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The Effect of Opening in Oriented Corrugated Web Steel Beams

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Abstract
The use of corrugated webs in steel beams has been found to increase their efficiency in resisting loads and natural frequencies. This practice has the same efficiency as flat webs with greater thickness. A study analyzing 23 beams with flat and corrugated webs using finite element numerical analysis showed that the three types of corrugated webs (trapezoidal, rectangular, and triangular) had different effects on flexure mode shapes and natural frequencies. The results showed that FE numerical analysis accurately predicted natural frequencies and flexure mode shape changes in beams with corrugated webs, resulting in a 33% reduction in thickness compared to flat beams. The triangular type was more efficient in the first mode shape, while rectangular was better for other modes. The angle for the triangular type was found to be effective in resisting mode shape and frequencies, with decreases of 0.60 and 0.78, respectively. The effect of thickness and angle was perceived to be linear for specific cases. This paper receives a light on two intentions: the first one is the flexure behavior of corrugated web beams subjected to uniform or point load, while the second one is the effect of web openings on the load capacity of steel beams with corrugated webs. Trapezoidal corrugated steel webs in the cross-sectional plane (i.e. horizontal) and oriented in in-plan direction were investigated arithmetically by the use of a Finite Element (FE) technique. In the finite element analysis, 3D models were studied using ANSYS software and a non-linear analysis was performed through thirty models of simply supported beams. Results show that using corrugated web does not have significant effect on the beam resistance to bending but increases the beam resistance to shear.

Keywords
Corrugated Web, Finite Element, Moment, Shear, Deflection, FE analysis, flexure mode shapes; natural frequencies, Steel beam

1. Introduction
A wide range of industries, including aerospace, maritime, industrial, and civil construction, have made extensive use of corrugated web plate steel beams. The first fully corrugated web H-beam in history was created in 1985 by the Northeast Heavy Machinery Institute in China. When compared to flat web plates, these beams offer superior overall stability and good out-of-plane stiffness. The web plate's corrugated shape, which sets it apart from traditional flat plates, influences the way loads behave. Both domestically and abroad, research has been done on the fatigue resistance, shear strength, stress concentration, and stability performance of corrugated web H-beams.

The I-section beams are the most frequently used shape in steel works. In structural steel design, the web is usually in charge of resistance of shear in the beam while the flanges oversee resistance of flexure. Most of section material is concentrated in the parallel flanges (Zhang et al, 2000), therefore, the compressive stress in the web exceeds the critical point prior to the yielding occurs in the manner where the flat web loses its stability and deforms transversely. To improve web resistance, corrugated web is considered a good alternative to the plane web. It produces higher stability and strength without the need for additional stiffening or the use of larger thickness. In addition, new design codes have started to consider corrugated web beams in their design instructions (Johansson et al, 2007; Eurocode 3, 2012). The early literature studies, addressed the corrugated web, focused on the vertically trapezoidal corrugation; even some companies have already started fabricating steel beams with vertical corrugated web.

On the other side, openings in the webs of steel beams are frequently required due to the installations, but the openings decrease the maximum capacity and beams' efficiency to resist the applied loads (Sayed, 2022). This paper considers a simply supported beam that has an opening under point and uniform loads as well as a simply supported beam with two openings under the same load cases.

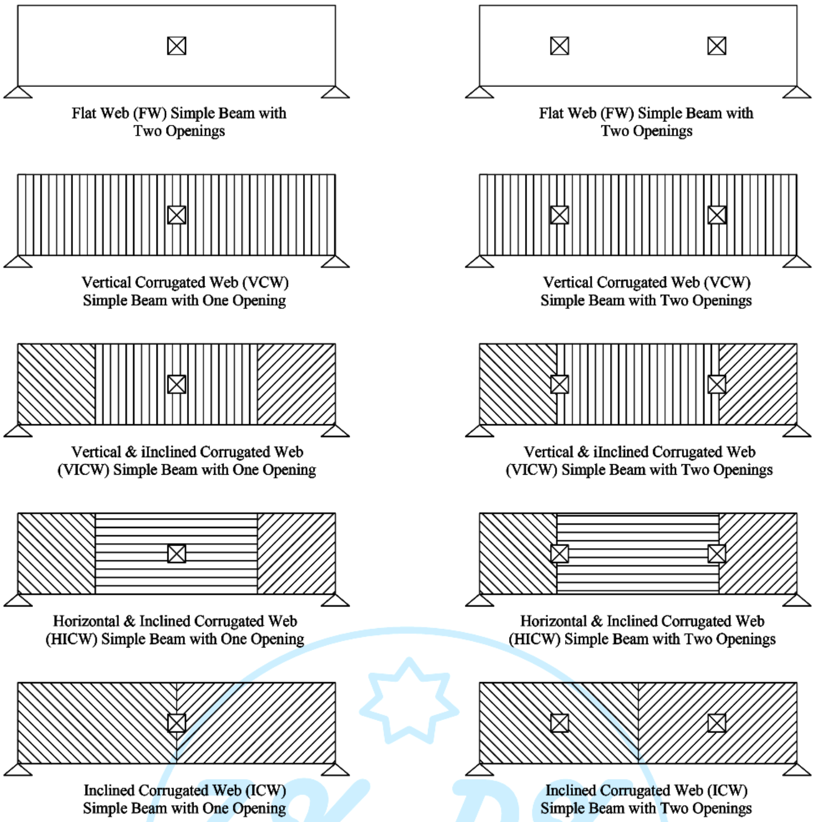


Fig. 1 Profiles of studied models of the simple beams with one & two openings

2. Literature Survey

Many scholars such as Elgaaly et al., 1996 studied the vertically trapezoidal corrugation and revealed that the shear failure of beams is due to two types of buckling: local buckling on the web for coarse corrugation, and global buckling on the web for dense corrugation. Kazemi et al., 2010 and Jamali, 2004 considered the effect of corrugation of web on the lateral torsion buckling (LTB). Jamali focused on the torsional properties and showed that torsional constant warping have an influence on the lateral torsion capacity of trapezoidal web profile section. Also, she performed LTB tests on four beams: two beams with normal flat web, and two beams with trapezoidal web profile. Her results revealed that beams with trapezoidal web profile have a greater resistance in lateral buckling.

Khaled et al., 2004 has conducted a comparison between finite element models and experimental test on corrugated web beams and proved that beams with vertical corrugated web can stand up to 30% higher load than the flat web beams. Similar results by Fatimah and Hashim, 2012 who proved that corrugated web beams have greater resistance to bending in each of minor and major axis when the web is corrugated in different angles.

In addition, Zubkov et al, 2018 proved that the bearing capacity of corrugated web beams is affected by eccentricity between the axes of webs and flanges. Other studies focused on the effect of openings of corrugated web beams such Kudryavtsev, 2019 and Morkhade et al., 2019 which proved that corrugated web beam, which has an opening, has larger capacity than flat web beam.

Sayed, 2022 used FE simulation for 51 steel beams with flat web, corrugated web and different openings and the results showed that the openings in corrugated web achieved a reduction of approximately 40% of used steel material with respect to the flat web. The shape of corrugated web also played a significant role in the web efficiency such that rectangular corrugated webs are more efficient than the triangular and trapezoidal corrugated ones.

Zhong et al., 2023 conducted numerical investigation to address the collapse behavior of steel-concrete composite frames. Their frames contained corrugated webs with and without openings. The results revealed the importance of many factors such as the opening type, diameter, end distance, and spacing on the collapse behavior. They proposed three strategies for improving the resistance of the corrugated web beams with openings: reinforcement by stub tubes, kinked plates, and a skin diaphragm.

According to shear and buckling failure, Riahi F. et al (2018) noted that the thick plate's corrugated web cannot actually attain the yield shear strength, and the buckling load is significantly influenced by the web's thickness, and it is recommended using corrugated webs, rather than the elasticity and yielding of the material, influences interaction shear buckling strength.

On the other hand, Li X. et al (2019) interested in local bearing capacity and showed that it is directly influenced by web thickness, web material strength, flange thickness, and flange material strength. Also, it seems low when the corrugations wavelength is long, or the strip is wide. Furthermore, Lin X. et al (2019) studied structural behavior of corrugated web I beams and found that up to 20% of the material weight and one-fifth of the beams section depth can be reduced by switching out traditional web beams for corrugated web beams with the same capacity, and this is also indirectly lowering CO2 emissions and the impact of humans on the environment.

And Ahmed S. Tohamy et al. (May 2022) interested in investigating the behavior of girders with corrugated webs (GCWs) having cut outs under shear loading and it showed that the failure of the section occurs mainly due to the buckling of web and distortional buckling around the cut-outs. And the connection between corrugated web and stiffeners gives efficient joints, because of providing point weld at regular intervals. And the results show that the ultimate load carrying capacity decreased with the appearance of one or more cut-outs.

Ahmed M. Sayed (2022) studied 51 steel beams with flat and corrugated webs and different openings to predict the maximum load capacity and the corresponding deflection of beams and it showed that when using rectangular corrugated webs with openings provides an efficiency higher than obtained from using triangular and trapezoidal corrugated webs. And by Increasing the aspect ratio of rectangular openings decreases the maximum load capacity of the beams independent of the type of the web, flat or corrugated. And the same efficiency as in beams with flat webs can be obtained by using beams with corrugated webs that have a smaller thickness and thereby material savings up to 40% are possible. while in flat or corrugated webs, the effect of circular openings on the maximum load capacity of the beams is less than that of rectangular openings when the width of the rectangular opening is equal to the diameter of the circular opening.

Also, Omnia Fawzy Kharoob (2019) elastic bifurcation buckling analysis was carried out on a corrugated web with a square opening. And the analysis showed that for the solid web plate, the increase in the height of the web plate leads to a decrease in the shear buckling coefficient kt value. On the other hand, for a small opening, the increase of the height of the web plate leads to clear decreases in the shear buckling coefficient value compared to the big square opening where this change may be neglected and The increase in the value of width fold (b) causes an increase in the value of shear buckling coefficient kt. and the increasing in corrugated depth causes an increase in the value of the shear buckling coefficient (kt) until $hr = 30mm$. The shear buckling coefficient decreases for the depth of corrugation more than 30mm and this decrease is high after hr=120 mm.

This study examines the bending and deflection behavior of steel beams with or without in-plane inclinations and trapezoidal web corrugation. The purpose of this study is to ascertain how the load-carrying capacity of the beam is affected by the web corrugation and the angle of corrugation in a plane direction. For these reasons, the finite element method was used. To compare the results with corrugated ones, five in-plane corrugation directions were taken into consideration when modelling regular plane web beams.

For the beam with trapezoidal-corrugated web type, the effects of end restraints, loading type, and in-plane corrugation direction were examined.

