VOL. 15, NO. 4, FEBRUARY 2020 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

ANALYSIS OF STEEL PLATE GIRDERS WITH ELLIPTICAL WEB OPENINGS

Alireza Bahrami[1,2] and Mahdi Najarnasab[2]
[1]Department of Building Engineering, Energy Systems, and Sustainability Science, Faculty of Engineering and Sustainable Development, University of Gävle, 801 76 Gävle, Sweden
[2]Department of Civil Engineering, Abadan Branch, Islamic Azad University, Abadan, Iran
E-Mail: Alireza.Bahrami@hig.se

ABSTRACT

In this research work, steel plate girders (SPGs) having the web openings with the elliptical shape are analysed. The finite element ABAQUS software is applied. An experimentally tested SPG is used for the modelling verification. Then, the SPGs are developed. Three-dimensional (3D) finite element models of the SPGs are analysed nonlinearly considering various variables. The variables are adopted in order to deeply examine the performance of the SPGs using the finite element method. These variables include: 1) number of the openings, 2) arrangement of the openings, 3) using steel frame around the openings, 4) utilising diagonal steel stiffeners to connect the steel frame around the openings to the corners of the SPGs, and 5) thicknesses of the steel frame and the diagonal steel stiffeners. The obtained results are compared and discussed considering the effects of the variables. It is concluded that increasing the number of the openings has an adverse impact on the ultimate strength of the SPGs. The arrangement of the openings in the SPGs significantly affects their performance. The horizontal openings are superior to the vertical ones. Utilising the steel frame around the openings and/or the steel stiffeners improves the ultimate strength. Enhancing the thickness of the steel frame and/or stiffeners increases the ultimate strength. The assessment of the failure modes of the SPGs is also done.

Keywords: plate girder, steel, ultimate strength, finite element method.

1. INTRODUCTION

Since the 1950s, with the development of the welding industry, the use of the SPGs has increasingly attracted engineers and designers to cover structural spans larger than 15 m. Generally, the SPGs consist of 2 flange plates and 1 web plate that are welded together to form a cross-section with I shape. The use of the steel plates with different yield stresses at the cross-section as well as along the span allows the designers to design sections with high bending capacity at locations of the SPGs where experience a large bending moment.

The SPGs are structural bending members in which the appropriate combination of steel plates is used to make them. In the cases when existing rolled steel profiles are not able to withstand the applied loads to the bending members, employing the beams made of plates is inevitable. In addition to having good performance against the applied loads, the SPGs are also economically more cost-effective than the rolled steel beams. Meanwhile, the SPGs vastly serve as main structural members in the construction of bridges and overpasses with relatively large spans, ordinary buildings with large spans as well as frames of industrial structures.

The SPGs have large surfaces of low-thickness steel sheets forming their web and enclosed between the upper and lower flanges and vertical stiffeners. To reduce the weight of the SPGs, their web is considered thinner than their flanges. This is the reason why the web of the SPGs is buckled or yielded by the shear forces before they obtain their ultimate flexural strength.

Due to the large depth of the SPGs, they take a large space of the structures, which contradicts architectural designs and structural aesthetics. For the optimise use of this space, researchers have proposed the solution of using the SPGs with openings in their web. However, these openings have made their structural problems such as lower strength, local buckling, and instability.

Because of the wide use of the SPGs, a considerable amount of research has been directed towards them without and with the web openings [1-12]. However, limited research exists on the SPGs having openings with the elliptical shape which is done and developed in this paper.

This study focuses on the analysis of the SPGs with the elliptical web openings. Following the modelling verification using ABAQUS, 3D finite element models are developed to extensively investigate the SPGs having the web openings with the elliptical shape. The variables considered in the developed SPGs are as number of the openings, arrangement of the openings, using steel frame around the openings, utilising diagonal steel stiffeners to connect the steel frame around the openings to the corners of the SPGs, and thicknesses of the steel frame and the diagonal steel stiffeners. The effects of these variables on the performance of the SPGs are evaluated. Failure modes of the SPGs are indicated and assessed.

2. EXPERIMENTAL TESTING OF SPG

An experimental test of SPG [2] has been simulated to demonstrate the modelling accuracy. Details of the SPG have been presented in Figure-1 and Table-1. The Poisson's ratio and modulus of elasticity of the steel material are 0.3 and 210000 MPa, respectively. The flanges, web, and vertical and horizontal stiffeners of the SPG have been connected to each other by welding. The end supports of the specimen have 1 and 2 degrees of

ARPN Journal of Engineering and Applied Sciences

freedom and the patch loading has been applied at the mid-span.

3. VERIFICATION OF FINITE ELEMENT MODELLING OF SPG

In order to accurately simulate the tested SPG, the steel material, loading, and boundary conditions have exactly been simulated considering the features of the tested SPG.

In the software, the loading can be applied by two methods of the force or displacement control. In the first method, the value of the force is applied to the structure and then the software gives its corresponding displacement value while in the second method, the displacement value is applied to the structure and the software presents the value of the force required for this displacement. In this research, the force method has been employed at the mid-span of the SPG and the type of the loading is patch and ascending. The boundary conditions of the tested specimen have accurately been simulated by restraining the appropriate degrees of freedom.

