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Finite Element Investigation of the Ultimate Capacity of Hollow-Flange Steel Girders with Web Openings

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ABSTRACT

The goal of structural design is to select member sizes that are proportional to the structural geometry in order to achieve the most cost-effective design. Steel girders were typically made of webs, flanges and a number of internal stuffeners, the main objective of this research is to develop a finite element model to study the effect of the shapes and locations of openings on the behavior of hollow flange steel plate girders. In this study, seven models were analyzed in two groups. The first group study the effect of web openings shape openings on the behavior of hollow flange steel plate girders, while the second group study the effect of web openings location on the behavior of hollow flange steel plate girders. The girders are analyzed until the final failure has occurred. The results obtained from finite element analysis showed that that the absence of opening had an important effect on the ultimate load capacity. The ultimate capacity of hollow flange steel plate girder with four squares opening decreased about 5% compared to hollow flanges steel plate girder without openings.

1. Introduction

Hollow flange steel plate girders, which are fabricate by connecting two plate as flanges, a flat plate as web, and a series of longitudinal or transverse stiffeners together, have been widely used in a lot of fields. The cold-formed steel sections have become widely used in the construction region in recent decades due to their advantages compare with the hot-rolled steel sections. On the other hand, these cold-formed steel sections are mono-symmetric section, open section or point-symmetric section designed for short span applications.

Many numerical studies have been published in the literature that emphasize behavior of several types of steel bridges under various loadings and supports types [1-8]. Analytical studies proposed finite element models for steel girder analysis, which were designed to give improved analyses and knowledge of the behavior of various steel girders [9].

A rectangular hollow flange beams with screw-fastened for construction are developed by Wanniarachchi and Mahendran [10]. The flexural behavior of lite steel beams was studied by Jeyaragan and Mahendran [11].

Siahaan et al. [12] recently investigated the flexural behavior of rectangular hollow flange concrete beams, it is a riveted rectangular hollow flanges with channel section for use in medium span floor systems.

Numerous researchers have been investigated a many of hollow flange sections for use in short span structures (less than 15 m) as flexural members. However, until now, research on sections with hollow flange for long

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spans has been limited. In long span applications, advanced designs are increasing the innovative steel members with better properties. Developing an appropriate hollow flanges steel plate girder is useful for long span applications due to the features of hollow flange sections, Girders with hollow tubular flanges can be used in bridge construction [13-15].

Numerical analyses were utilized by Hassanein and Silvester [16] to check the flexural and shear efficiency of hollow flange steel girders. They evaluated the performance of hollow flange steel girders to I-section plate girders in their research and found that hollow flange steel girders had greater capacities than I-section plate girders. Hollow flange sections, according to the literature, are more efficient than open I-girders.

Abbas et al. [17] developed a model for optimizing the prestressing steel girder. The ANSYS software program was used to determine the best steel girder design. Two objective functions and seven design variables are studied in this research. The result shows that the optimum values of section area for the non-prestresing girder are more than for the prestresing girder.

Perera and Mahendran [18] tested twelve hollow flange steel plate girders fabricated from rectangular hollow section flanges and steel web plates. Loading tests along the main axis of hollow flange steel plate girders were used to assess the section moment capacities of girders. The findings indicate that all of the hollow flange steel plate girder specimens failed due to local buckling of elements in the uniform moment zone.

A volume optimization model for the I-beam was developed by Mohammedali et al. [19]. The goal of this study is to reduce the steel beam total volume. Stress of steel beam and the mid-span displacement are the limitations considered in this study. According to the optimization results, the overall volume was decreased by roughly 52%.

Hassanein [20] studied the effect of using square shape opening sizes on the shear performance of hollow tubular flange girders. The analysis has been done by ABAQUS computer program. It was found that the contributions of both the web and tubular flanges should be considered in design of these girders.

Abou-Rayan et al. [21] conducted an experimental study to investigate the flexural behavior of steel cold-formed I-beams with reinforced hollow tubular flanges. Different types of wood waste, light weight concrete, and polymer mortar were used as strengthened materials. The study observed that the highest capacity was achieved by using polymer-mortar rather.

Hadidy et al. [22] investigated the effect of hollow tubular flanges on the strength and behavior of bridge girders with corrugated webs and hollow tubular flanges. The results show that adding upper and lower tubular flanges has a significant effect on the strength and stiffness of the girders when compared to flat flange girders.

The behavior and shear strength of hollow tubular flange girders with web openings was investigated by El-Khoriby et al. [23] using ABAQUS program. The results show that the tubular flanges are subjected to significant shear even when web openings are present.

