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The Impact of Oriented Corrugated Web Steel Beams Under Various Loads

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Abstract

I-section steel beams are highly used in steel structures, and the point of corrugated beams was had become known recently. In this research, various orientation assemblies of corrugated web steel beams were investigated in order to study the effect of web corrugation on flexure and shear behavior. Ten models of simply supported beams and another eight of cantilever beams were studied by using ANSYS software under concentrated and uniform load. The webs were corrugated and oriented in trapezoidal shape in the direction of web cross-sectional plane. Non-linear finite element analysis was studied, and the results show that the corrugated steel webs in I-section steel beams have a low effect on beam flexural resistance and they can enhance beam shear resistance.

Keywords

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

1. Introduction

Steel structures frequently use I-section steel beams. The majority of shear and bending stresses in a loaded beam are resisted by the web, and the majority of bending stresses are resisted by the flanges. According to Zhang (2000), a common cause of web deterioration is the concentration of most materials in only parallel flanges. This is because the compressive stress of the web may exceed the critical point, which is the point before yielding and causes transverse deformation and stability loss, ultimately resulting in flat web failure. Since corrugation webs can increase strength and stability without adding more stiffeners or thickness, they are thought to be a good option for enhancing plane web resistance. Additionally, corrugated webs in steel beams have recently been taken into account by new design codes in their guidelines (Johansson, 2007; Beg, 2012). Furthermore, vertical corrugated web steel beams are now being produced by a few fabrication companies.

For a long time, corrugated web plates have been in widespread use. It was first widely used in the marine and aerospace industries before spreading to the industrial and civil construction sectors. The world's first fully corrugated web H-beam was successfully produced in 1985 thanks to groundbreaking research conducted in the early 1980s by the Northeast Heavy Machinery Institute of China. Even in the absence of stiffeners, corrugated web plate steel beams show good out-of-plane stiffness. They show better overall stability than beams with flat web plates, which permits the use of thinner web plate thickness to withstand shear buckling capacity. The load characteristics of the web plate are different from those of traditional flat web plates because of its corrugated shape. The stability performance, shear strength, stress concentration, and fatigue resistance of corrugated web H-beams have been extensively studied both domestically and abroad.

The stability performance, shear strength, stress concentration, and fatigue resistance of corrugated web H-beams have been extensively studied both domestically and abroad. The assessment of flexural strength is crucial for steel beam design. The present study aims to determine the flexural capacity of conventional steel I beams and steel beams with corrugated web (CW) through an experimental and analytical investigation. Tests have been conducted on full-scale steel beams with flat webs (FW) or CW to confirm the flexural behaviour of each type of beam.