The material modelling has been done as the significant part of the finite element method [13-15]. The bilinear kinematic hardening behaviour has been considered for the steel to adopt progressive hardening and softening effects [16, 17]. The elastic and the metal plasticity with the plastic options have been specified for the material properties of the steel.

The shell element S4R8 has been employed to model the steel plates and the stiffeners. It is a four-node element, in which each node owns 8 degrees of freedom. This element is suitable for large and nonlinear deformations. Also, it is preferable to be used in the cases where the sections have a dimension smaller than other dimensions such as in this study in which the thickness is smaller than other dimensions of the SPG. Quadrilateral element has been used for the steel plates and the stiffeners. Due to the regular geometry of the SPG, this type of the element is efficient that has been employed in the current study. To analyse the nonlinear response of the SPG under loading, the Newton's iterative technique has been adopted.

From examining different mesh sizes for the simulated SPG, the suitable mesh size achieving more accurate result has been selected for the analysis. The simulated SPG is illustrated in Figure-2. Finally, the nonlinear analysis of the simulated SPG was carried out using ABAQUS.

The load-vertical deflection diagram has been depicted from the obtained modelling result. Based on the comparison of the modelling result with that of the experiment, verification of the modelling has been assessed, as shown in Figure-3. The figure uncovers that the maximum force carried by the simulated SPG is 3.4 t while it is 3.35 t by the tested SPG. Consequently, they have a very small difference from each other. On the other hand, the tested and simulated SPGs behave similarly under the load. As a conclusion, the finite element modelling of the tested SPG has been done accurately and the modelling has been verified. Thus, the proposed modelling is completely capable to predict the performance of the SPGs.

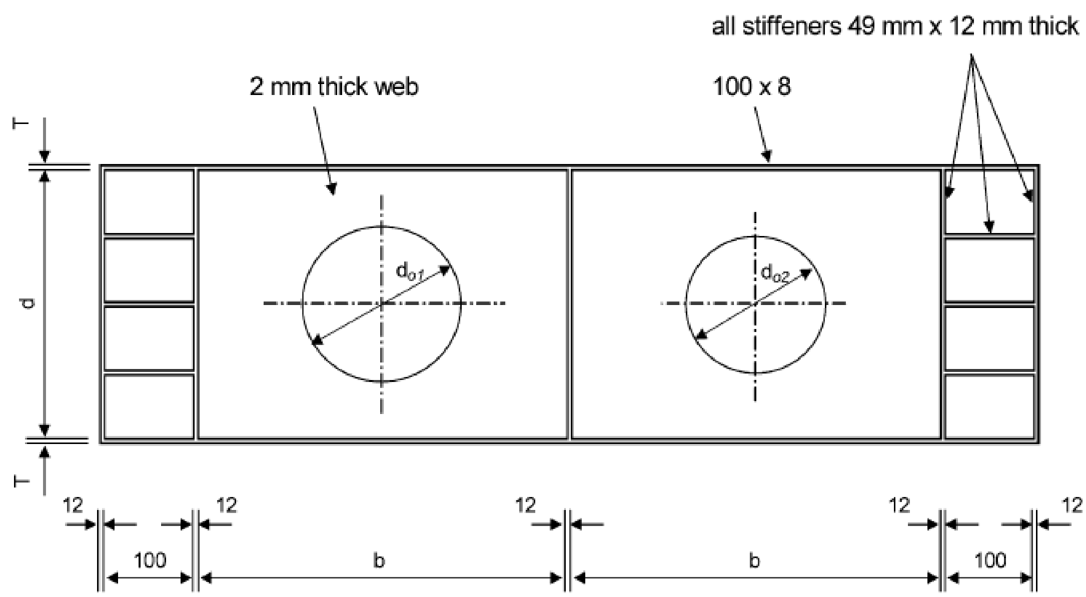


Figure-1. SPG [3].

Table-1. Specifications of tested SPG.

Tested specimen	Flange		Web		Diameter of opening		Yield stress (N/mm^2)	
	T (mm)	Width (mm)	b (mm)	d (mm)	d_{01} (mm)	d_{02} (mm)	Flange	Web
SPG	8	100	750	500	350	400	245	230

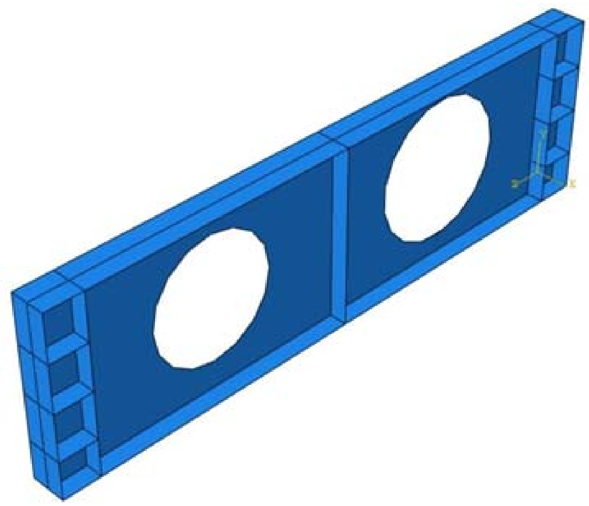


Figure-2. Simulated SPG for modelling verification.