3. Finite Element Analysis

The Finite Element Method (FEM), which is also known as finite element analysis, is a common method to solve differential equations arising in engineering and mathematical modeling numerically. It was conducted by ANSYS software using SOLID45 to model beams with 3D modeling of plasticity, creep, swelling, stress stiffening, large deflection, and large strain capabilities (Hutton, 2004; ANSYS, 2017). The element is determined by eight nodes and each node has three degrees of freedom in the nodal directions.

3.1 Model Description

Corrugated web beams are built-up girders with thin-walled, corrugated web and wide plate flanges. The profiling of the web generally avoids failure of the beam due to loss of stability before the plastic limit-loading for the web is reached. In addition to benefits in production technology, the sinusoidal corrugation has the advantage over trapezoidal profiling of eliminating local buckling of the flat plate strips.

Corrugated web beams may be used as beams (roof or slab beams, structural beams) or as components subject to normal forces (columns or frame columns) virtually without structural limitations. The optimum area of application is in steel structural engineering wherever rolled profiles of structural height greater than 450 mm or low lattice girders of structural height below approximately 1,800 mm were formerly used.

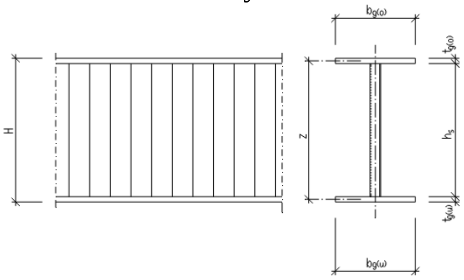


Fig. 2 Specimen details of the studied models

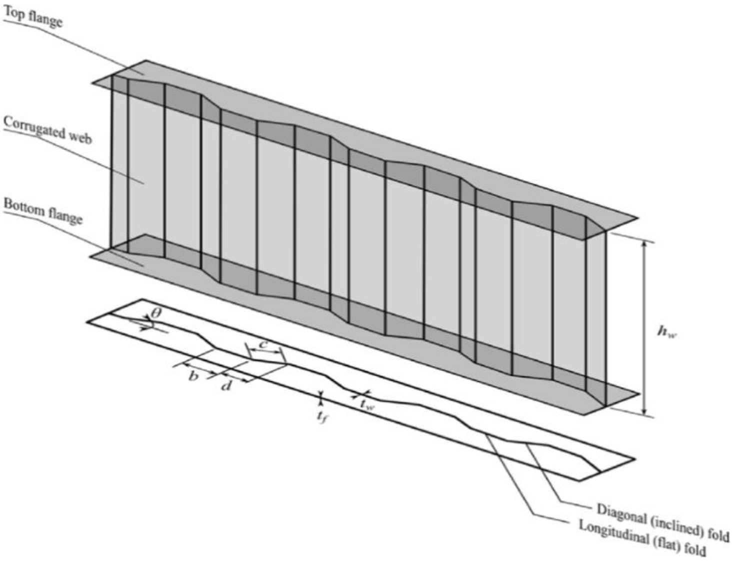


Fig. 3 Couragted Web Panel

3.1.1 Input Data

Figure 4 shows the geometry and element loads represented as pressure or surface loads on the element faces.

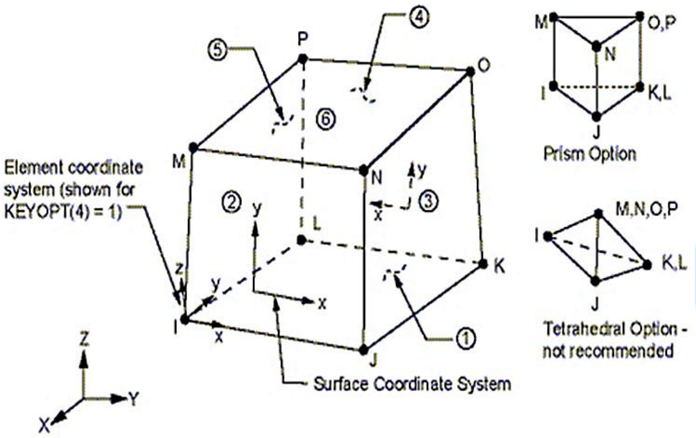


Fig. 4 Solid 45 3-D structural solid [10]

3.1.2 Output Data

Figure 5 shows the surface stress outputs and the coordinate systems for different faces. The other surface coordinate systems follow similar orientations as indicated by the pressure face node description.

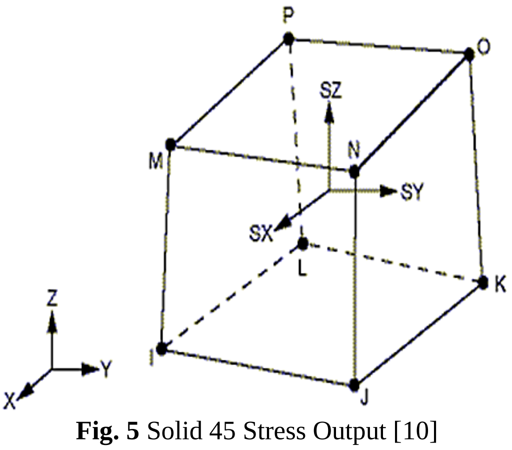


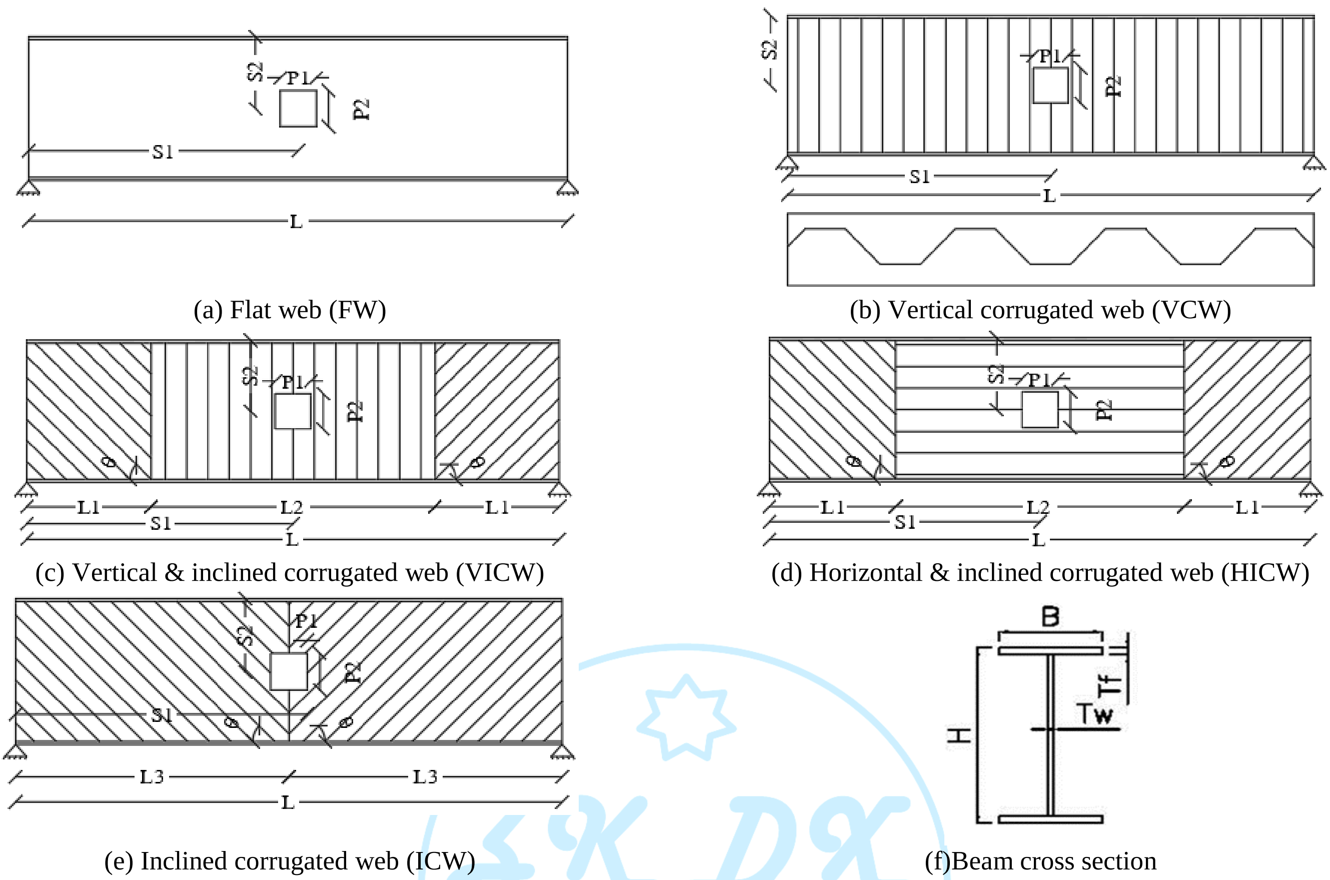
Fig. 5 Solid 45 Stress Output [10]

3.2 Material Modeling

The Finite Element Method (FEM), sometimes referred to as finite element analysis, is a popular method for numerically solving differential equations arising in engineering and mathematical modeling. ANSYS and SOLID 45 are software used for the 3D modeling of plasticity, creep, swelling, stress stiffening, large deflection, and large strain capabilities (Hutton, 2004; ANSYS, 2017).