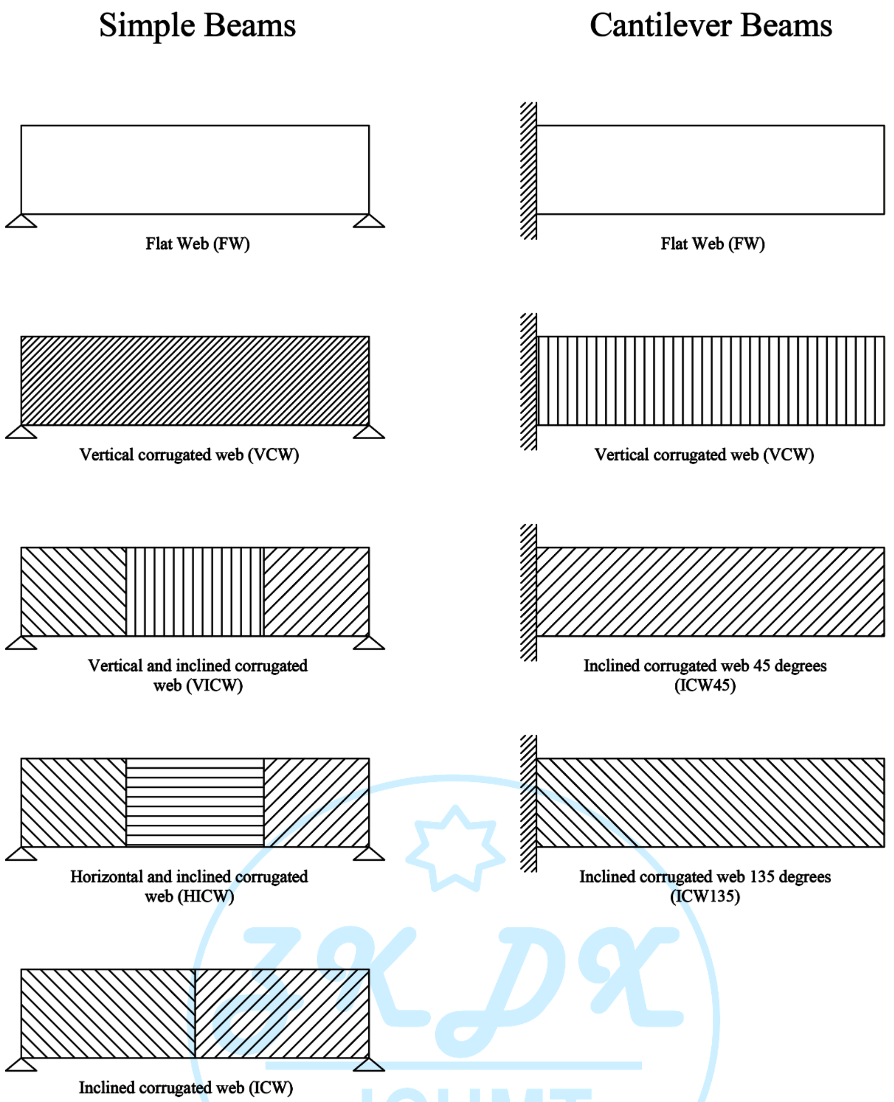


Fig. 1 profiles of studied models of the simple beams and cantilever beam

2. Literature Survey

Lots of scholars studied the vertically trapezoidal corrugation such as Elgaaly et al. (1996), it was found that there is main two types of buckling which may lead to beam shear failure: first, local buckling which is due to web coarse corrugation, and second, global buckling which is due to web dense corrugation. Korrani et al. (2010) were interested in the relationship between the corrugated webs and the lateral torsion buckling (LTB) using four beams: two of them are with flat web, and another two beams are with trapezoidal corrugated web.

Khalid et al. (2004) has conducted a validation of finite element models with experimental test on steel beams with corrugated web and proved that vertical corrugated web beams can endure load up to 30% higher than flat web cases. Similar to Fatimah’s and Nor’s (2011) studies, who stated that different angles corrugated web beams have a greater durability to bending in both minor and major axes.

Another scholar was interested in sinusoidal-shaped webs, conducted experiments on corrugated sinusoidal-shaped web beams (Kudryavtsev, 2018) proved that the spacing between webs and flanges influences web beams bearing capacity. Other studies focused on the openings effect in corrugated web beams on beam capacity such as Zubkov et al. (2018) and Morkhade et al. (2019) and proved that corrugated web beam with opening, has capacity larger than the flat web one.

According to shear and buckling failure, Riahi F. et al (2018) noted that the thick plate's corrugated web cannot 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. Elamary (2022) studied trapezoidal corrugated web short steel beams. Affected by two variables loading position and beams depth and showed that the load application on the horizontal folds (HFs) increased the capacity and beam toughness. Particularly, CWSBs loaded over the HFs outperformed its counterpart loaded over the inclined folds (Ifs), in terms of the moment capacity. The loading positions with respect to the IFs and HFs had negligible effects on the stiffness of the beam and increasing the stiffness and capacities of the beams. And The failure mechanism and moment capacity of the trapezoidally corrugated web beams were strongly influenced by the flange-to-web thickness ratio, which varies based on the corrugation thickness. The flange-to-web thickness ratio should be less than 3 to exhibit reasonable buckling of the specimens.

And, this paper Muslim A. Al-Kannoon (2020), the bending capacity of structural beams web beams had been studied experimentally. Based on the results acquired: The flexural capacity of the beam with corrugated web greater than flat web built-up beam. However, the increase was about (10-21%). And The web contribution in bending capacity were found to be (7-11%). And Web local and global buckling failure appeared in flat web beams (standard IPEA300 and built-up), a combined with compression flange local buckling. While all the corrugation shapes prevent local web buckling. And the rectangular corrugated web showed the higher carrying capacity and stiffness among all corrugation profiles in addition to the rectangular shape had better stiffens and yielded into minimum compression flange failure region.

Also, Ezzeldin Yazeed (June 2007) used a numerical model to investigate the local buckling of the compression flange of corrugated web girders. It is concluded that the flange outstand-to-thickness ratio, which is currently used by codes of practice as one of the criteria classifying the section compactness, should be based on the large outstand of the corrugated web girder’s flange.