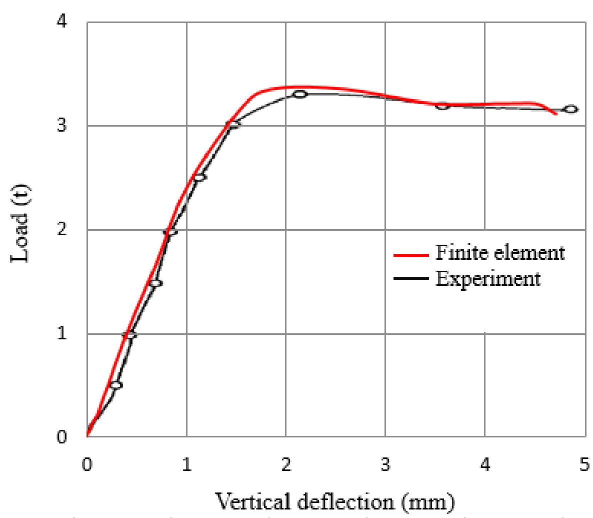


Figure-3. Load-vertical deflection curves for SPG.

4. RESULTS AND DISCUSSIONS OF DEVELOPED SPGs

The SPG has been developed using the elliptical web openings. In the view of the verified finite element modelling, the proposed modelling has been applied for the extensive analyses of the SPGs. Different variables have been considered for the analyses of the SPGs. Table-2 summarises the specifications and obtained ultimate strengths of the studied SPGs. In the SPGs designations, E, H, V, F, and S respectively represent Elliptical, Horizontal, Vertical, Frame, and Stiffeners. The dimensions of the simulated SPGs are the same and equal to those of the experimentally tested specimen. The simulated SPGs are presented in Figure-4. The variables include number of the openings, arrangement of the openings, using the steel frame around the openings, utilising the diagonal steel stiffeners, and thicknesses of the steel frame and the diagonal steel stiffeners. In addition, effects of the variables on the performance of the SPGs are discussed in the following.

4.1 Effect of number of openings

To investigate the effect of number of openings on the SPGs, two SPGs with 1 and 2 horizontal openings on each side of them have been simulated and designated as E1H and E2H which totally have 2 and 4 horizontal openings with the equal total area. According to the mentioned results in Table-2, increasing the number of the horizontal openings from 2 to 4 reduces the ultimate strength for 8.3%. Therefore, although the total area of the openings is equal, increasing the number of the openings has an adverse effect on the ultimate strength of the SPGs.

4.2 Effect of arrangement of openings

One SPG with 2 vertical openings on its each side has also been simulated to examine the effect of the arrangement of the openings. This SPG has been labelled as E2V which totally comprises 4 vertical openings. Comparison of the analyses results of E2H and E2V in Table-2 demonstrates that as the arrangement of the openings changes from horizontal to vertical, the ultimate strength decreases 22.7%. Thus, the horizontal openings are preferable to the vertical ones. Consequently, the arrangement of the openings in the SPGs significantly influences their performance.

4.3 Effect of using steel frame around openings

The steel frame has been used around the 2 horizontal openings on each side of the SPG in order to evaluate its effect. By the comparison of the obtained ultimate strengths for E1H and E1HF2, it can be observed that the ultimate strength has been increased 20.8% for E1HF2 compared with that of E1H. Accordingly, using the steel frame around the openings can enhance the ultimate strength.

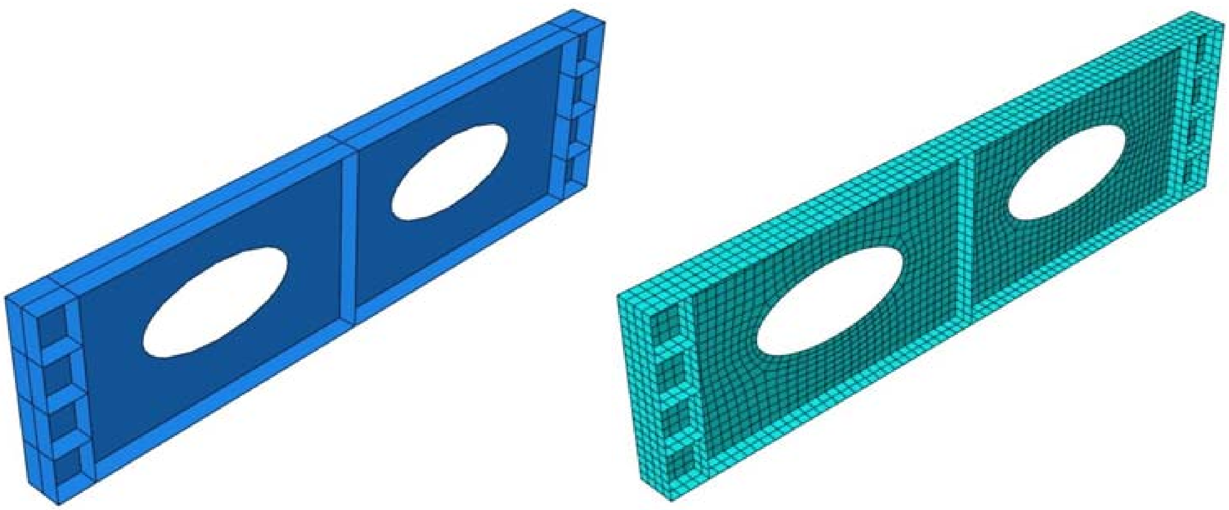
4.4 Effect of utilising diagonal steel stiffeners