This paper developed a finite element model using ANSYS software to study the behavior of hollow flange steel plate girders. The proposed model was validated with previously existing experimental study tested by Perera and Mahendran [19] and was used to investigate the effect of the vertical loading on the flexural behavior of girders. The proposed model was used to study the effect of shape and location of openings on the behavior of hollow flange steel girders as parametric study. Very few researches are presented in literature on the effect of shape and location of openings on behavior of hollow flange steel plate girders especially the numerical analysis. The girders are analyzed until the final failure has occurred.

2. Finite element modeling

For analyzing the hollow flange steel girders, the ANSYS [24] computer software is used. To simulate the hollow flange steel plate girder in finite element a 4-node SHELL181 element was used. The element has 4-nodes; each node has 6-degrees of freedom: three of them translations in the x, y, and z-axes directions and the other rotations in the x, y, and z-axes. The element is utilized in both linear and nonlinear analysis. Large deflections, stress stiffening and plasticity are also considered [24].

The material properties an important data in finite element analysis. The values of material property must be input as data into the ANSYS program. In this study, the bilinear steel stress-strain relation was considered.

3. Analysis of hollow flange steel girder

For the verification of the current numerical model, experimental hollow flange steel girder tested by Perera and Mahendran [18] was chosen. The girder was designated as HFSPG5 (HFSPG-75 × 25 × 1.6-100 × 3), which was subjected to four- point load and simply supported [18].

Fig. 1 illustrates the common layout of the hollow flange steel girder [18]. Because of the four-point loading, the bending moment are constant at middle part of girder. As a result, the girder was both short enough to avoid global buckling. To avoid shear buckling, the spacing between the loading points was chosen to be smaller than the spacing between the loading point and the support [18]. Fig. 2 shows the HFSPG5's cross-sectional dimension [18].

The load application and support conditions were same to tests. Table 1 listed the materials property used in this present study. The present girder analysis is a static non-linear analysis under four-point loads.

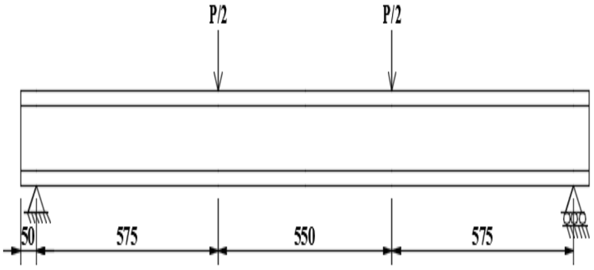


Figure 1. Details of loading and geometry of girder HFSPG5 [18] (dimension are in mm)

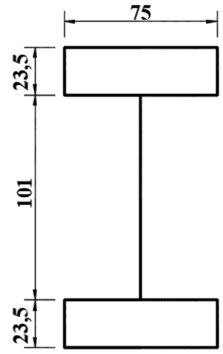


Figure 2. Cross section of the girder HFSPG5 [18] (dimension are in mm)

Table 1: Material properties of web, flange and stiffener for HFSPG5

	Web	Flange	Stiffener
Yield strength (MPa)	238.5	449	238.5
Poisson’s ratio	0.30	0.30	0.30
Modulus of elasticity (GPa)	200	200	200
Thickness (mm)	2.97	1.57	6.0

Fig. 3 shows the experimental and numerical moment-deflection curves for girder HFSPG5, indicating the good agreement between finite element and experimental results. The numerical moment was slightly larger than the experimental moment at the ultimate state. The ultimate moment capacity of the test girder was 16.23 kN.m with a 28 mm middle deflection, compared to 17.09 kN.m and 10.4 mm obtained from the theoretical analysis. The ultimate moment capacity predicted using the finite element model was 5.2 % bigger than that obtained from the experiment. The finite element failure mode was local buckling in flange and web corresponded to the failure mode in test. The present analysis was identical to the theoretical analysis done by Perera and Mahendran [18] as shown in Fig. 3. Table 2 listed the experimental and finite element results for the HFSPG5 girder.