This paper investigates the bending and shear stresses and deflection behavior of I-section steel beams with trapezoidal corrugated web, and with or without in plane inclinations. This study aims to determine the effects of web corrugation and the angle of corrugation in plane direction to the beam’s load-carrying capacity. The finite element method with non-linear analysis was adopted for these purposes. Five in plane corrugation directions were considered while the ordinary plane web beams were modeled to compare its results with corrugated ones.

The effect of in plane corrugation direction, type of loading, and end restraints for the beam with trapezoidal-corrugated web type were investigated.

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

Wide plate flanges and thin-walled corrugated web are features of built-up girders known as corrugated web beams. By profiling the web, failure of the beam owing to loss of stability before the web's plastic limit-loading is reached is typically prevented. Sinusoidal corrugation has an advantage over trapezoidal profiling in terms of production technology as well as the ability to eliminate local buckling of the flat plate strips.

Almost without structural restrictions, corrugated web beams can be used as beams (roof or slab beams, structural beams) or as components subject to normal forces (columns or frame columns). 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.

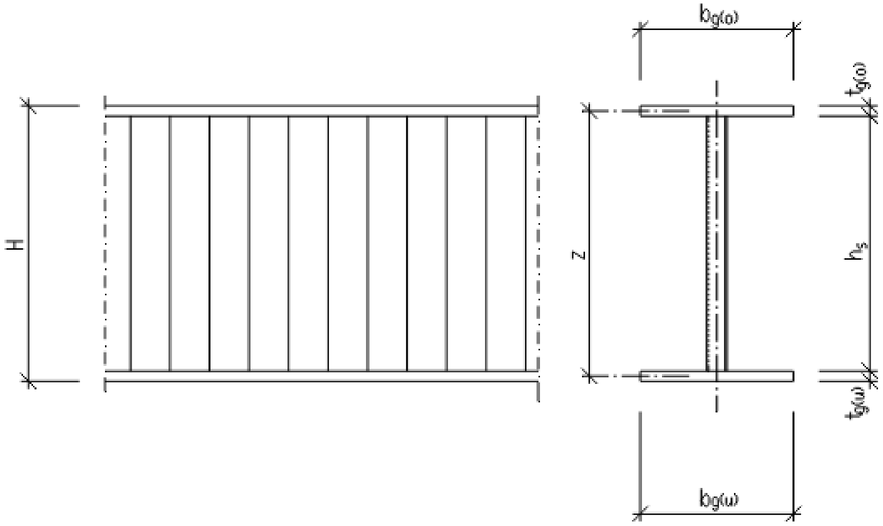


Fig. 2 Specimen details of the studied models

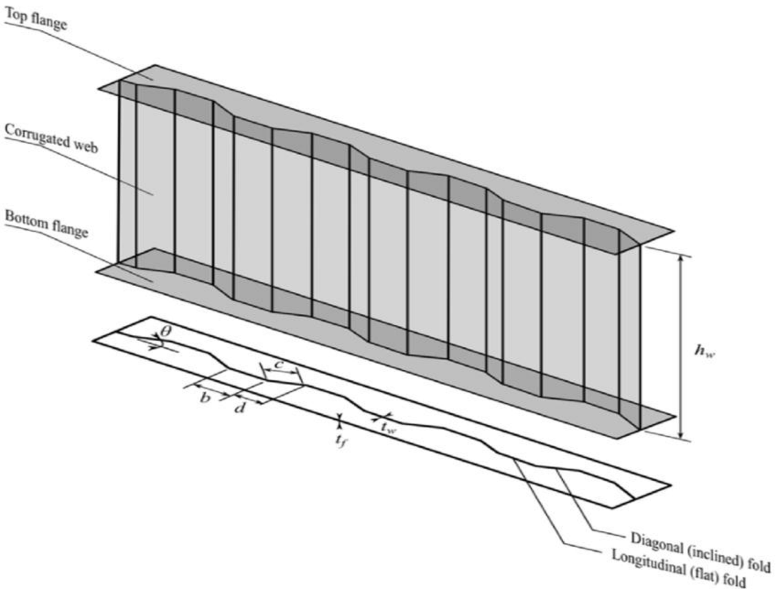


Fig. 3 Couragted Web Panel

3.1.1 Input Data

Figure 4 shows the solid 45 element geometry, the coordinate system and element loads defined as pressure or area loads on the element each face (numbers in circles). The element is determined by eight nodes and the orthotropic material properties.