Diagonal steel stiffeners have been employed to connect the frame around the openings to the corners of the SPGs which have made E1HF2S2. Using the diagonal steel stiffeners in E1HF2S2 compared with E1HF2 leads to 6.9% enhancement of the ultimate strength. As a consequence, utilising the steel stiffeners improves the ultimate strength.

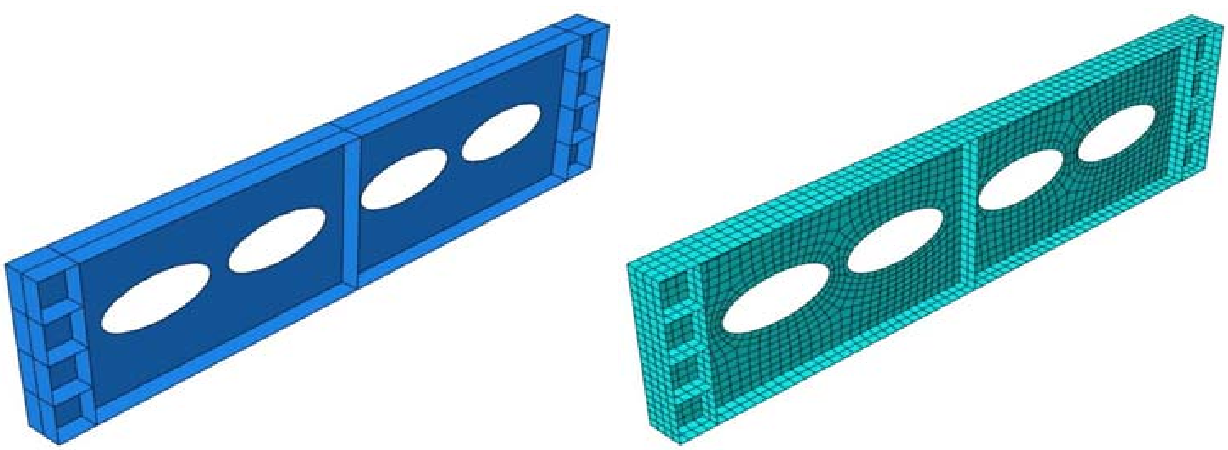
ARPN Journal of Engineering and Applied Sciences

Table-2. Specifications and obtained ultimate strengths of SPGs with elliptical web openings.

No.	SPG label	Number of horizontal opening on each side	Number of vertical opening on each side	Frame (mm)	Stiffener (mm)	Ultimate strength (kN)
1	E1H	1	-	-	-	24
2	E2H	2	-	-	-	22
3	E2V	-	2	-	-	17
4	E1HF2	1	-	2	-	29
5	E1HF2S2	1	-	2	2	31
6	E1HF2S4	1	-	2	4	32
7	E1HF4S2	1	-	4	2	35
8	E1HF4S4	1	-	4	4	36