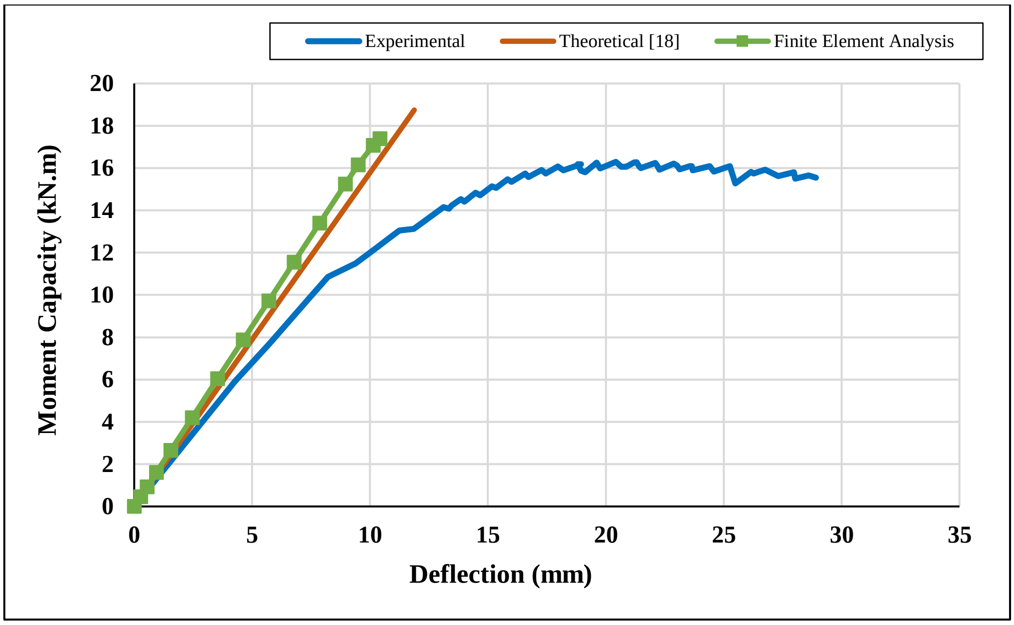


Figure 3. Moment versus vertical deflection curves for HFSPG5 girder.

Table 2: Experimental and finite element results for the HFSPG5 girder

	Experimental Result	**Finite element Result**	**% of increment**
Ultimate moment capacity (kN.m)	16.23	17.09	5.2
Mid span deflection (mm)	28	10.4	-62

4. Parametric study

The verified finite element model was used to study the overall behavior of hollow flange steel girder with web openings. Table 3 listed the materials property used in the parametric study.

Table 3: Type and Dimensions of Web's Openings

	Web	**Flange**	**Stiffener**
Yield strength (MPa)	400	445	400
Poisson's ratio	0.30	0.30	0.30
Modulus of elasticity (GPa)	200	200	200

Seven proposed models were considered in this study, which are hollow flanges steel plate girder (HFSPG0), hollow flanges steel plate girder with four circles opening R250 (HFSPG1), hollow flanges steel plate girder with four circles opening R282 (HFSPG2), hollow flange steel plate girder with four squares opening 500*500 (HFSPG3), hollow flange steel plate girder with circle opening R250 near the support (HFSPG4), hollow flange steel plate girder with circle opening R250 in quarter (HFSPG5) and hollow flange steel plate girder with circle opening R250 in center (HFSPG6). The geometry and loading of the proposed models are shown in Figs. 4-5 and Table 4. For all models, the web thickness and height was 10 and 1000 mm respectively. The hollow flange dimensions were 150 mm for inner height, 400 mm for width and 15 mm for thickness. Three concentrated point load are subjected to the hollow flange steel plate girders, one at the center and two in each quarter of the steel girder. The proposed hollow flange steel plate girder is simply supported at ends. The steel plate girder was modeled in this study using three dimensional solid elements. The stiffeners located two on supports, two in each quarter and one in center for each seven models. The load was applied at flange.

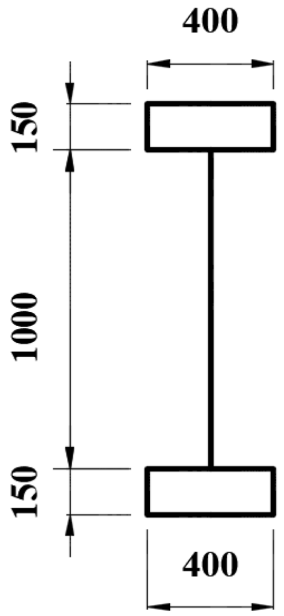
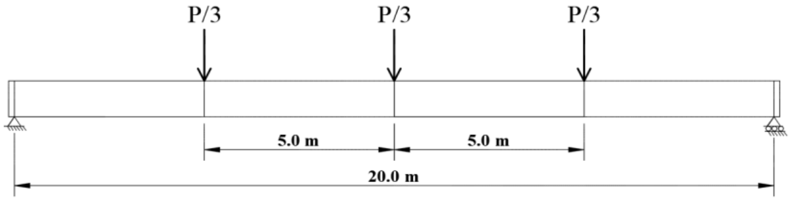


Figure 4. Cross section of proposed steel plate girders

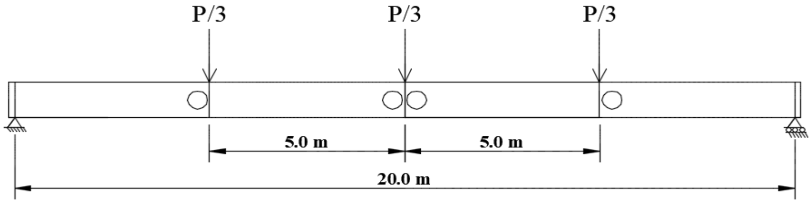
Table 4: Type and Dimensions of Web's Openings.