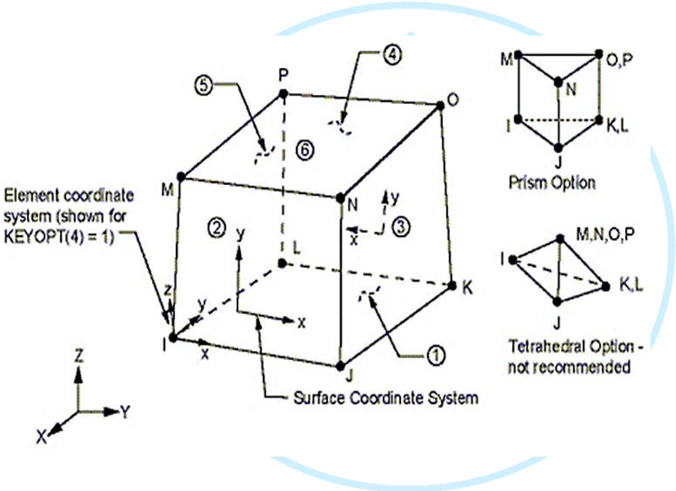


Fig. 4 Solid 45, 3-D structural solid [10]

3.1.2 Output Data

The analysis output which is linked to the element type has the same behavior of the nodal displacement is included in the overall nodal solution. Figure 5 shows the area stress outputs and the coordinate systems for each face. The other surface area coordinate systems simulate alike orientations as specified by the pressure face node description.

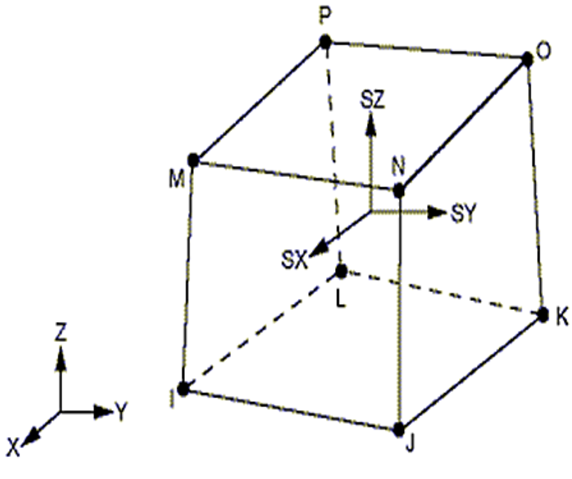


Fig. 5 Solid 45 Stress Output [10]

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.