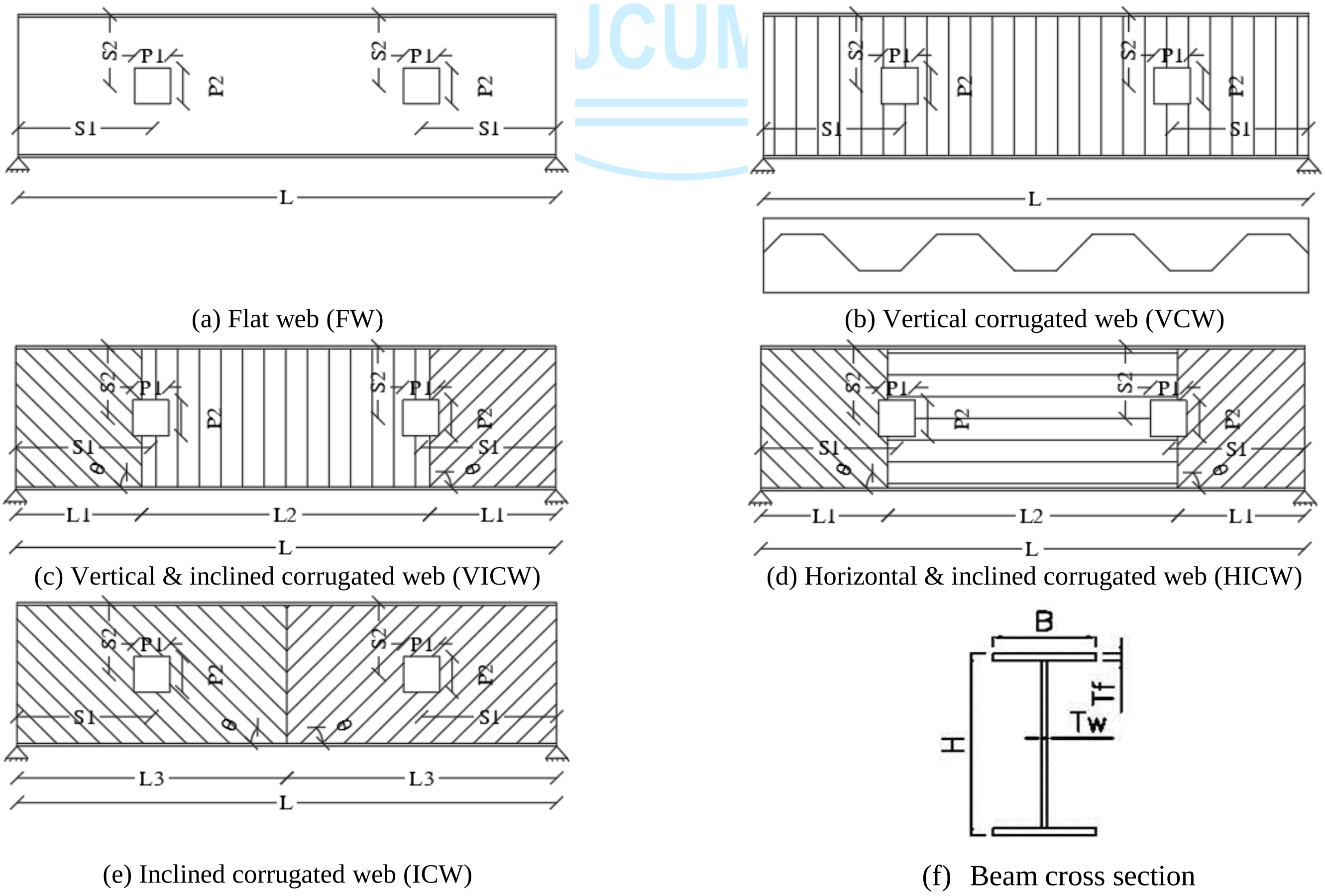
3.2.1 Boundary Elements Dimensions and Properties

Figures 6 to 8 show corrugation profiles of the selected beams while Table 2 and 3 show the used parameters shown on these figures.



(a) Flat web (FW)
(b) Vertical corrugated web (VCW)
(c) Vertical & inclined corrugated web (VICW)
(d) Horizontal & inclined corrugated web (HICW)
(e) Inclined corrugated web (ICW)
(f)Beam cross section

Fig. 6 Corrugation profiles of the simple beams with one opening

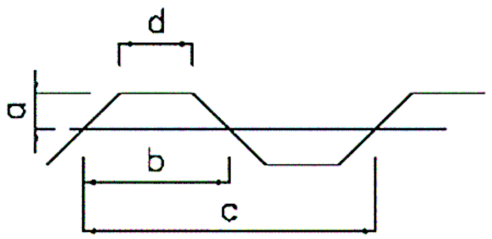


(a) Flat web (FW)
(b) Vertical corrugated web (VCW)
(c) Vertical & inclined corrugated web (VICW)
(d) Horizontal & inclined corrugated web (HICW)
(e) Inclined corrugated web (ICW)
(f) Beam cross section

Fig. 7 Corrugation profiles of the simple beams with two openings

Table 1 Used parameters for simple beams

Item		Value	Unit	Item	Value	Unit
H		2000	mm	L_1	3500	mm
T_f		40	mm	L_2	8000	mm
L		15000	mm	L_3	7500	mm
B		500	mm	S_1	3750	mm
T_w		12	mm	S_2	1000	mm
θ	(for VCW)	90	degree	P_1	1000	mm
	(for other profiles)	45	degree	P_2	1000	mm



a = 125 mm
b = 250 mm
c = 500 mm
d = 150 mm

Figure 8 Dimension of trapezoidal corrugation profile

Table 2 Used parameters for cantilever beams

Item		Value	Unit	Item	Value	Unit
H		2000	mm	T_f	40	mm
L		7500	mm	B	500	mm
T_w		12	mm	S_1	1875	mm
Ø	(for VCW)	90	degree	S_2	1000	mm
	(for ICW135)	135	degree	P_1	1000	mm
	(for other profiles)	45	degree	P_2	1000	mm

3.2.2 *The Parameter Illustration of Steel Plate Shear Wall Structures with Different Structural Constructions*

The used different statical systems under point load (P) or uniform load (w) that are applied in the model are shown in Figure 5. The point load (P) equals 1500 kN and is applied in 15 steps from 100 to 1500. The uniform load (w) equals 400 kN/m and is applied in 30 steps from 100 to 3000.

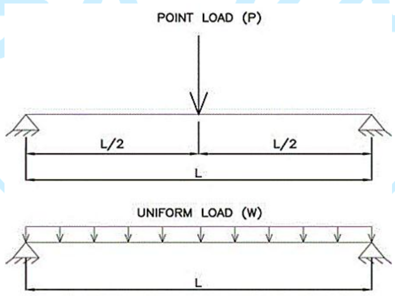


Fig. 9 Type of loading and end restraints

Table 3 Models Details

#	Model ID	Beam Title	No. of openings	With/ without corrugation	Opening Position	Load Type
1	M - 01	Flat web (FW)	1	Without	Center	Point Load
2	M - 02	Vertical corrugated web (VCW)	1	With	Center	Point Load
3	M - 03	Vertical & inclined corrugated web (VICW)	1	With	Center	Point Load
4	M - 04	Horizontal & inclined corrugated web (HICW)	1	With	Center	Point Load
5	M - 05	Inclined corrugated web (ICW)	1	With	Center	Point Load
6	M - 06	Flat web (FW)	1	Without	Center	Uniform Load
7	M - 07	Vertical corrugated web (VCW)	1	With	Center	Uniform Load
8	M - 08	Vertical & inclined corrugated web (VICW)	1	With	Center	Uniform Load
9	M - 09	Horizontal & inclined corrugated web (HICW)	1	With	Center	Uniform Load
10	M - 10	Inclined corrugated web (ICW)	1	With	Center	Uniform Load
11	M - 11	Flat web (FW)	2	Without	@ S1	Point Load
12	M - 12	Vertical corrugated web (VCW)	2	With	@ S1	Point Load
13	M – 13	Vertical & inclined corrugated web (VICW)	2	With	@ S1	Point Load
14	M - 14	Horizontal & inclined corrugated web (HICW)	2	With	@ S1	Point Load
15	M - 15	Inclined corrugated web (ICW)	2	With	@ S1	Point Load
16	M - 16	Flat web (FW)	2	Without	@ S1	Uniform Load
17	M - 17	Vertical corrugated web (VCW)	2	With	@ S1	Uniform Load
18	M - 18	Vertical & inclined corrugated web (VICW)	2	With	@ S1	Uniform Load
19	M - 19	Horizontal & inclined corrugated web (HICW)	2	With	@ S1	Uniform Load
20	M - 20	Inclined corrugated web (ICW)	2	With	@ S1	Uniform Load

3.2.3 Material Characteristics and Constraint Condition

Figure 10 shows the assumed tri-linear elastic-plastic strain-hardening stress-strain curve. Residual stresses are not considered in this work, though it is relevant in this type of analysis.

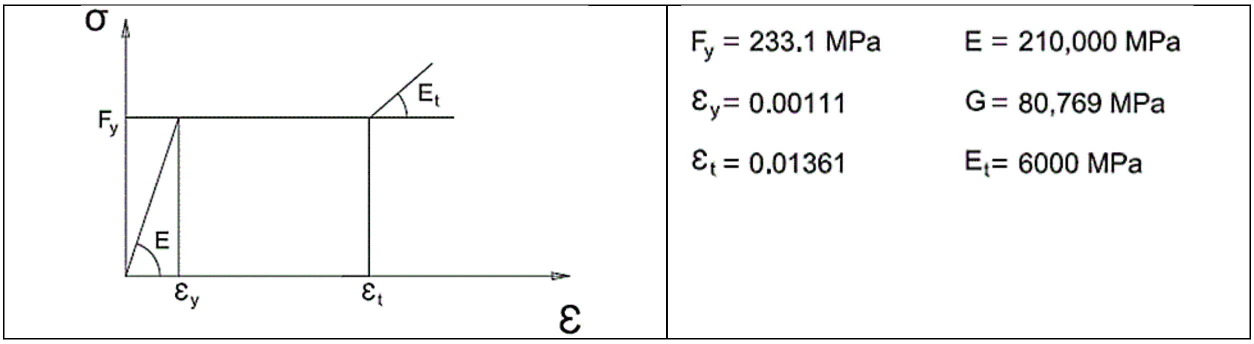


Fig. 10 Uniaxial constitutive model cons.

3.3 Computing Platform

The Finite Element Method (FEM), also known as finite element analysis, is a widely used numerical method for solving differential equations that arise in mathematical modelling and engineering. Hutton (2004) and ANSYS (2017) state that the 3D modelling of plasticity, creep, swelling, stress stiffening, large deflection, and large strain capabilities is done using ANSYS and SOLID 45 software.

4. Results Validation

In order to validate the results of this paper, an additional model has been built according to another paper to compare its results with the results obtained in this paper. The reference paper (Khalid et al, 2004) studied bending behavior for sinusoidal corrugated web I beam, it used plane, vertically and horizontally corrugated webs in experimentally and finite element modelling cases, and both were in good agreement with each other. The results showed that vertically corrugated web beams were able to withstand loads up to 32.8% higher than planar webs. Also, web corrugation contributed more to bending capacity in the vertical direction than in the horizontal direction. In addition, by employing vertically corrugated web, the weight of the beam could be decreased by 13.6%, and finally, greater corrugation radius results in higher moment capacity. This paper selected one of plane web models and simulated it by using ANSYS software to validate results in solid element model. The results were compared with analytical ones in the reference paper. Figure 11 shows the ultimate displacement (9.7 mm) at ultimate load (110 KN) in one case of plane web model with dimensions (b_f = 75 mm, T_f = 6 mm, H = 113.6 mm, T_w = 4.5 mm, L = 600 mm), while the average ultimate displacement (10 mm) at ultimate load (113.5 KN) in the reference paper (Khalid et al, 2004) as shown in Table 4. Finally, this simulation is in good agreement with the reference paper.