	Openings Shape	**Openings Dimension (mm)**	**No. of openings**
HFSPG0	——	——	——
HFSPG1	Circle	R250	4
HFSPG2	Circle	R282	4
HFSPG3	Square	500*500	4
HFSPG4	Circle	R250	1
HFSPG5	Circle	R250	1
HFSPG6	Circle	R250	1

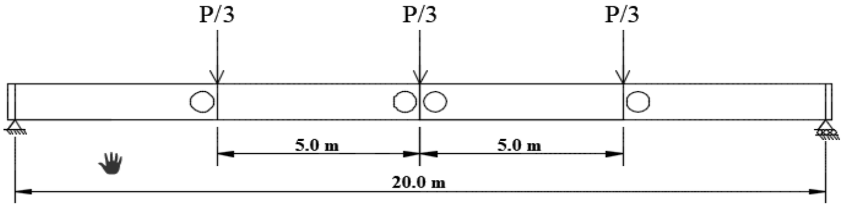
In finite element analysis, the point load must be distributed to avoid numerical problems. Fig. 6 shows finite element mesh of HFSPG1 and HFSPG3 girders.



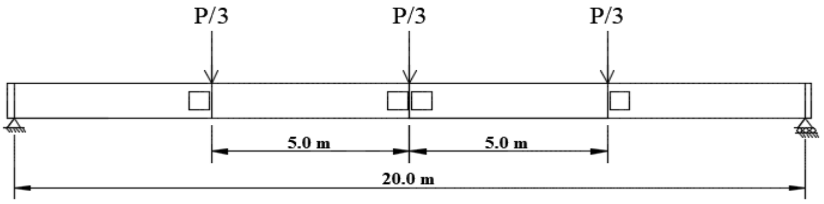
a) HFSPG0 girder



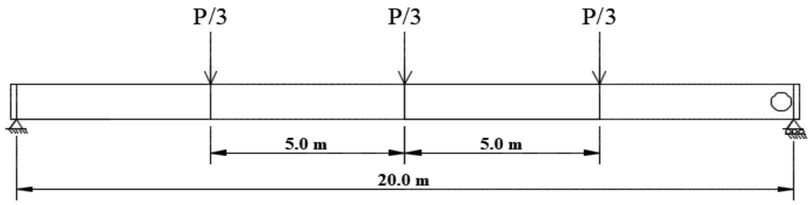
b) HFSPG1 girder



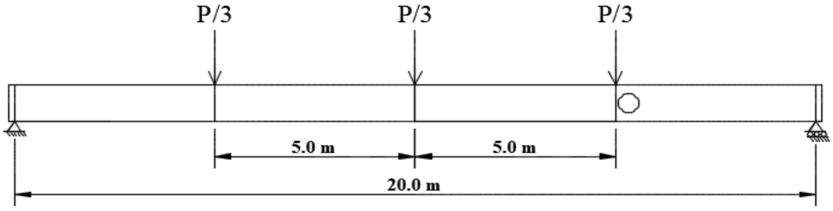
c) HFSPG2 girder



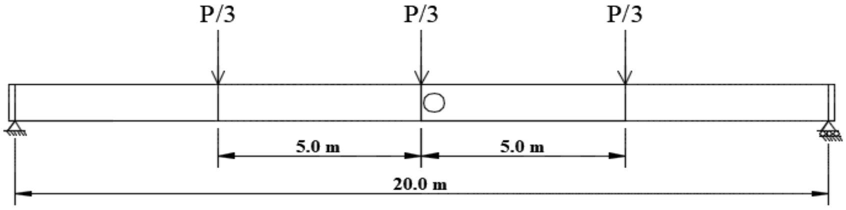
d) HFSPG3 girder



e) HFSPG4 girder

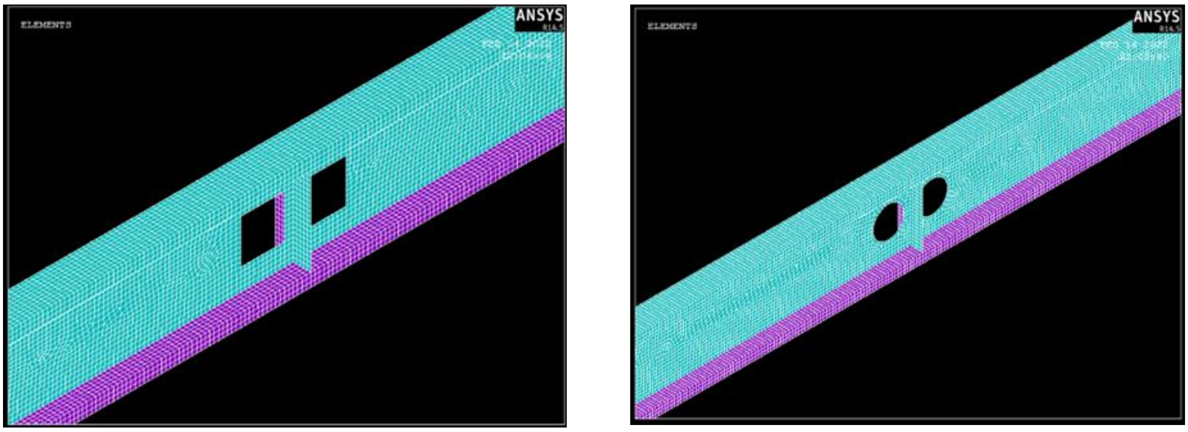


f) HFSPG5 girder



g) HFSPG6 girder

Figure 5. Geometry, support and loading for the proposed steel plate girders.



a) HFSPG3 girder

b) HFSPG1 girder

Figure 6. Mesh for the proposed steel plate girders

After apply loading, the strains and stresses are calculated at combination points of these small elements [24]. To model the flange, web, supports and stiffener, the three dimensional solid element (SHELL181) was used.

Steel girders are currently subject to nonlinear static analysis under flexural load. The total load applied to a finite element model in nonlinear finite element analysis is divide into increments known as load steps.

The nonlinear analysis is carry out until failure occurs, allowing the failure load to be determined. After each load step increment, the matrix of stiffness is changed to reflect the non-linear changes. The Newton-Raphson equilibrium iterations are used by ANSYS to update the model stiffness.