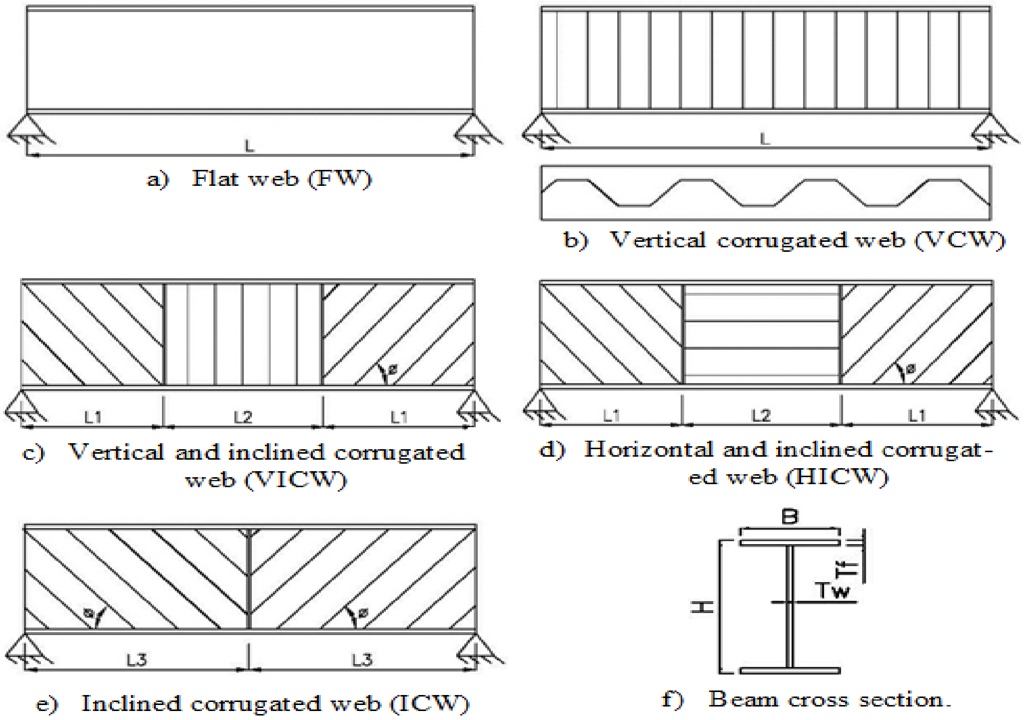


Fig. 6 Corrugation profiles of the selected simple beams

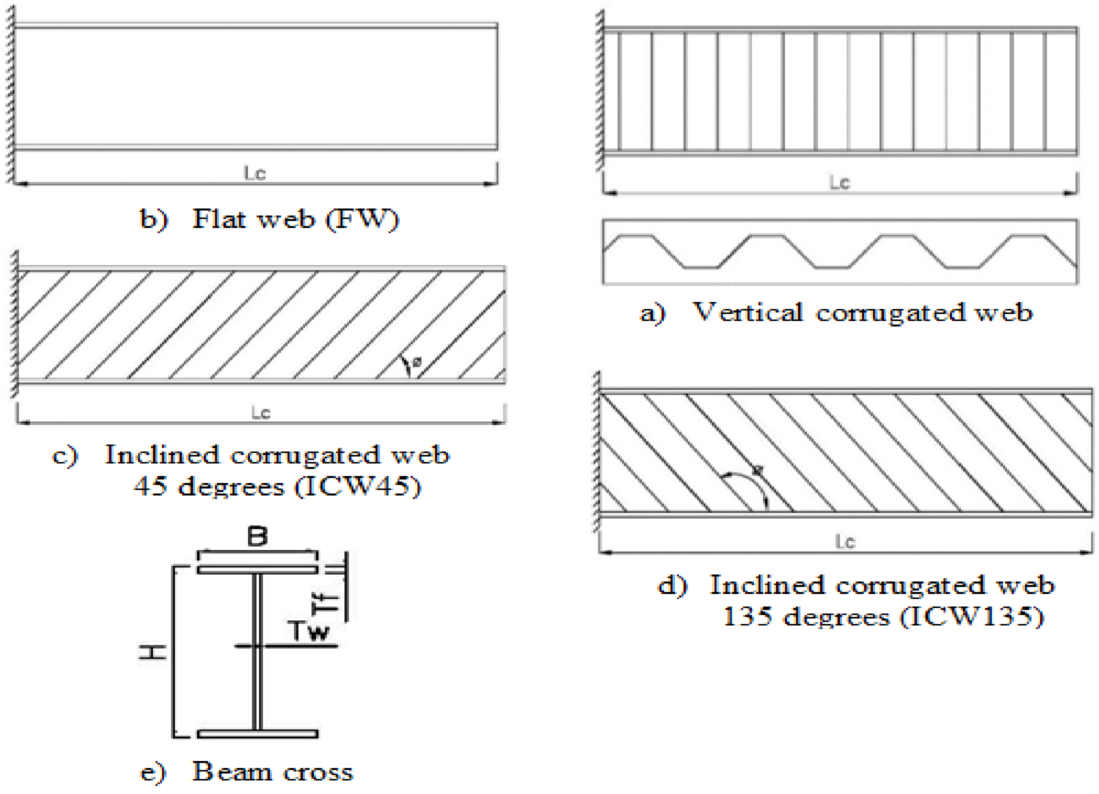
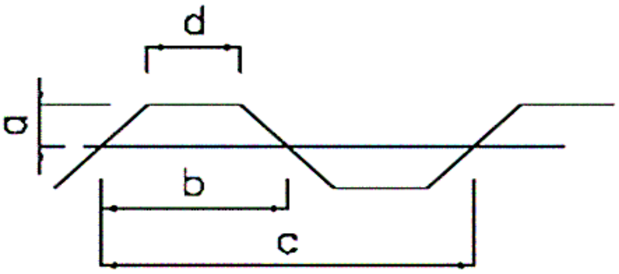