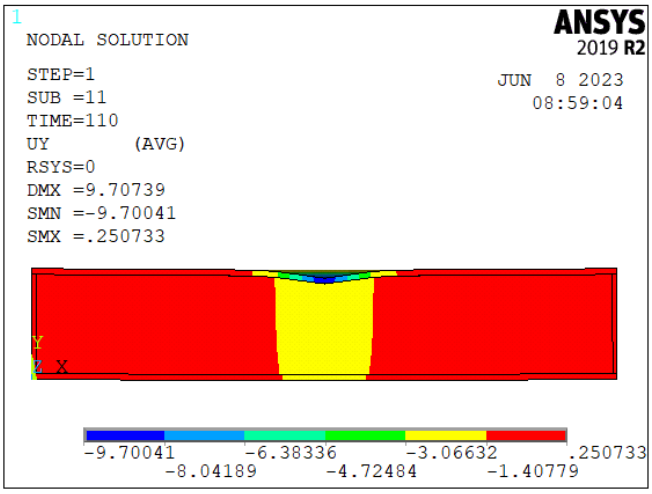


Fig. 11 Displacement results for the simulated beam

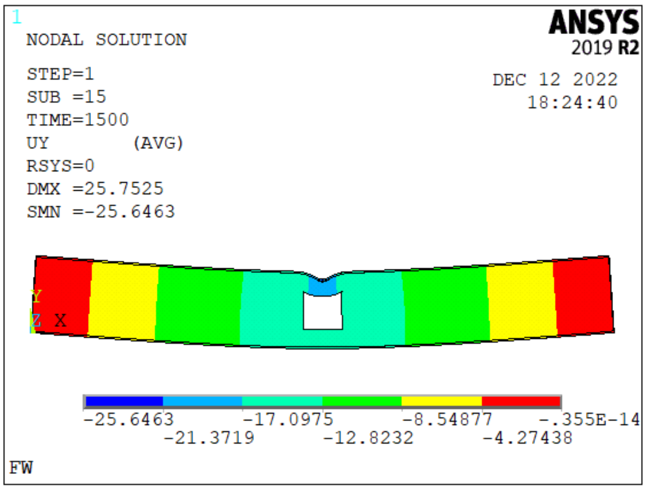
Table 4 Experimental and theoretical results for the simulated model

Experimental results		Theoretical results		Simulated model results	
Average yield load (KN)	Average ultimate load (KN)	Average ultimate load (KN)	Average ultimate displacement (mm)	Ultimate load (KN)	Average ultimate displacement (mm)
54.79	113.5	113	10	110	9.7

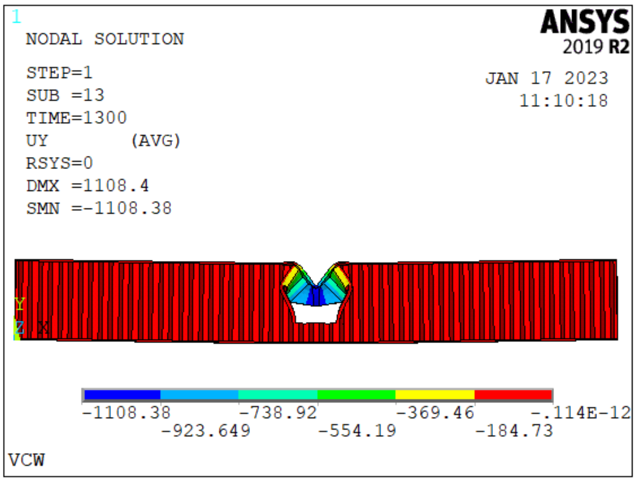
5. Results and Discussion

A total of 20 FE models were created and tested using ANSYS software package. All models were assigned with different geometry and same material properties to explore the influences of each variable to the beam's behavior. Load-displacement graphs, load-bending stresses graphs and load-shear stresses graphs were plotted for each case. Then all values for different models were discussed.

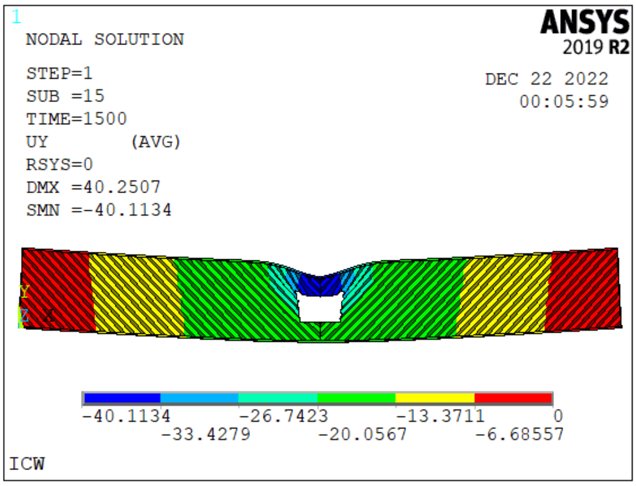
For the case of point load (P) with one opening, the deflection behavior, bending stresses and shear stresses are collected from the ANSYS models. For example, Figure 9 shows the deflection behavior. The supportive graphs (at top flange middle point in the mid span for deflection and bending stress and 500 mm away from support for shear stress) are shown in Figure 13. Results are compared at point of failure of the weakest element as shown in Table 5 and Table 6 at the same points.



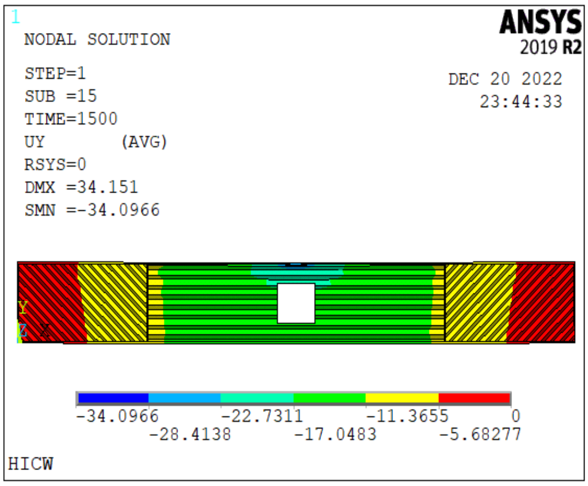
(a) Flat web (FW)



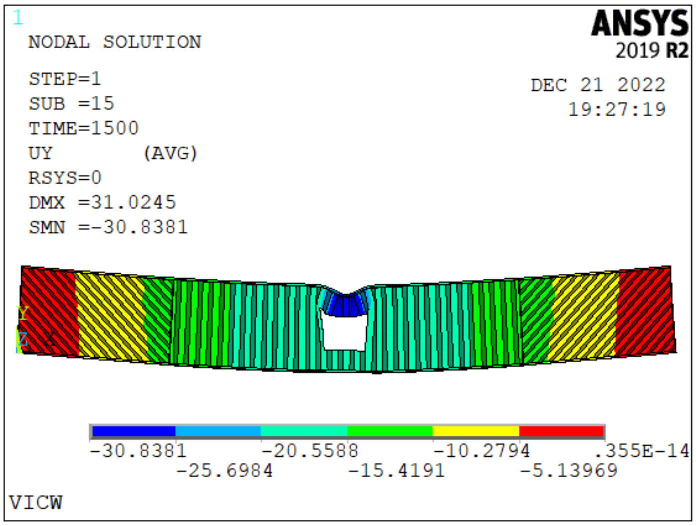
(b) Vertical corrugated web (VCW)



(c) Inclined corrugated web (ICW)

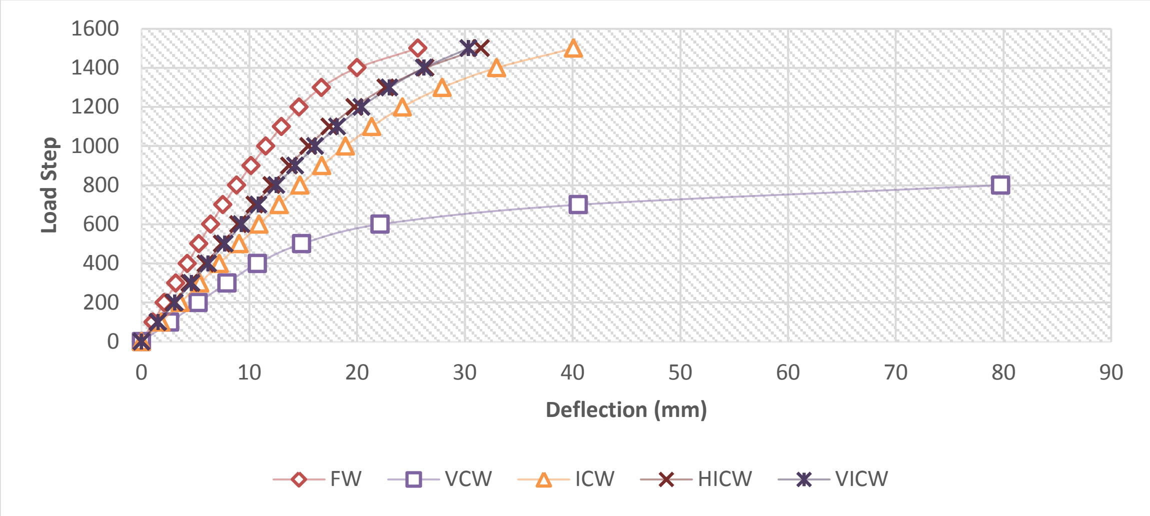


(d) Horizontal & inclined corrugated web (HICW)

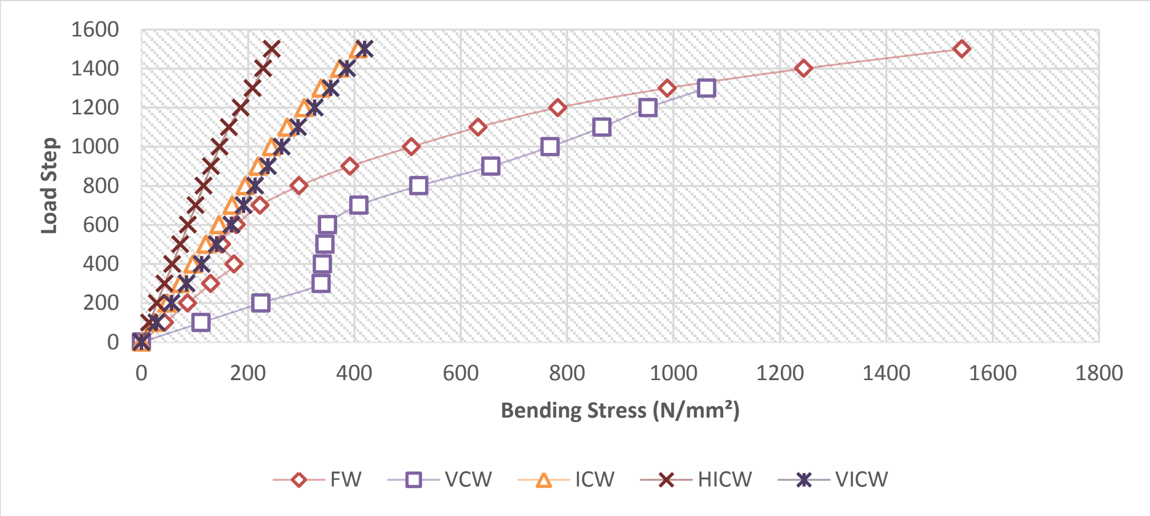


(e) Vertical & inclined corrugated web (VICW)