To achieve convergence of the solutions, criteria of convergence based on displacement were used for the steel girder elements, and the limit of convergence tolerance was set at 5%. If the convergence behavior is smooth, the increment of load increases up to a maximum step size, and the increment of load bisects until it equals a minimum step size if the convergence behavior is unexpected

In this paper seven models were analyzed in two parts to study the effect of shape and size of web openings on the ultimate capacity of girders. The cross section area of steel girders is same for all models. Table 5 lists the ultimate capacities of the analyzed HFSPGs.

Table 5: Ultimate capacity of the steel plate girders

	Ultimate capacity (kN)	**Maximum displacement (mm)**
HFSPG0	2644	186.7
HFSPG1	2531	154.9
HFSPG2	2521	163.5
HFSPG3	2507	161.1
HFSPG4	2633	177.5
HFSPG5	2502	146.6
HFSPG6	2550	159.5

4.1 Effect of openings shape on ultimate capacity

Figs. 7 illustrate the load versus deflection curves for HFSPG0, HFSPG1, HFSPG2 and HFSPG3 girders. From this figure, it can be noticed that the HFSPG1 girder have a stiffer response and a higher failure load capacity compared with HFSPG2 and HFSPG3 girders. This stiffer response because of the decreasing the area of opening comparing with the other models. As a result, the ultimate capacity of the circle openings was higher than that of the square openings. All analyzed HFSPGs failed mainly in compression zone due to local buckling of plate elements.