Fig. 7 Corrugation profiles of the selected cantilever beams

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

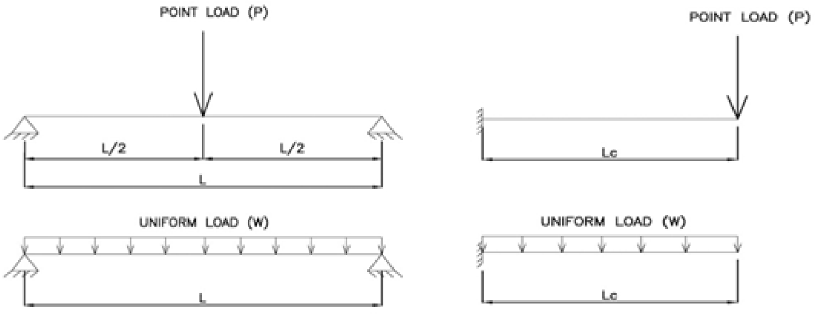
Figure 8: Dimension of trapezoidal corrugation profile

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 Corrugated Web Steel Beams With Different Types of Loading and End Restraints

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.



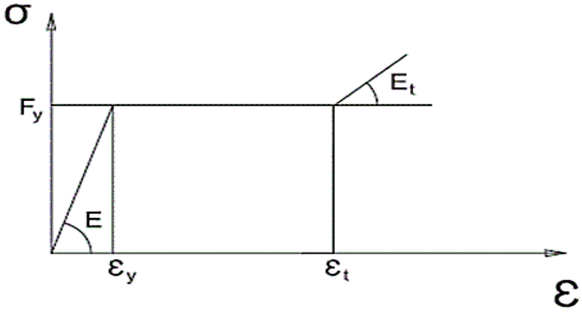
a) Simple beam b) Cantilever beam.

- Where, $P_{max} = 1500$ kN, $W_{max} = 400$ kN/m

Fig. 9 Type of loading and end restraints

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.



F_y = 233.1 MPa
ε_y = 0.00111
ε_t = 0.01361

E = 210,000 MPa
G = 80,769 MPa
E_t = 6000 MPa

Fig. 10 Uniaxial constitutive model cons

3.2 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 12 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.

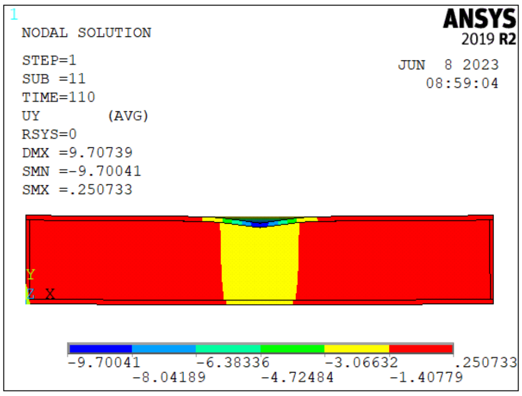


Fig. 12 Displacement results for the simulated beam

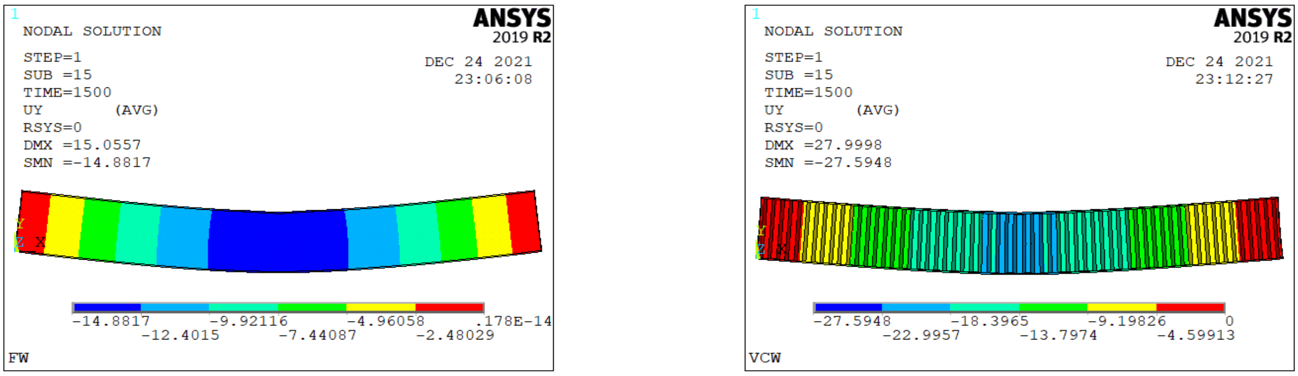
Table 4 Experimental and theoretical results for the simulated model