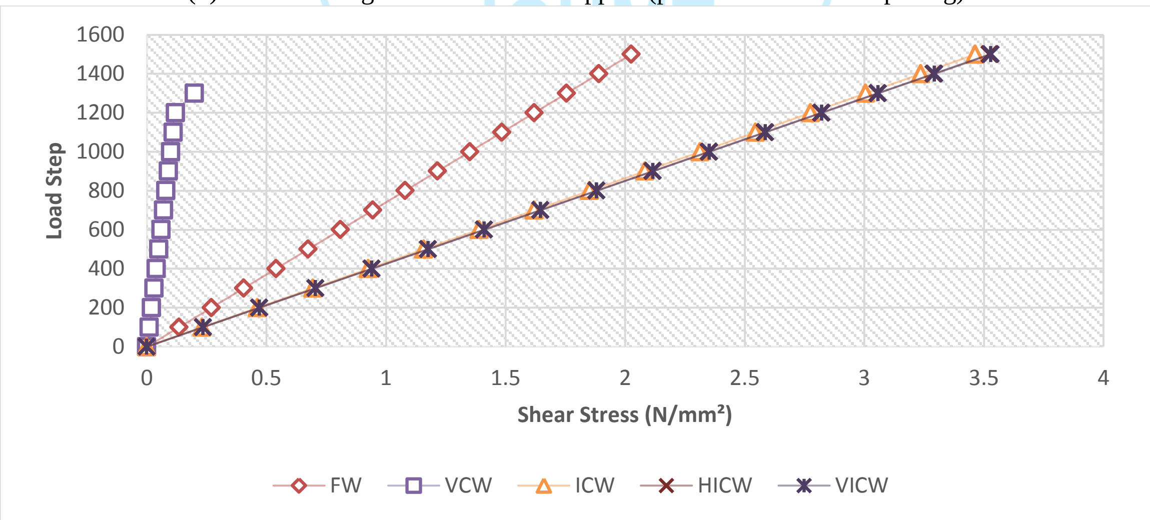
Fig. 12 Deflection behavior of the steel beams (point load with one opening)



(a) Load-deflection curve at support (point load with one opening)



(b) Load-bending stresses curve at support (point load with one opening)



(c) Shear stress of the steel beams (point load with one opening)

Fig. 13 Stresses and deflection of the steel beams (point load with one opening)

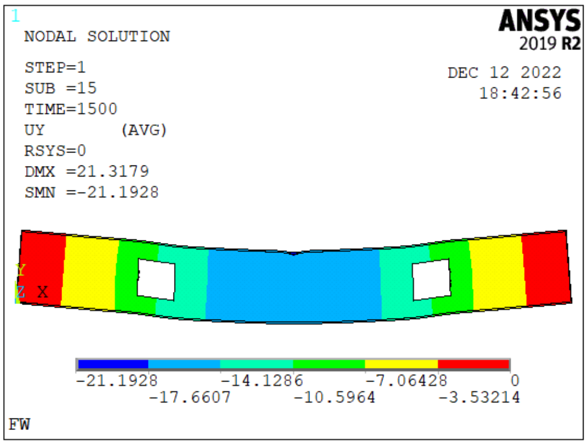
Table 5 Comparison between the behaviors of different profiles under point load with one opening

Profile	Values at Point Load 1300 kN			
	Deflection (mm)	Deflection ration with respect to FW	Bending Stress (N/mm^2)	Bending Stress ration with respect to FW
FW	16.72	1.00	988.49	1.00
VCW	1072.48	0.02	1062.45	0.93
ICW	27.93	0.60	337.93	2.93
HICW	22.65	0.74	208.91	4.73
VICW	23.02	0.73	356.02	2.78

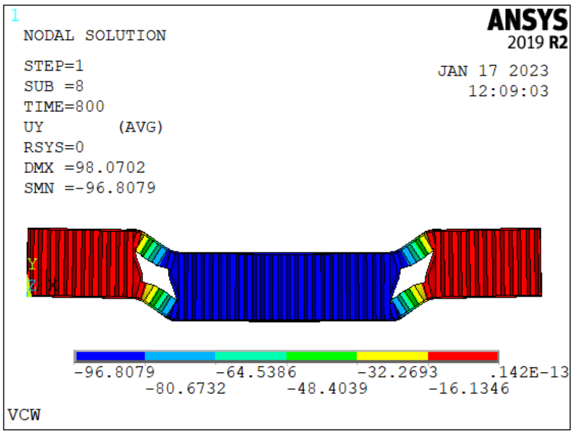
Table 6 Comparison between the behaviors of different profiles under point load with one opening

Profile	Values at Point Load 1300 kN	
	Shear Stress (N/mm^2)	Shear Stress ratio with respect to FW
FW	1.76	1.00
VCW	0.20	8.80
ICW	3.01	0.58
HICW	3.06	0.58
VICW	3.06	0.58

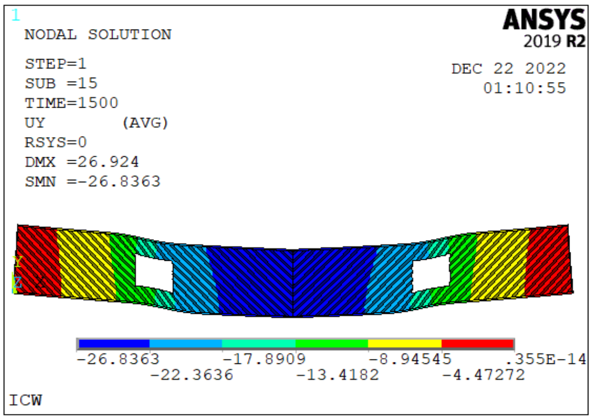
For the case of point load (P) with two openings, the deflection behavior, bending stresses and shear stresses are collected from the ANSYS models. For example, Figure 14 shows the deflection behavior. The supportive graphs (at top flange middle point in the mid span for deflection and bending stress and 500 mm away from support for shear stress) are shown in Figure 15. Results are compared at point of failure of the weakest element as shown in Table 7 and Table 8 at the same points.



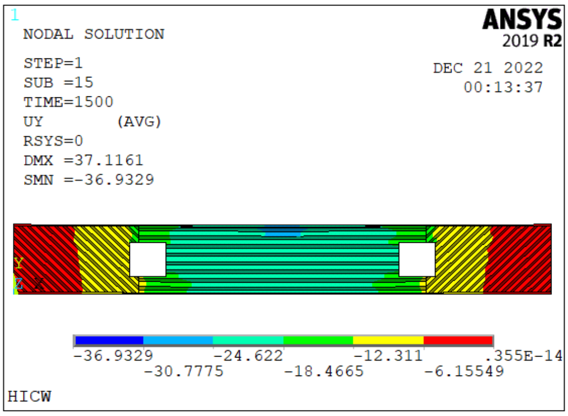
(a) Flat web (FW)



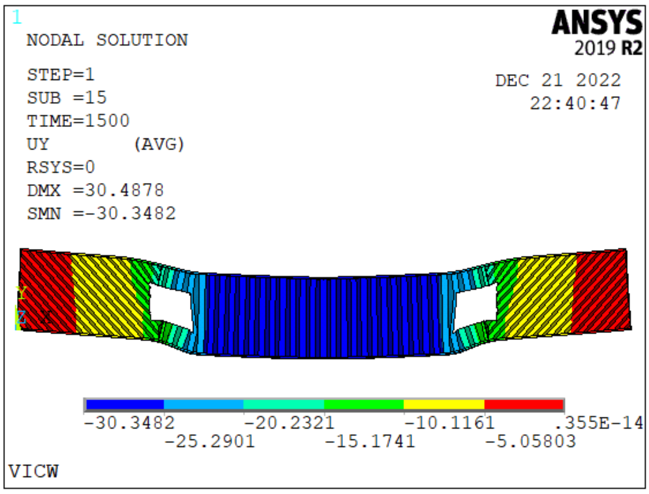
(b) Vertical corrugated web (VCW)



(c) Inclined corrugated web (ICW)

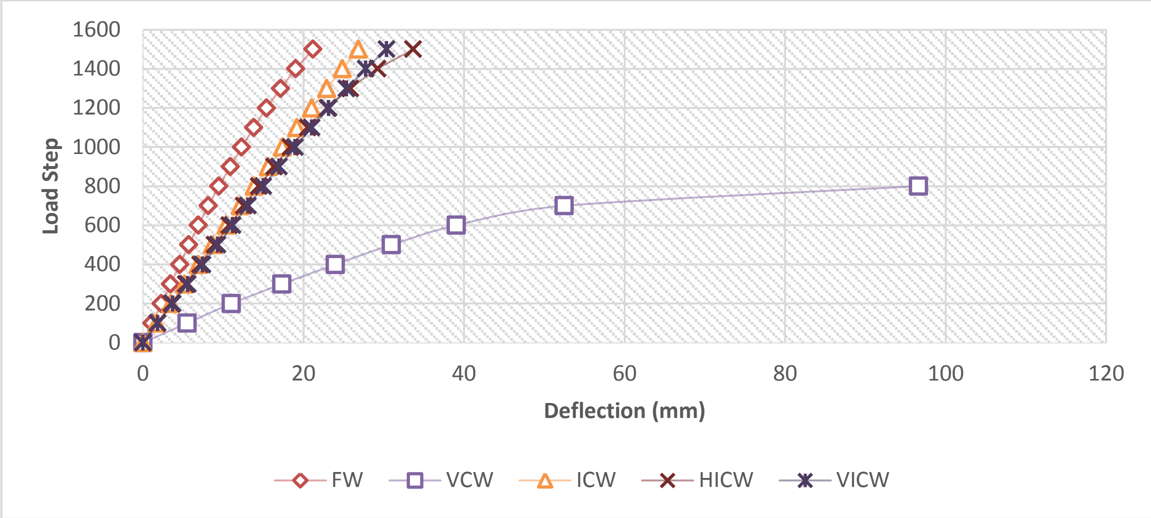


(d) Horizontal & inclined corrugated web (HICW)