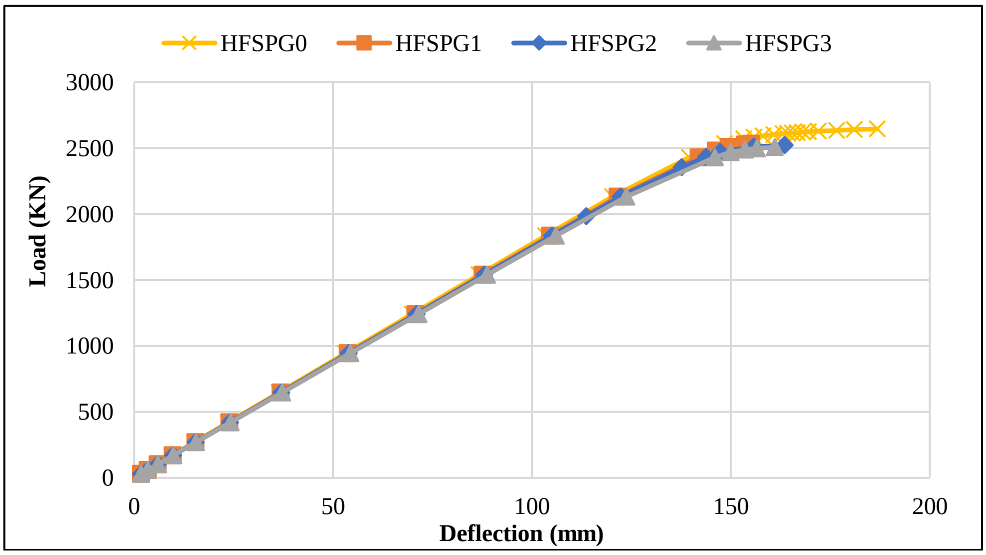


Figure 7. Load-displacement curves for the HFSPG1, HFSPG2 and HFSPG3 girders

The ultimate capacity is 2531, 2521, 2507 kN for HFSPG1, HFSPG2 and HFSPG3 respectively. From the Fig. 7, it can be noticed that the hollow flange steel plate girder with circle openings are able to carry more loads than hollow flange steel plate girder with square openings. The ultimate capacity of HFSPG1 increased about 1% than the HFSPG3 for the same dimension of openings, and HFSPG2 increase by 0.5% than the HFSPG3 as the same area openings. Figs. 8-10 show the Von Mises stresses for HFSPG1, HFSPG2 and HFSPG3 girders.

From the Fig. 7, it can be note that the deflection of HFSPG1 is lower than the deflection of HFSPG2 and HFSPG3, which means that the stiffness of HFSPG1 is greater than the HFSPG2 and HFSPG3.

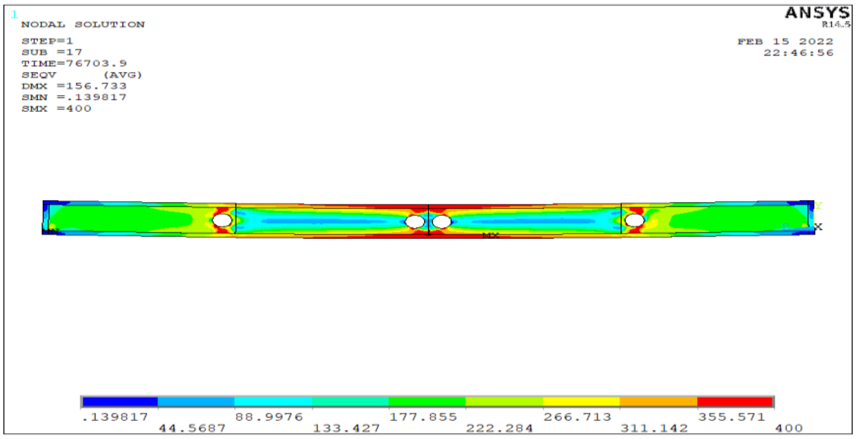


Figure 8. Von Mises stresses for HFSPG1 girder

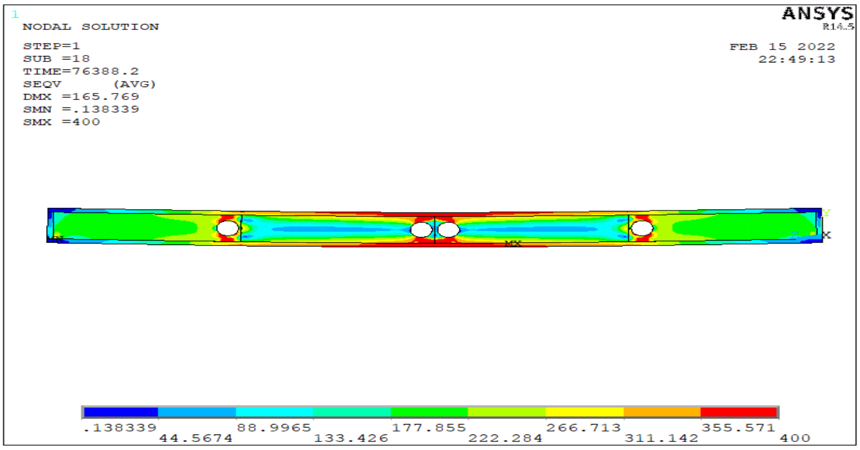


Figure 9. Von Mises stresses for HFSPG2 girder

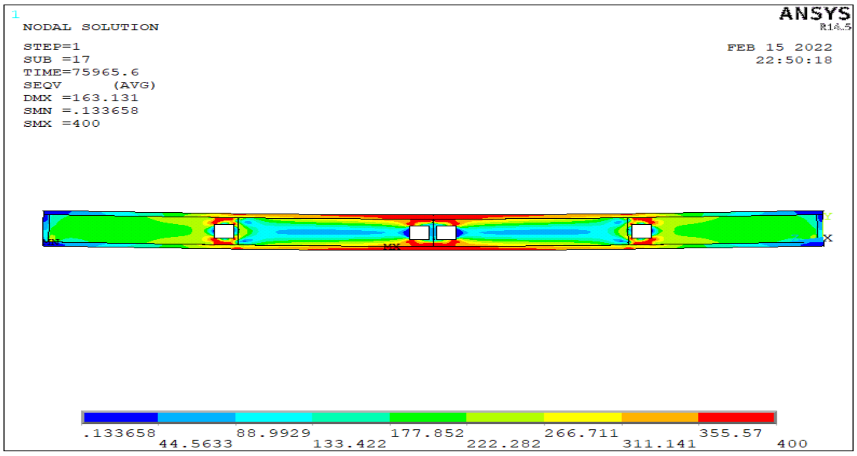


Figure 10. Von Mises stresses for HFSPG3 girder

From the Figs. 7-10 and Table 5, it can be concluded the HFSPG1 has greater ultimate capacity compared with the HFSPG2 and HFSPG3, that due to that the girder with circle openings have more resistant in buckling compared to girder with square openings.