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

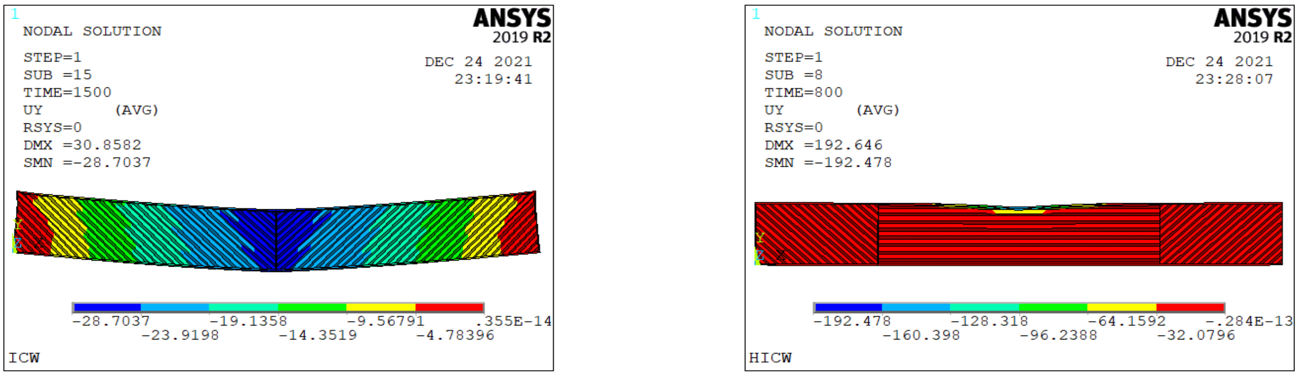
A total of 20 FE models were created and tested using ANSYS software package. All models were assigned with A total of 18 finite element models were created and tested using ANSYS software package to explore the influences of each variable to the beam's behavior. Load–displacement graphs, load-bending stresses graphs, and Load-shear stresses were plotted for each case. Then all values for different models were discussed.

Regarding simple beams for the case of point load (P), the deflection behavior, bending stresses and shear stresses are collected from the ANSYS models. For example, Figure 13 shows the deflection behavior. The supportive graphs are shown in Figure 10. Results are compared at point of failure of the weakest element as shown in Table 4 and Table 5.

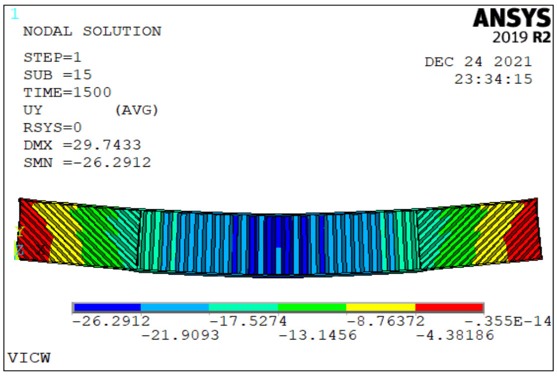


(a) Flat web (FW)

(b) Vertical corrugated web (VCW)

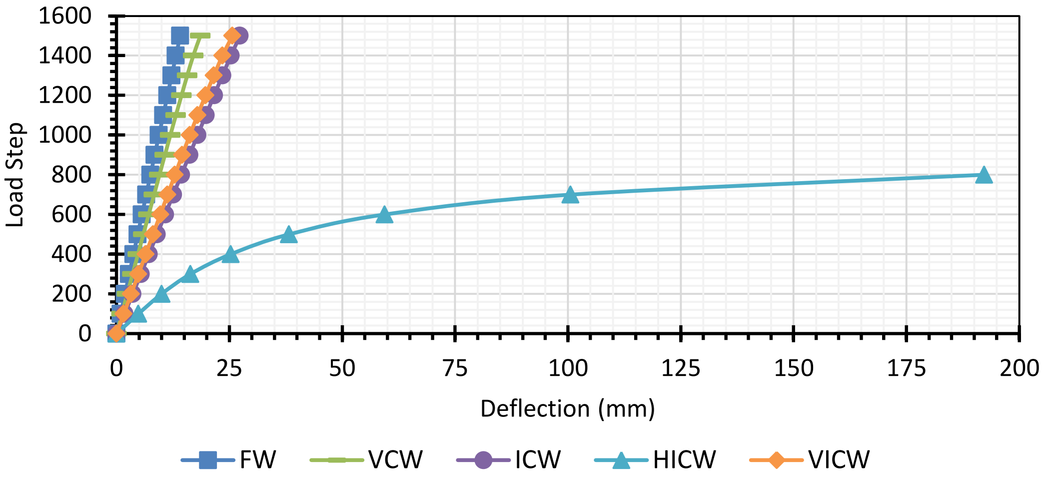


(c) Inclined corrugated web (ICW) (d) Horizontal & inclined corrugated web (HICW)