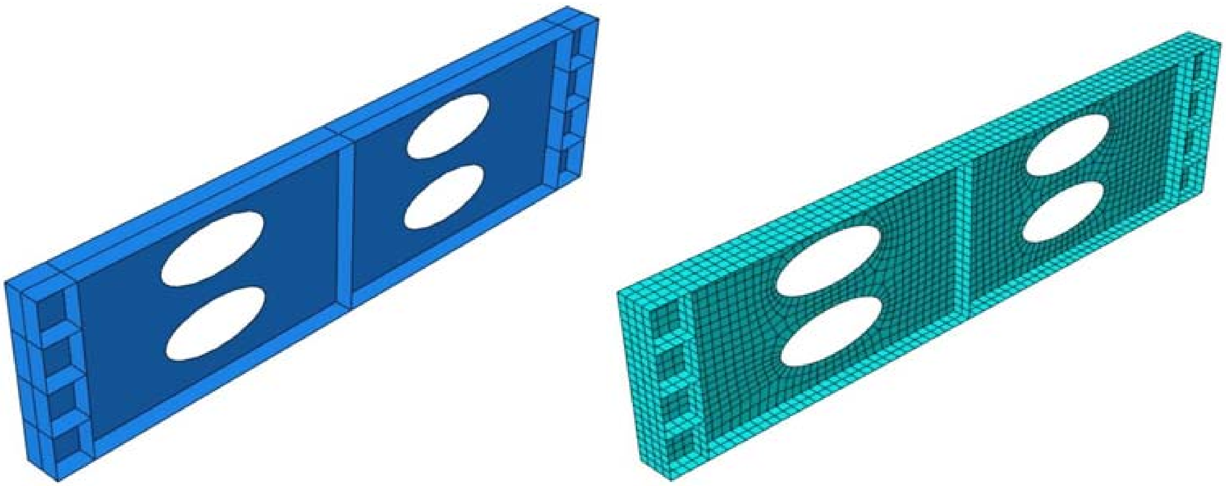
E1H



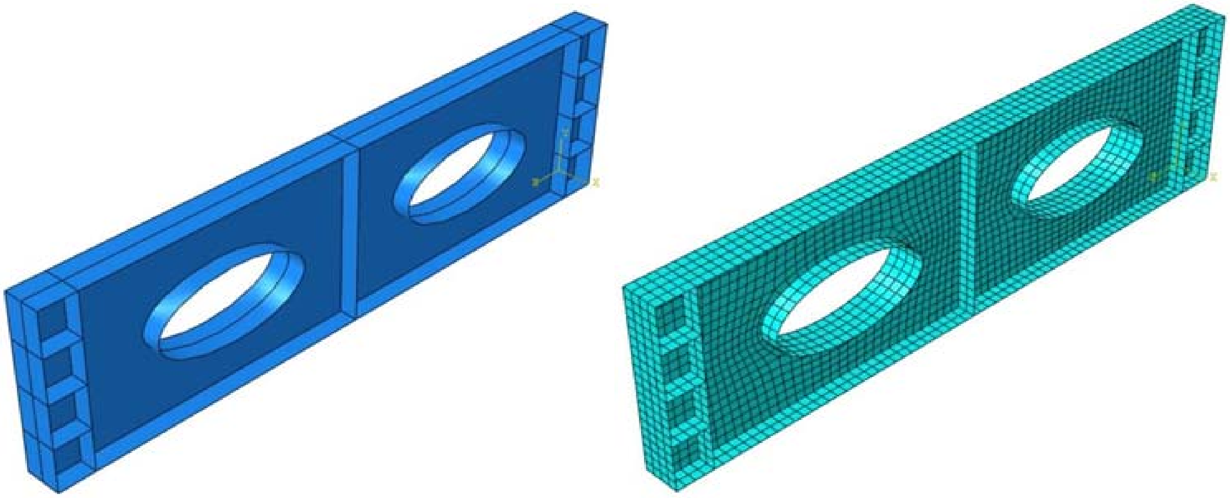
E2H

Figure-4. SPGs with elliptical web openings.

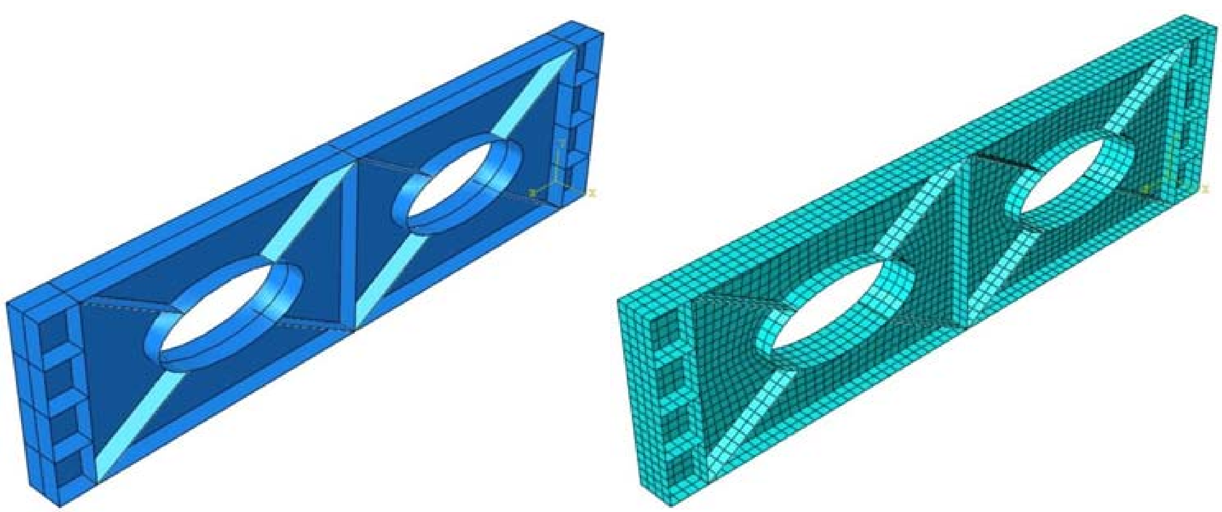
ISSN 1819-6608



E2V



E1HF2



E1HF2S2, E1HF2S4, E1HF4S2, E1HF4S4

Figure-4. Continued.

