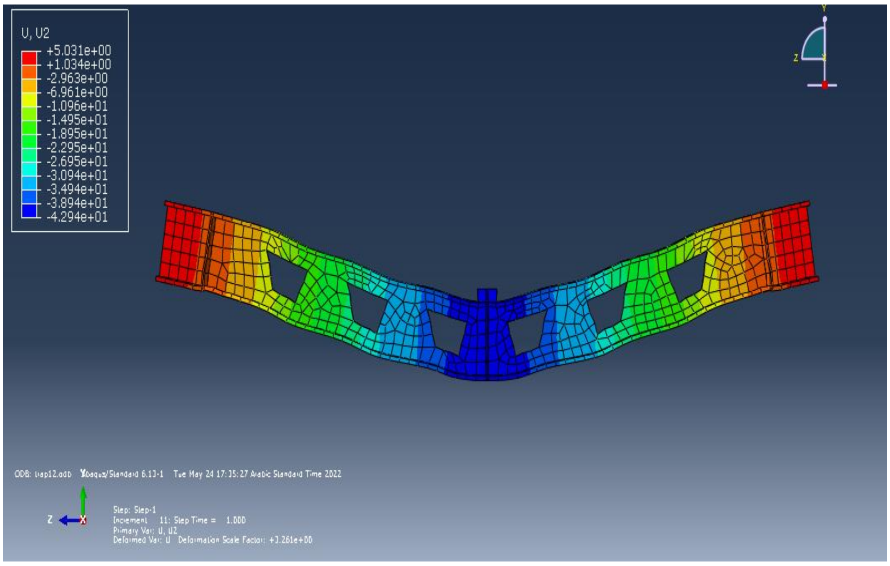


Figure 36. Deformation of steel I beam with trapezoid (T2) openings shape having aspect ratio=2.5

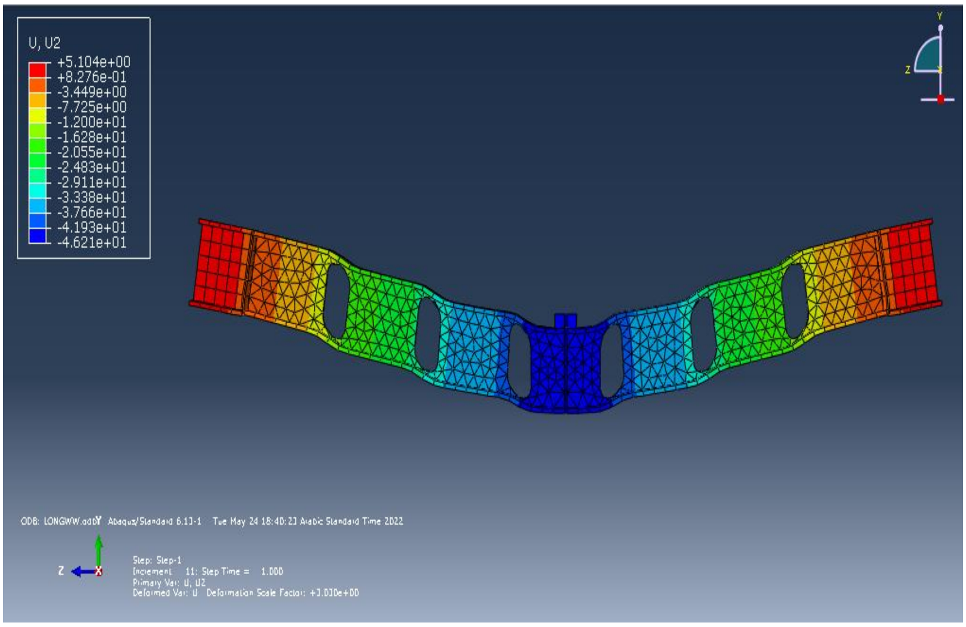


Figure 37. Deformation of steel I beam with transverse ellipse openings shape having aspect ratio=2.5