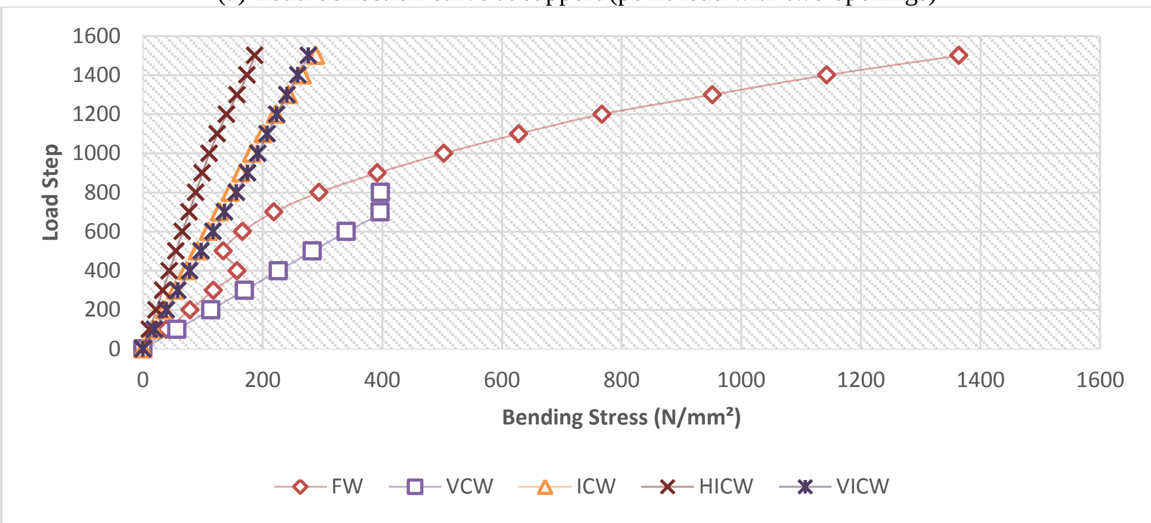


(e) Vertical & inclined corrugated web (VICW)

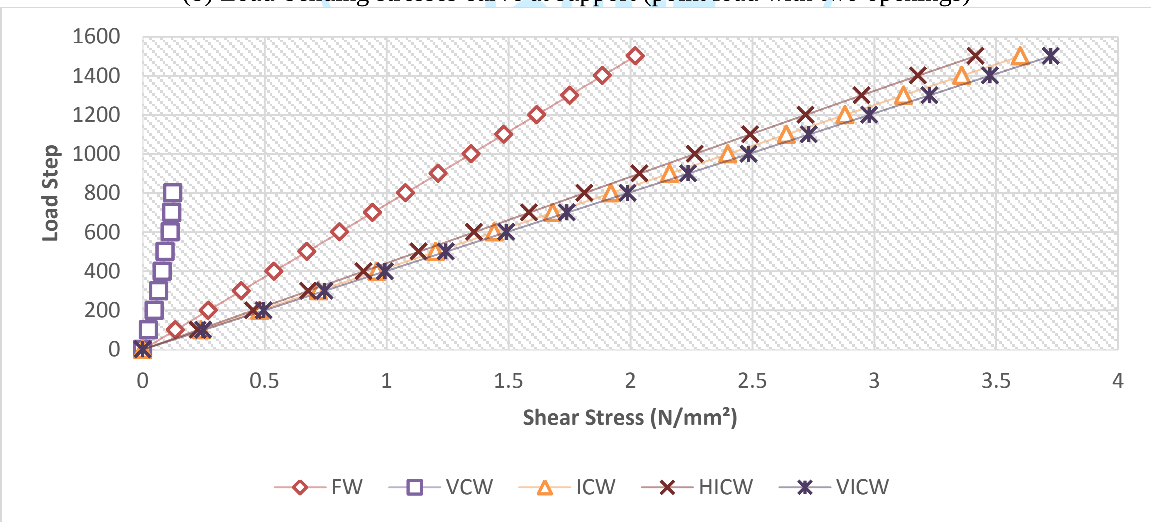
Fig. 14 Deflection behavior of the steel beams (point load with two openings)



(a) Load-deflection curve at support (point load with two openings)



(b) Load-bending stresses curve at support (point load with two openings)



(c) Shear stress of the steel beams (point load with two openings)

Fig. 15 Stresses and deflection of the steel beams (point load with two openings)

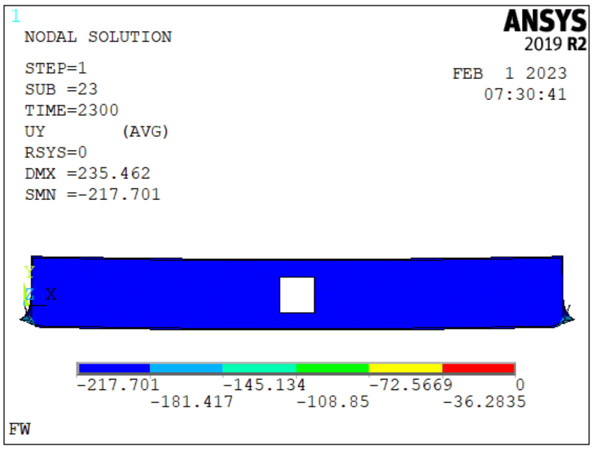
Table 7 Comparison between the behaviors of different profiles under point load with two openings

Profile	Values at Point Load 800 kN			
	Deflection (mm)	Deflection ration with respect to FW	Bending Stress (N/mm^2)	Bending Stress ration with respect to FW
FW	9.48	1.00	294.28	1.00
VCW	96.64	0.10	396.74	0.74
ICW	13.87	0.68	146.09	2.01
HICW	14.45	0.66	88.41	3.33
VICW	15.00	0.63	156.23	1.88

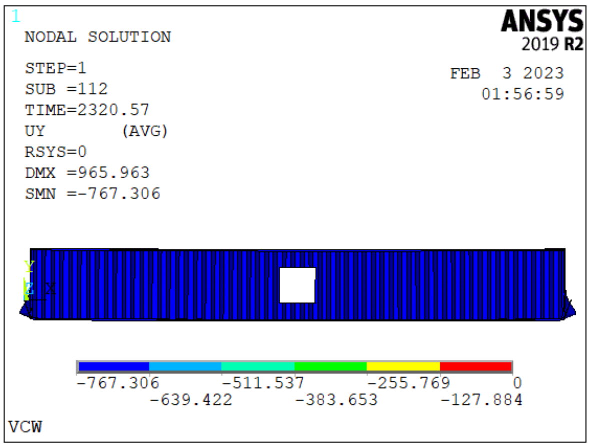
Table 8 Comparison between the behaviors of different profiles under point load with two openings

Profile	Values at Point Load 800 kN	
	Shear Stress (N/mm^2)	Shear Stress ratio with respect to FW
FW	1.08	1.00
VCW	0.12	9.00
ICW	1.92	0.56
HICW	1.81	0.60
VICW	1.99	0.54

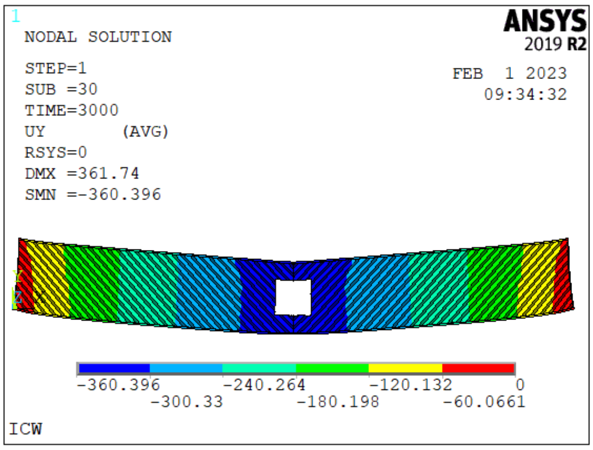
For the case of uniform load (w) with one opening, the deflection behavior, bending stresses and shear stresses are collected from the ANSYS models. For example, Figure 16 shows the deflection behavior. The supportive graphs (at top flange middle point in the mid span for deflection and bending stress and 500 mm away from support for shear stress) are shown in Figure 17. Results are compared at the point of failure of the weakest element as shown in Table 9 and Table 10 at the same points.



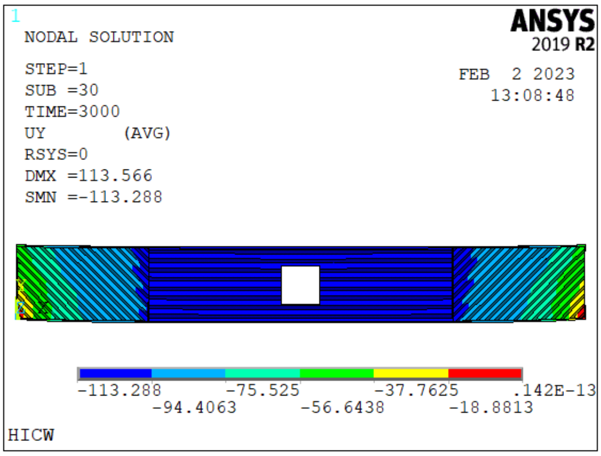
(a) Flat web (FW)



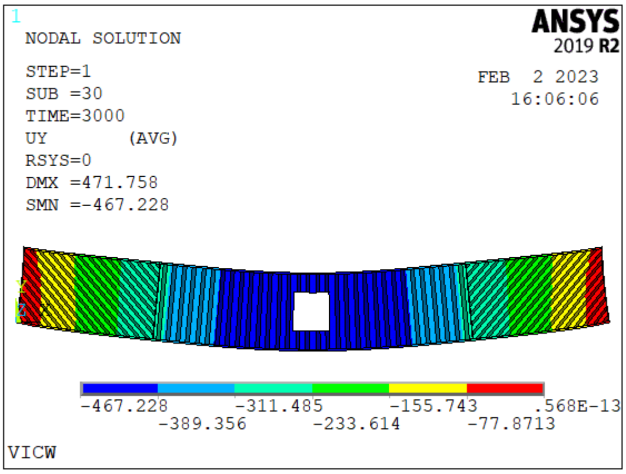
(b) Vertical corrugated web (VCW)



(c) Inclined corrugated web (ICW)