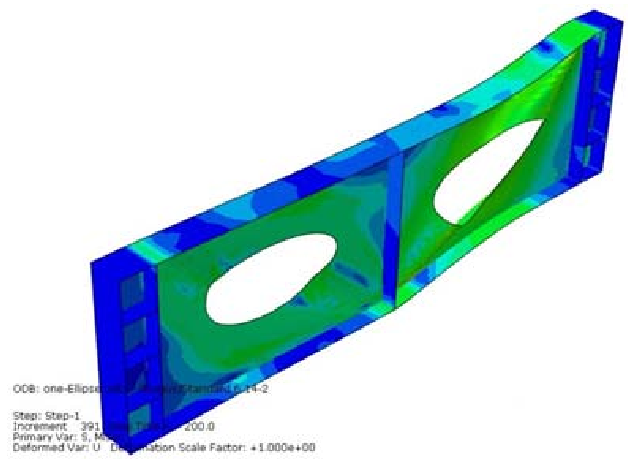
ARPN Journal of Engineering and Applied Sciences

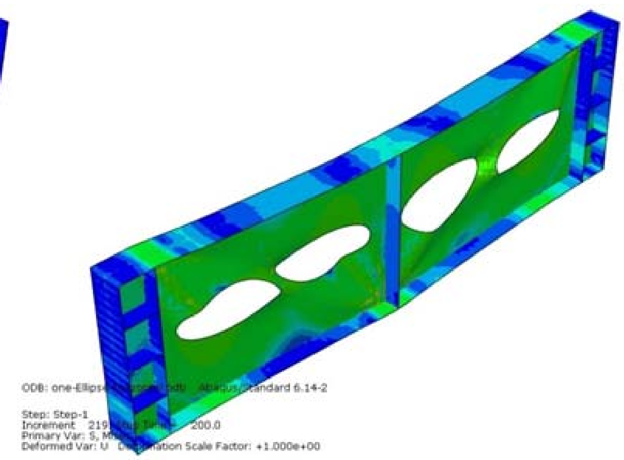
4.5 Effect of thicknesses of steel frame and diagonal steel stiffeners

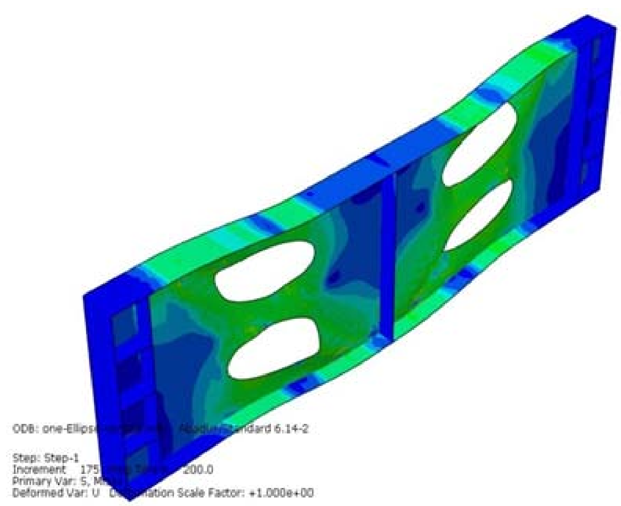
Thickness of 4 mm has also been adopted for the steel frame and diagonal steel stiffeners to evaluate the effect of their thicknesses on the SPGs. Enhancing the steel frame thickness of E1HF2S2 from 2 mm to 4 mm in E1HF4S2 enhances its ultimate strength for 12.9%. However, increasing the thickness of the diagonal steel stiffeners from 2 mm (E1HF2S2) to 4 mm (E1HF2S4) results in 3.2% improvement of the ultimate strength (Table-2). As a conclusion, increasing the thickness of the steel frame and/or stiffeners advances the ultimate strength of the SPGs; however, the enhancement of the steel frame thickness has more remarkable effect on improving the ultimate strength of the SPGs than increasing the stiffeners thickness.

4.6 Failure modes of SPGs

Figure-5 illustrates the failure modes of the SPGs. The applied load is distributed as shear stress in the SPGs. When 4 horizontal openings are used (E2H), the stress is distributed equally over the openings which leads to less deflection of the SPG compared with that of the SPG with 2 horizontal openings (E1H). On the other hand, employing 4 vertical openings (E2V) causes the weakness of the SPGs in which most of the stresses are absorbed around the openings. Utilising the frame around the openings and/or diagonal stiffeners (E1HF2, E1HF2S2, E1HF2S4, E1HF4S2, and E1HF4S4) makes the SPGs stronger to carry larger loads for much longer time so that they reach their plastic state.