4.2 Effect of openings location on ultimate capacity

Figs. 11 illustrate the load versus deflection curves for the HFSPG0, HFSPG4, HFSPG5 and HFSPG6 girders. From this figure, it can be observed that the HFSPG4 girder had a stiffer response and a higher failure load capacity. This stiffer response because of the opening is far away from the loaded zone comparing with the other girders. As a result, the ultimate capacity of the HFSPG4 was higher than that of the HFSPG5 and HGSPG6.

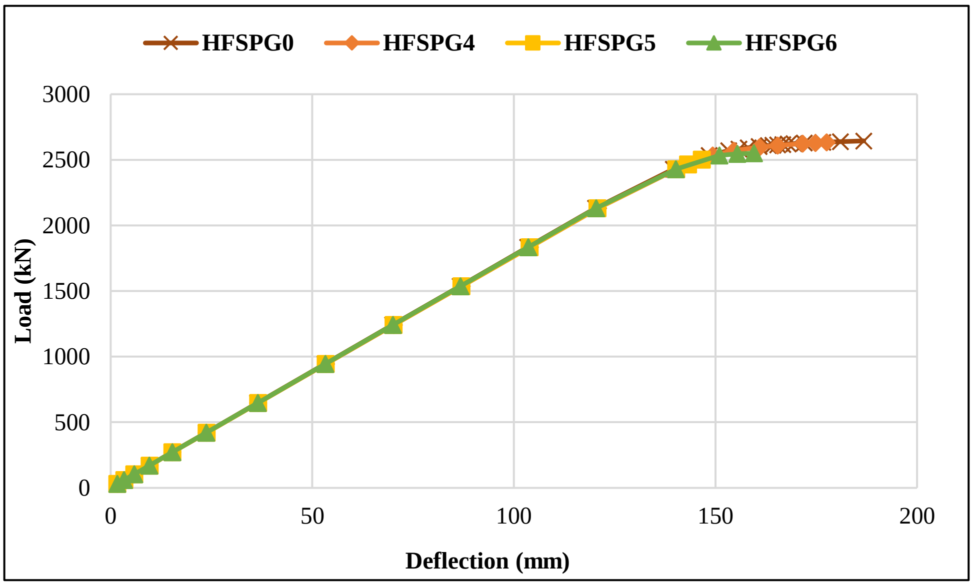


Figure 11. Load-displacement curves for the steel plate girders part two

The ultimate capacity is 2633, 2502 and 2550 kN for HFSPG4, HFSPG5 and HFSPG6 girders respectively. From the Fig. 11, can be noticed that the HFSPG4 girder can carry loads more than the HFSPG5 and HFSPG6 girders. The ultimate capacity of HFSPG4 girder increased by 5% and 3% compared with HFSPG5 and HFSPG6 respectively. Figs. 12-14 show the Von Mises stresses for HFSPG4, HFSPG5 and HFSPG6 girders.