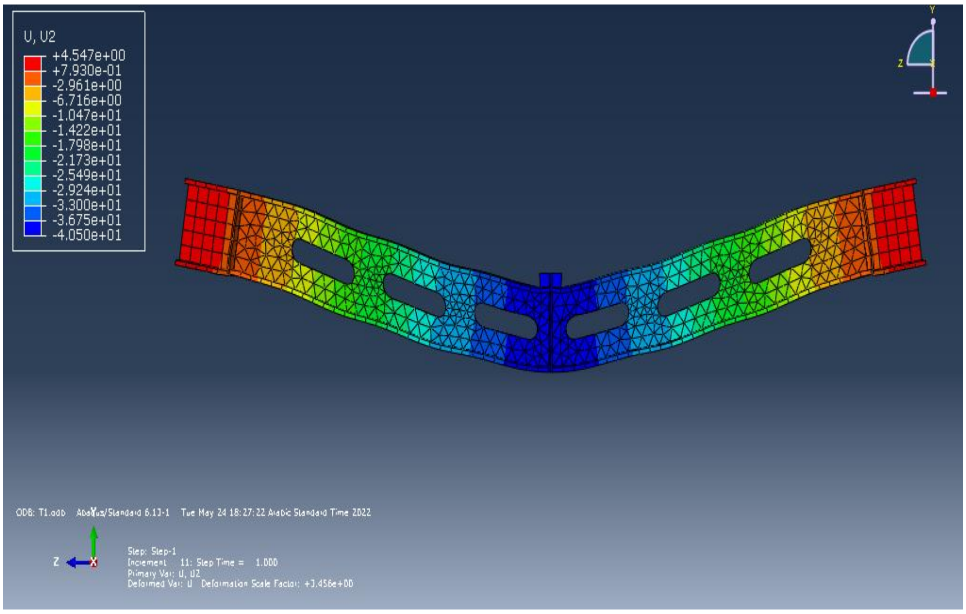


Figure 38. Deformation of steel I beam with longitudinal ellipse openings shape having aspect ratio=2.5

Figure 39 shows the effect of different shapes of web openings on the values of midspan deflection versus axial load. In this figure, a comparison is made between seven steel I-beams of the same aspect ratio but with different shapes of openings. The mode of failure was characterized by a flexural mechanism, local buckling of the steel beam. It can be noticed that the steel I-beam with a circular opening, which had been tested experimentally and modeled by the Abaqus program, is the best case and gives a higher failure load as compared to other cases.

According to Figure 39, it can be noticed that a steel I beam with a diamond web opening gives an approximately similar performance to a steel I beam with an octagonal opening. The diamond recorded a higher failure load (about 2.76%) than that for octagonal and an increased midspan deflection (about 3.42%). As concerned with the steel I beam with trapezoidal web opening of configuration (T1), it can be noticed that the failure load is higher by about 1.64% than that of the steel I beam with trapezoidal web opening of configuration (T2). Furthermore, the failure load of a steel I beam with a transverse ellipse increases by about 4% when compared to a steel I beam with a longitudinal ellipse.