E1H


E2H


E2V

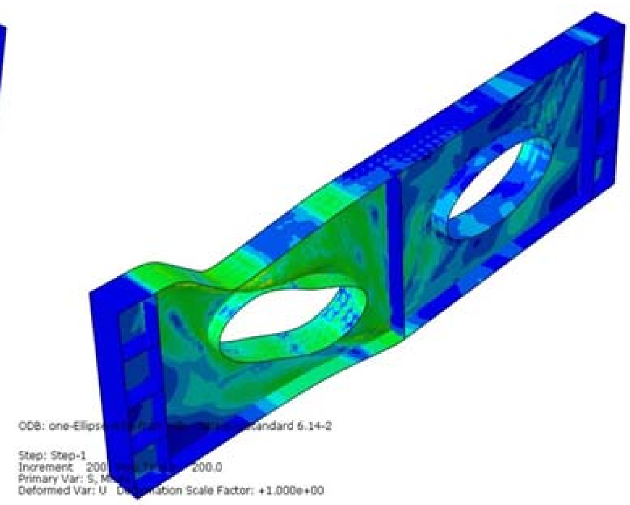
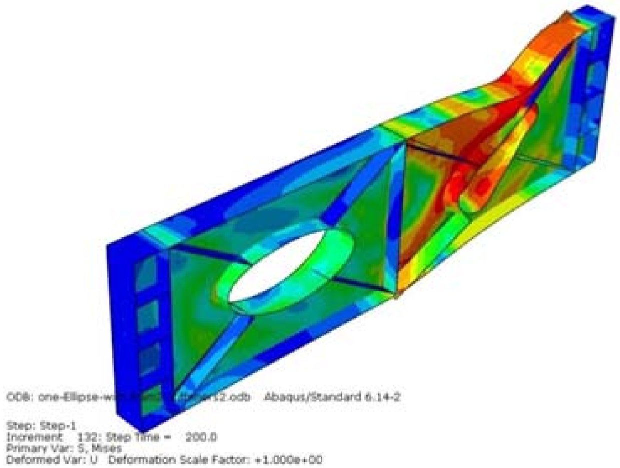

E1HF2

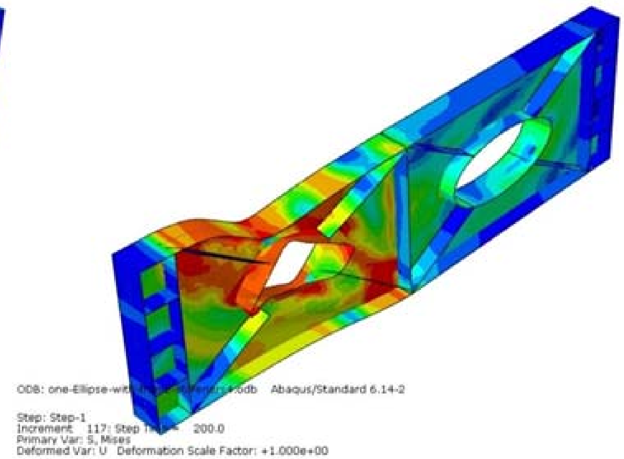
Figure-5. Failure modes of SPGs.

VOL. 15, NO. 4, FEBRUARY 2020 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

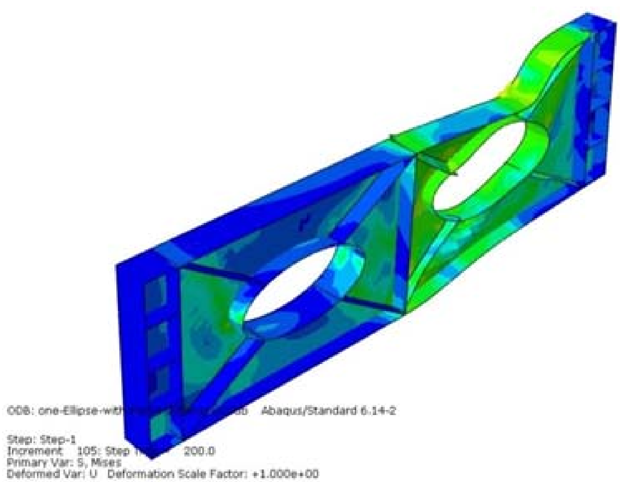
www.arpnjournals.com



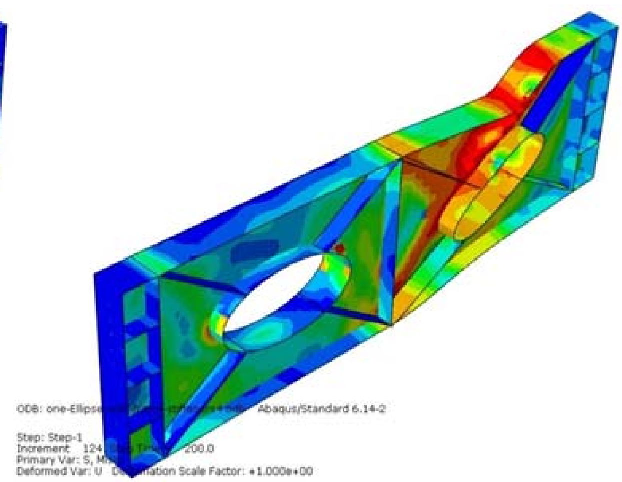
E1HF2S2



E1HF2S4



E1HF4S2



E1HF4S4

Figure-5. Continued.