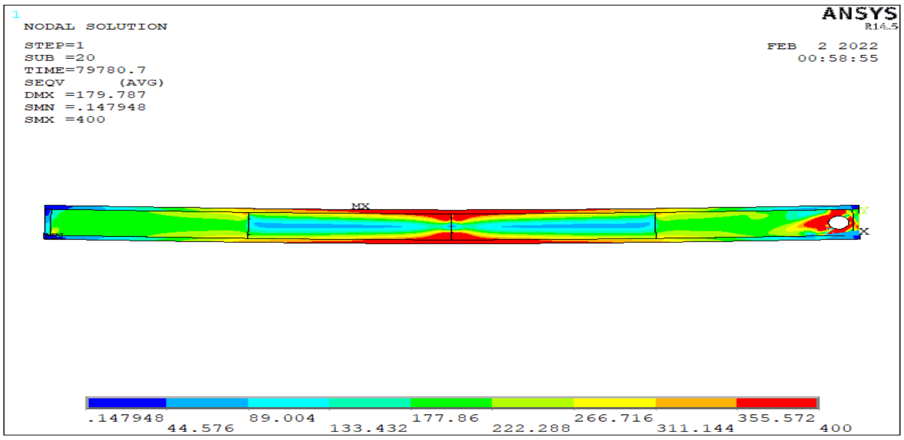


Figure 12. Von Mises stresses for HFSPG4 girder

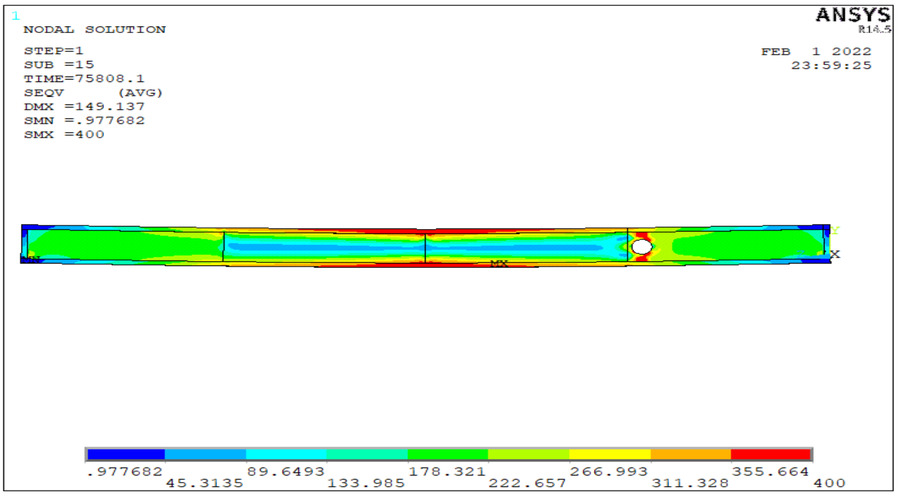


Figure 13. Von Mises stresses for HFSPG5 girder

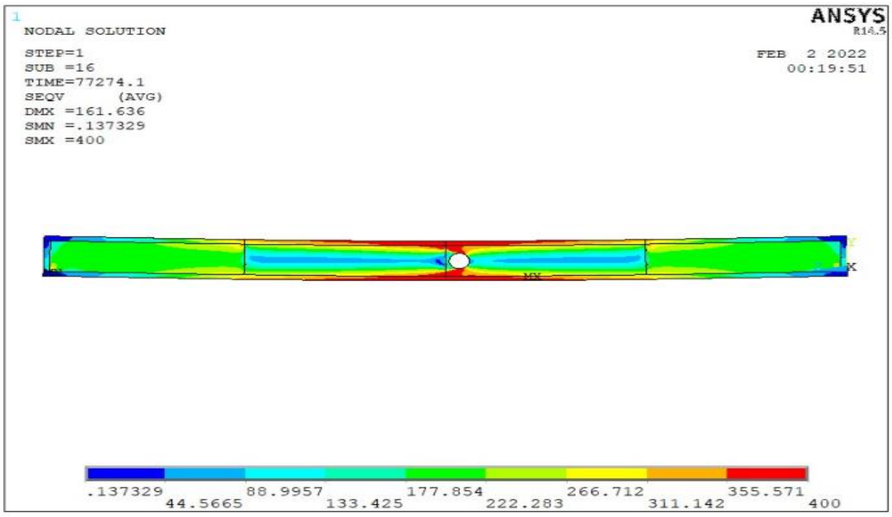


Figure 14. Von Mises stresses for HFSPG6 girder

From the Figs. 8, 12-14, and Table 5, it can be concluding the HFSPG4 has greater ultimate capacity compared with the HFSPG5 and HFSPG6, because of the location of the opening is far away from the loaded zone.

4. Conclusions

The main goal of this research is to develop 3D finite element model to study the effect of various shapes openings in web of hollow flange steel plate girders with the same cross section. A three-dimensional finite element ANSYS software was used to modelling the hollow flange steel plate girder. For numerical analyses verification, an experimental hollow flange steel plate girder from the literature was chosen, the test results and the numerical model were in good agreement. From the analytical result the following conclusions that can be drawn:

1. The ultimate moment capacity predicted using this finite element model was 5.2 % bigger than that from the test.
2. The analysis indicate that the absence of opening had an important effect on the ultimate load capacity. The ultimate capacity of hollow flange steel plate girder with four squares opening 500*500 decreased about 5% compared to hollow flanges steel plate girder without openings.
3. The ultimate capacity of steel girder with circle openings is bigger about 1% compared to the steel girder with square openings

4. The ultimate capacity of steel girder with openings near support is bigger compared to the steel girder with openings in quarter and centre of girder.
5. The failure load in hollow flange steel plate girder with circle opening R250 near the support is bigger by 5% and 3% compared to the hollow flange steel plate girder with circle opening R250 in quarter and hollow flange steel plate girder with circle opening R250 in centre respectively.
6. The results indicate that the ultimate capacity of a girder with circle openings is greater than that of a girder with square openings.

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