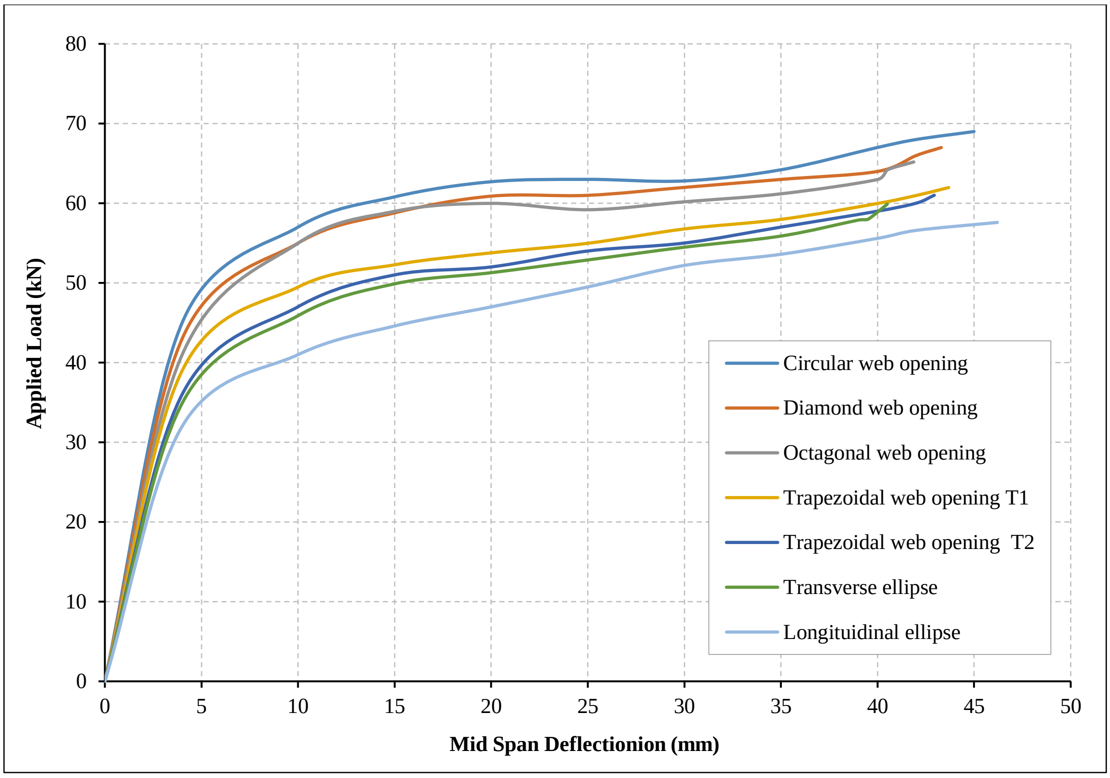


Figure 39. Load versus mid span deflection for all beams

8. Conclusion

Based on the overall results attained from the experimental work, it can be concluded that the concentration of stress nearby the corners and regions of the openings is critical. Thus, these corners should be curved to eliminate or minimize the stress concentration. Besides, it has been detected a decrease in both the stiffness and ultimate load with an increase in the area of openings and the location of the openings. This difference is due to the effect of the load due to the number of openings; the higher the number of openings, the more weight is reduced and the structural performance efficiency increases, leading to less resistance to the applied load, faster deformation, and faster failure. Besides, the steel beam with circular openings is more resistant to failure and more rigid to bear the load imposed in the center than the beams with rectangular openings. The reason for this is the shape of the opening. A circular aperture has a stronger shape than a rectangular one because a rectangle has fast deflection and torsion angles, so its resistance to an applied load is lower than that of a circular aperture. The beam with hexagonal openings is more resistant to deflection and deformation than the one with rectangular openings. Thus, the rate of increase in peak load is about (3.72%, 3.71%) for beams with circular and rectangular openings having an aspect ratio of 1.71 and 2.5, respectively.

The shape of the opening has an effect on the bearing capacity of the beam. So, the decreasing rate in peak load was about 12.38% as the shape of the opening transferred from hexagonal to rectangular and about 7% as it transferred from circular to hexagonal. In the case of beams having an aspect ratio of 2.5, the rate of decrease in peak load was about 12.39% as the shape of the opening changed from circular to rectangular.

According to the parametric study, the diamond recorded an increased failure load and deflection by about 2.76% and 3.42%, respectively, compared to that with an octagonal opening. In addition, the beam with trapezoidal opening T1 recorded an increase in failure load of about 1.64% over that with trapezoidal opening T2. Finally, the increasing rate of failure load of a beam with a transverse ellipse was about 4% higher than that of a steel beam with a longitudinal ellipse.

9. Declarations

9.1. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

9.2. Funding

The author received no financial support for the research, authorship, and/or publication of this article.

9.3. Conflicts of Interest

The authors declare no conflict of interest.

10. References

[1] Bower, J. E. (1968). Design of Beams with Web Openings. Journal of the Structural Division, 94(3), 783–807. doi:10.1061/jsdeag.0001916.

[2] Lawson, R.M. (1987) Design for Openings in the Webs of Composite Beams. CIRIA/Steel Construction Institute, CIRIA Special Publication and SCI Publication 068, Ascot, United Kingdom.

[3] Darwin, D., & Lucas, W. K. (1990). LRFD for Steel and Composite Beams with Web Openings. Journal of Structural Engineering, 116(6), 1579–1593. doi:10.1061/(asce)0733-9445(1990)116:6(1579).

[4] Chan, P. W., & Redwood, R. G. (1974). Stresses in Beams with Circular Eccentric Web Holes. Journal of the Structural Division (ASCE), 100(ST1), 231–248. doi:10.1061/jsdeag.0003693.

[5] Olander, H. C. (1953). A method for calculating stresses in rigid frame corners. In Proceedings of the American Society of Civil Engineers, 79(8), 1-21.

[6] Sahmel, P. (1969). The design, construction and approximate analysis of weld beams and torsion members having large web openings. Schweissen und Schneiden, 21(3), 116-122. (In German).

[7] EN 1993-1-3. (2006). Eurocode 3: Design of steel structures-Part 1-3: General rules-Supplementary rules for cold-formed members and sheeting. European Committee for Standardization (CEN), Brussels, Belgium.

[8] Thevendran, V., & Shanmugam, N. E. (1991). Lateral Buckling of Doubly Symmetric Beams Containing Openings. Journal of Engineering Mechanics, 117(7), 1427–1441. doi:10.1061/(asce)0733-9399(1991)117:7(1427).

[9] Lian, V. T., & Shanmugam, N. E. (2003). Openings in horizontally curved plate girder webs. Thin-Walled Structures, 41(2–3), 245–269. doi:10.1016/S0263-8231(02)00090-3.

[10] Dinehart D. W., Dionisio M. C., Hoffman R. M., Yost J. R., Gross S. P. (2004). Determination of critical location for service load bending stresses in non-composite cellular beams. 17th ASCE Engineering Mechanics Conference, June 13–16, 2004, University of Delaware, Newark, United States.