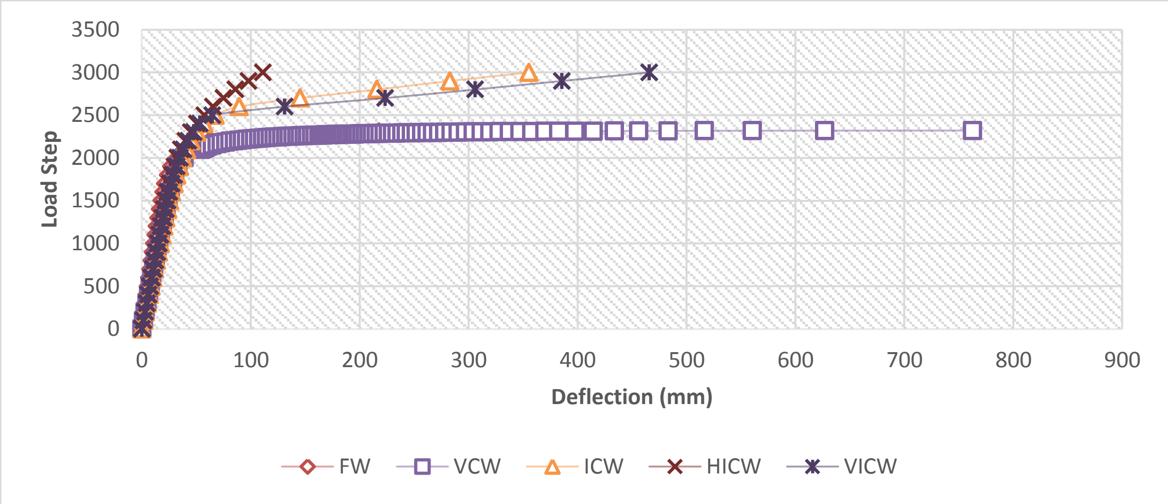


(d) Horizontal & inclined corrugated web (HICW)

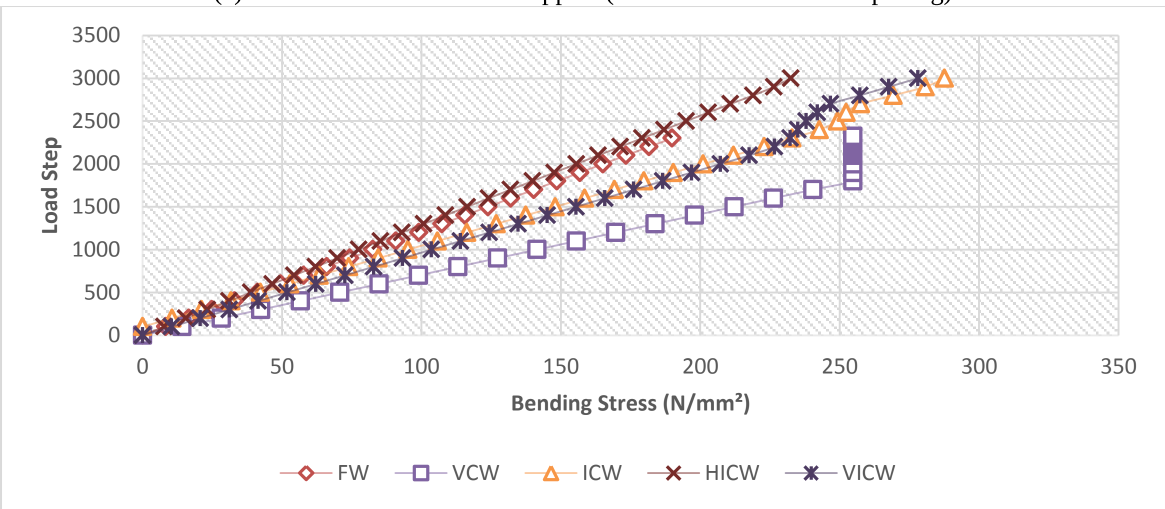


(e) Vertical & inclined corrugated web (VICW)

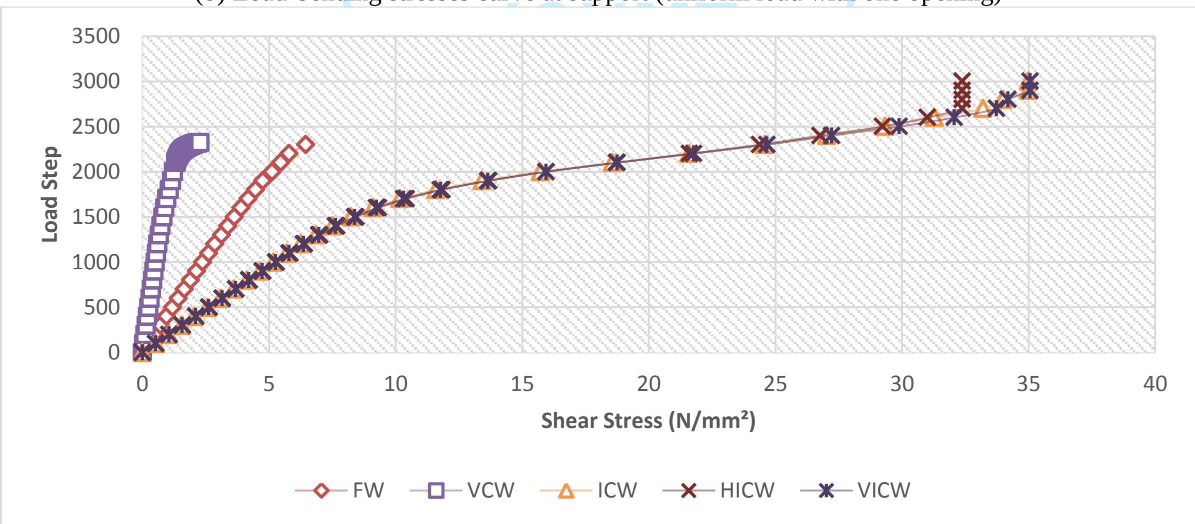
Fig. 16 Deflection Behavior of the steel beams (uniform load with one opening)



(a) Load-deflection curve at support (uniform load with one opening)



(b) Load-bending stresses curve at support (uniform load with one opening)



(c) Shear stress of the steel beams (uniform load with one opening)

Fig. 17 Stresses and deflection of the steel beams (uniform load with one opening)

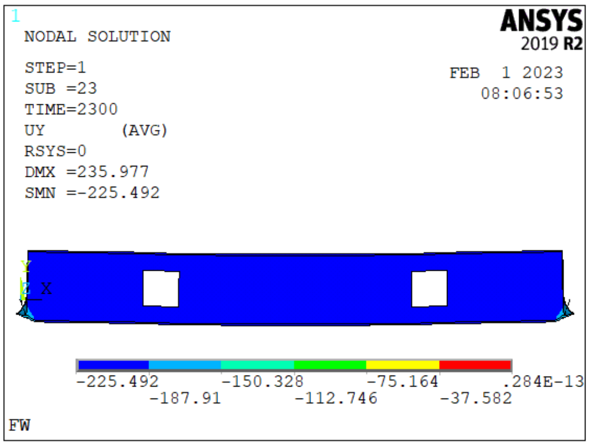
Table 9 Comparison between the behaviors of different profiles under uniform load with one opening

Profile	Values at Point Load 300 kN/m			
	Deflection (mm)	**Deflection ration with respect to FW**	**Bending Stress (N/mm^2)**	**Bending Stress ration with respect to FW**
FW	217.45	1.00	189.90	1.00
VCW	278.09	0.78	243.03	0.78
ICW	50.49	4.31	242.71	0.78
HICW	45.00	4.83	179.16	1.06
VICW	47.53	4.58	232.26	0.82

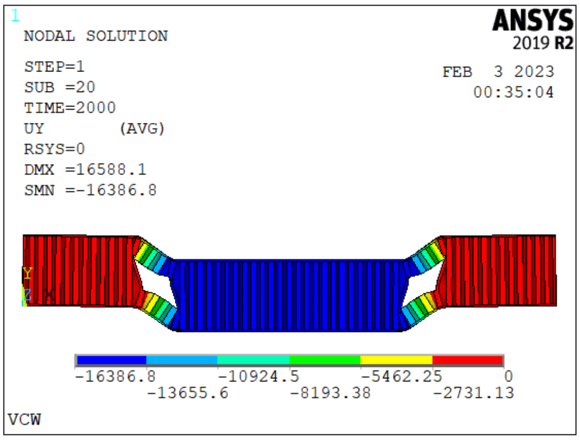
Table 10 Comparison between the behaviors of different profiles under uniform load with one opening

Profile	Values at Point Load 300 kN/m	
	Shear Stress (N/mm^2)	Shear Stress ratio with respect to FW
FW	6.45	1.00
VCW	1.98	3.26
ICW	24.57	0.26
HICW	24.37	0.26
VICW	24.66	0.26

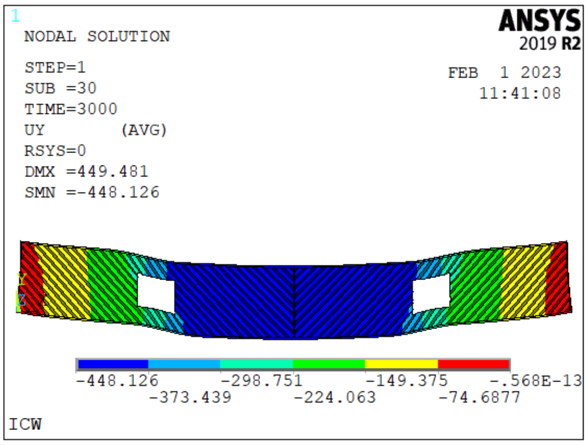
For the case of uniform load (w) with two openings, the deflection behavior, bending stresses and shear stresses are collected from the ANSYS models. For example, Figure 18 shows the deflection behavior. The supportive graphs (at top flange middle point in the mid span for deflection and bending stress and 500 mm away from support for shear stress) are shown in Figure 19. Results are compared at point of failure of the weakest element as shown in Table 11 and Table 12 at the same points.