5. CONCLUSIONS

The SPGs with the elliptical web openings were analysed in this paper. The finite element software ABAQUS was used to analyse the SPGs. The accuracy of the modelling was demonstrated by comparing the experimental test result with the modelling result. Then, the SPGs were developed. Various variables were taken into account for the analyses of the SPGs. The variables were number of the openings, arrangement of the openings, utilising the steel frame, using the diagonal steel stiffeners, and thicknesses of the steel frame and the diagonal steel stiffeners. The effects of these variables on the performance of the SPGs were evaluated. It was resulted that enhancing the number of the openings adversely influences the ultimate strength. The arrangement of the openings in the SPGs remarkably affects their performance. The horizontal openings are more desirable than the vertical ones. Utilising the steel frame around the openings increases the ultimate strength. Also, using the steel stiffeners develops the ultimate strength. Furthermore, increasing the thickness of the steel frame and/or diagonal steel stiffeners improves the ultimate strength. Nonetheless, enhancing the frame thickness is more considerably effective on increasing the ultimate strength than the enhancement of the stiffeners thickness. Failure modes of the SPGs were evaluated.

REFERENCES

[1] T. Höglund. 1971. Strength of thin plate girders with circular or rectangular web holes without web stiffeners. Technical licentiate. Department of Building Statics and Structural Engineering. The Royal Institute of Technology. Stockholm. Sweden. 353-365.

[2] R. Narayanan and K. C. Rockey. 1981. Ultimate load capacity of plate girders with webs containing circular cut-outs. Proceedings of the Institution of Civil Engineers. 845-862.

ARPN Journal of Engineering and Applied Sciences

[3] N. E. Shanmugam, V. T. Lian and V. Thevendran. 2002. Finite element modelling of plate girders with web openings. Thin-Walled Structures. 40: 443-464.

[4] V. T. Lian and N. E. Shanmugam. 2004. Design of horizontally curved plate girder webs containing circular openings. Thin-Walled Structures. 42: 719-739.

[5] I. Estrada, E. Real and E. Mirambell. 2007. General behaviour and effect of rigid and non-rigid end post in stainless steel plate girders loaded in shear. Part I: Experimental study. Journal of Constructional Steel Research. 63: 970-984.

[6] M. F. Hassanein and O. F. Kharoob. 2010. Shear strength and behavior of transversely stiffened tubular flange plate girders. Engineering Structures. 32(9): 2617-2630.

[7] R. Chacón, E. Mirambell and E. Real. 2013. Transversally stiffened plate girders subjected to patch loading. Part 2: Additional numerical study and design proposal. Journal of Constructional Steel Research. 84(1): 492–504.

[8] S. R. Armoosh, A. R. Khalim, and A. Sh. Mahmood. 2015. Shear response of lean duplex stainless steel plate girders. Structural Engineering and Mechanics. An International Journal. 54(6): 1267-1281.

[9] B. Liu and C. G. Soares. 2016. Analytical method to determine the crushing behaviour of girders with stiffened web. International Journal of Impact Engineering. 93: 49-61.

[10] R. Chacón, J. Herrera and L. Fargier-Gabaldón. 2017. Improved design of transversally stiffened steel plate girders subjected to patch loading. Engineering Structures. 150: 774-785.

[11] Y. Xiao, X. Y. Xue, F. F. Sun and G. Q. Li. 2018. Postbuckling shear capacity of high-strength steel plate girders. Journal of Constructional Steel Research. 150: 475-490

[12] V-H Truong, G. Papazafeiropoulos, V-T Pham and Q-V Vu. 2019. Effect of multiple longitudinal stiffeners on ultimate strength of steel plate girders. Structures. 22: 366-382.

[13] A. Bahrami, W. H. Wan Badaruzzaman and S. A. Osman. 2012. Structural behaviour of tapered concrete-filled steel composite (TCFSC) columns subjected to eccentric loading. Computers and Concrete. 9(6): 403-426.

[14] A. Bahrami, W. H. Wan Badaruzzaman and S. A. Osman. 2013. Investigation of concrete-filled steel composite (CFSC) stub columns with bar stiffeners. Journal of Civil Engineering and Management. 19(3): 433-446.

[15] A. Bahrami, W. H. Wan Badaruzzaman and S. A. Osman. 2013. Behaviour of stiffened concrete-filled steel composite (CFSC) stub columns. Latin American Journal of Solids and Structures. 10(2): 409-439.

[16] A. Bahrami and S. Matinrad. 2019. Response of steel beam-to-column bolted connections to blast loading. International Journal of Recent Technology and Engineering. 8(3): 3639-3648.

[17] A. Bahrami and M. Yavari. 2019. Hysteretic assessment of steel-concrete composite shear walls. International Journal of Recent Technology and Engineering. 8(2): 5640-5645.