[11] Basher, M. A., Shanmugam, N. E., & Khalim, A. R. (2009). Web openings in horizontally curved composite plate girders. Journal of Constructional Steel Research, 65(8–9), 1694–1704. doi:10.1016/j.jcsr.2009.02.009.

[12] Hagen, N. C., Larsen, P. K., & Aalberg, A. (2009). Shear capacity of steel plate girders with large web openings, Part I: Modeling and simulations. Journal of Constructional Steel Research, 65(1), 142–150. doi:10.1016/j.jcsr.2008.03.014.

[13] Radic, I., Markulak, D., & Veravac, D. (2008). Numerical simulation of lateral stability of castellated beams. Proceedings of the 5th European Conference on Steel Structures, Eurosteel, 3-5 September, 2008, Graz, Austria.

[14] EN 1993-1-1. (2005). Eurocode 3: Design of Steel Structures, Part 1-1: General Rules and Rules for Buildings. European Committee for Standardization (CEN), Brussels, Belgium.

[15] Fang, C., Wang, W., Qiu, C., Hu, S., MacRae, G. A., & Eatherton, M. R. (2022). Seismic resilient steel structures: A review of research, practice, challenges and opportunities. Journal of Constructional Steel Research, 191, 107172. doi:10.1016/j.jcsr.2022.107172.

[16] Panedpojaman, P., & Thepchatri, T. (2013). Finite element investigation on deflection of cellular beams with various configurations. International Journal of Steel Structures, 13(3), 487–494. doi:10.1007/s13296-013-3008-z.

[17] Rodrigues, F., da S. Vellasco, P. C. G., de Lima, L. R. O., & de Andrade, S. A. L. (2014). Finite Element Modelling of Steel Beams with Web Openings. Engineering, 06(13), 886–913. doi:10.4236/eng.2014.613082.

[18] Jichkar, R. R., Arukia, N. S., & Pachpor, P. D. (2014). Analysis of steel beam with web openings subjected to buckling load. Journal of Engineering Research and Applications, 4(5), 185-188.

[19] Elkafrawy, M., Alashkar, A., Hawileh, R., & Al-Hamaydeh, M. (2022). FEA investigation of elastic buckling for functionally graded material (FGM) thin plates with different hole shapes under uniaxial loading. Buildings, 12(6), 802. doi:10.3390/buildings12060802.

[20] Morkhade, S. G., & Gupta, L. M. (2015). Parametric Study of Steel Beams with Web Openings. Proceeding of 9th Structural Engineering Convention (SEC 14), 22-24 December, 2014, Indian Institute of Technology, Delhi, India.

[21] Manoharan, A. C., & Tripathi, R. K. (2017). Analysis of steel beams with circular opening. International Journal of Civil Engineering and Technology, 8(3), 411–422.

[22] Feng, R., Zhan, H., Meng, S., & Zhu, J. (2018). Experiments on H-shaped high-strength steel beams with perforated web. Engineering Structures, 177, 374–394. doi:10.1016/j.engstruct.2018.08.059.

[23] Morkhade, S. G., & Gupta, L. M. (2019). Ultimate load behaviour of steel beams with web openings. Australian Journal of Structural Engineering, 20(2), 124–133. doi:10.1080/13287982.2019.1607448.

[24] Morkhade, S. G., Kshirsagar, M., Dange, R., & Patil, A. (2019). Analytical study of effect of web opening on flexural behaviour of hybrid beams. Asian Journal of Civil Engineering, 20(4), 537–547. doi:10.1007/s42107-019-00122-4.

[25] Morkhade, S. G., & Gupta, L. M. (2022). Critical study of steel beams with web openings. Australian Journal of Structural Engineering. doi:10.1080/13287982.2022.2117319.

[26] De´nan, F., Hashim, N. S., & Mahinder Singh, A. K. (2022). Development of efficiency analysis for I-beam steel section with web opening via numerical method. World Journal of Engineering. doi:10.1108/WJE-03-2022-0117.

[27] De'nan, F., & Hashim, N. S. (2022). Stress analysis of I-beam with web opening via finite element analysis and experimental study. World Journal of Engineering. doi:10.1108/WJE-11-2021-0627.

[28] Shamass, R., Ferreira, F. P. V., Limbachiya, V., Santos, L. F. P., & Tsavdaridis, K. D. (2022). Web-post buckling prediction resistance of steel beams with elliptically-based web openings using Artificial Neural Networks (ANN). Thin-Walled Structures, 180, 109959. doi:10.1016/j.tws.2022.109959.