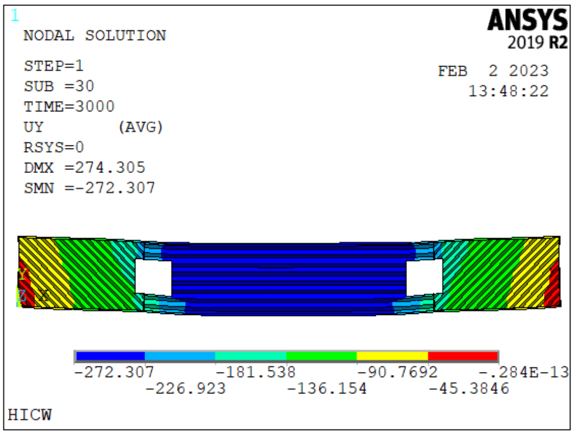
(a) Flat web (FW)



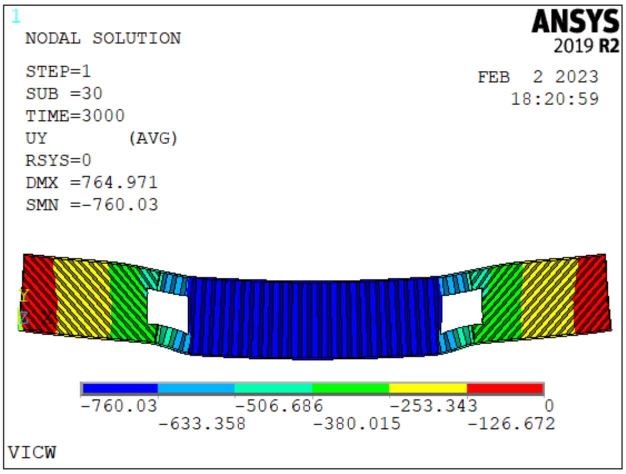
(b) Vertical corrugated web (VCW)



(c) Inclined corrugated web (ICW)

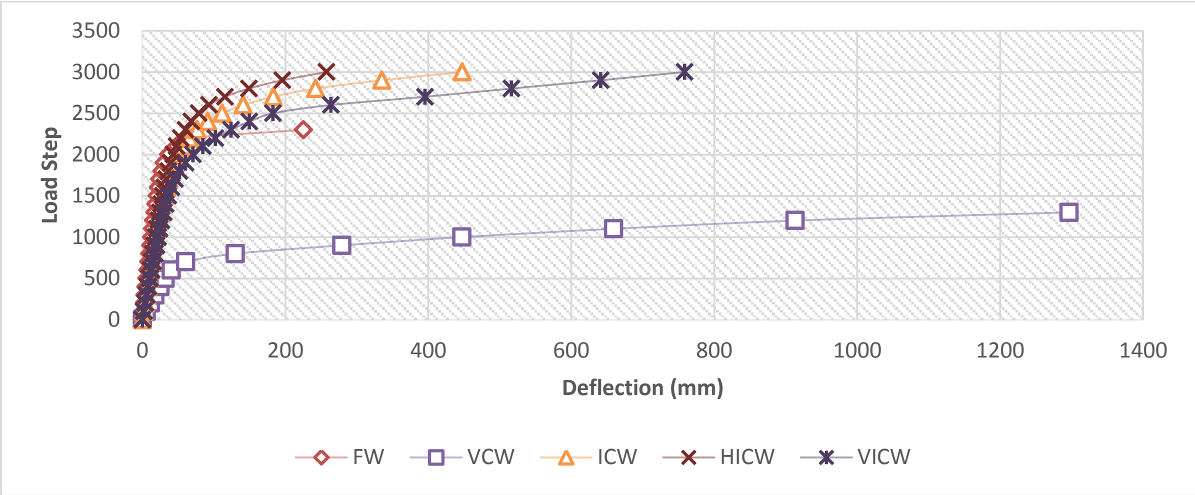


(d) Horizontal & inclined corrugated web (HICW)

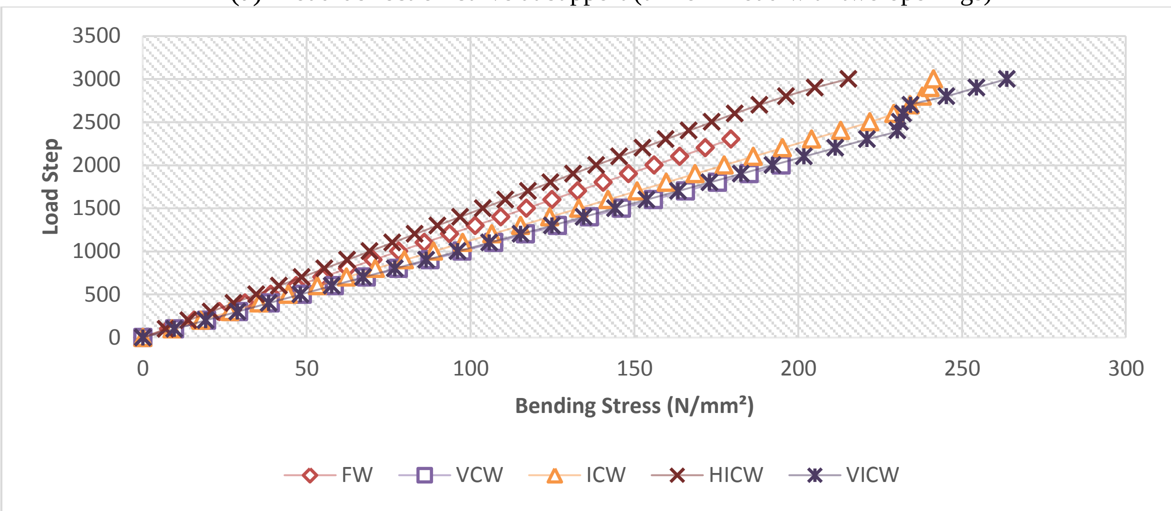


(e) Vertical & inclined corrugated web (VICW)

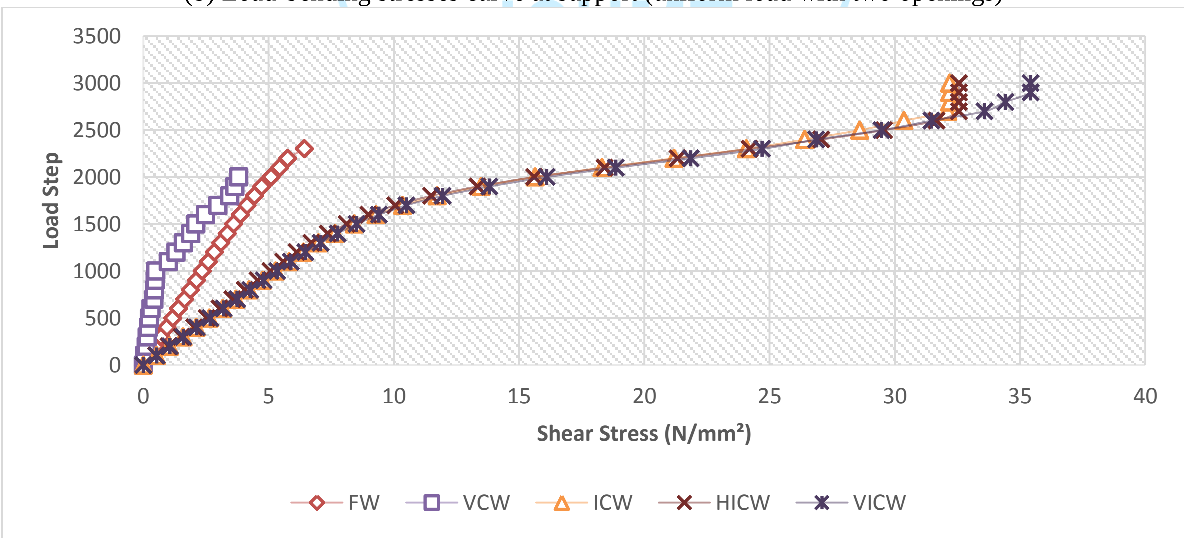
Fig. 18 Deflection Behavior of the steel beams (uniform load with two openings)



(a) Load-deflection curve at support (uniform load with two openings)



(b) Load-bending stresses curve at support (uniform load with two openings)



(c) Shear stress of the steel beams (uniform load with two openings)

Fig. 19 Stresses and deflection of the steel beams (uniform load with two openings)

Table 11 Comparison between the behaviors of different profiles under uniform load with two openings

Profile	Values at Point Load 175 kN/m			
	Deflection (mm)	Deflection ration with respect to FW	Bending Stress (N/mm^2)	Bending Stress ration with respect to FW
FW	17.41	1.00	101.44	1.00
VCW	1296.79	0.01	126.52	0.80
ICW	26.52	0.66	115.33	0.88
HICW	24.63	0.71	89.91	1.13
VICW	29.89	0.58	124.88	0.81

Table 12 Comparison between the behaviors of different profiles under uniform load with two openings

Profile	Values at Point Load 175 kN/m	
	Shear Stress (kN/mm^2)	Shear Stress ratio with respect to FW
FW	3.10	1.00
VCW	1.60	1.94
ICW	6.99	0.44
HICW	6.71	0.46
VICW	7.08	0.44

Considering failure of element VCW at point load 1300 and 800 kN (for one opening and two openings respectively) and uniform load 300 kN/m and 175 kN/m (for one opening and two openings respectively), tables from Table 5 to Table 12 show the deflection and stresses values for all profiles and the relative ratio to the flat web in case of point load and distributed load respectively.

The impact of web corrugation changes depending on the openings and the in-plan corrugation angle, as the preceding figures and tables demonstrate. The most important effect of web opening is on the VCW since it can greatly reduce the resistance to deflection while increasing the resistance to shear. Because the openings are at moments of stress and points of deflection, it looks very convincing. Furthermore, the behaviour of the VCW profile can be largely explained by the accordion effect. Nevertheless, the use of vertical stiffeners can help with the high deflection problem in the event of a point load. Openings affect other corrugation profiles in a different way than they affect the VCW. Compared to FW and VCW, ICW, HICW, and VICW are more resistant to bending stresses and less resistant to shear stresses. Since the angle of web corrugation converts bending stresses near openings into solid parts, it may be the primary cause of the behaviour; however, the vertical angle of corrugation at the VCW profile negates this benefit. In case of uniform load, all profiles are not affected in the same way as the point load due to the distribution to the load. The shear resistance is decreased but the bending resistance is almost the same.

6. Conclusion

In place of solid web beams, this study examined the behaviour of corrugated web steel I-Beams with various openings and locations. The results showed that the resistance of the beam to deflection, bending, and shear stresses was significantly impacted by the openings made in the vertical, horizontal, and/or inclined corrugated web beams. The investigation led to the following conclusions:

i. It is evident that the beam resistance to shear for beams applied with point load has been reduced to almost half of its initial capacity.
ii. For the HICW profile, the resistance to bending has increased by up to 400%.
iii. The beam's resistance to shear is further reduced to almost half of the capacity of a point load when a uniform load is applied.
iv. The resistance to bending has not changed appreciably when the beam is subjected to a uniform load.
v. Ultimately, the deflection increases when holes are made in corrugated web beams, especially in the vicinity of the openings that can be fixed with vertical stiffeners.
vi. Additional research on this topic is needed to increase the code's requirements. Further research is needed on this topic to determine the necessary ratios that determine the type of section—compact, non-compact, or slender. Lastly, a thorough investigation into the effects of fire, temperature, and fire on this kind of structure is necessary.

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