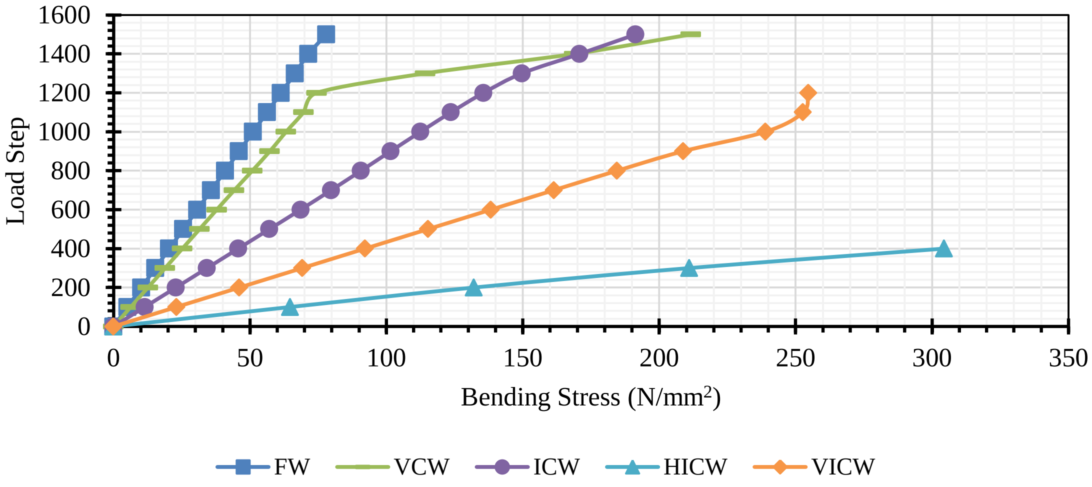


(e) Vertical & inclined corrugated web (VICW)

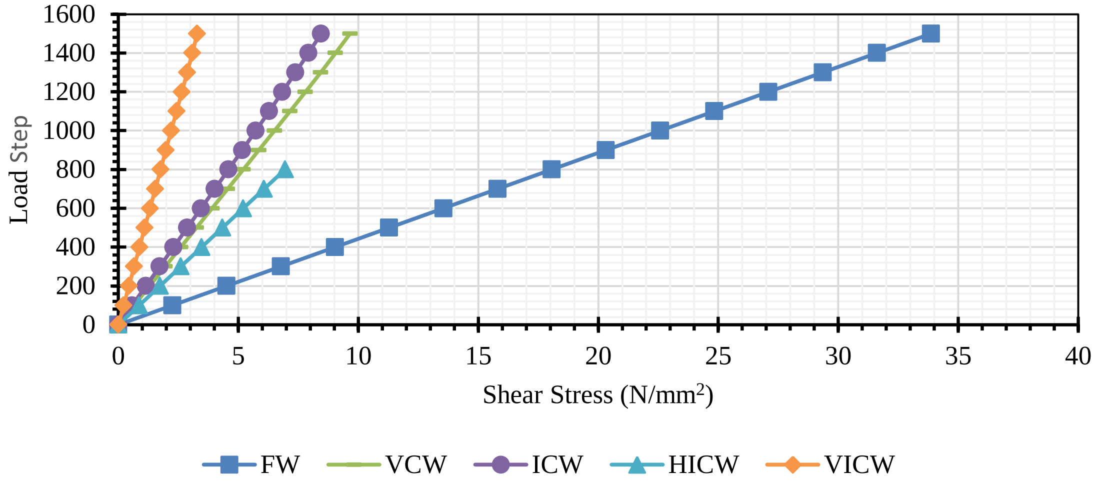
Fig. 13 Deflection behavior of simple beam (case of point load)



(a) Load-deflection curve at support (point load)



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



(c) Shear stress for simple beams (point load)

Fig. 14 Stresses and deflection for simple beams (case of point load)

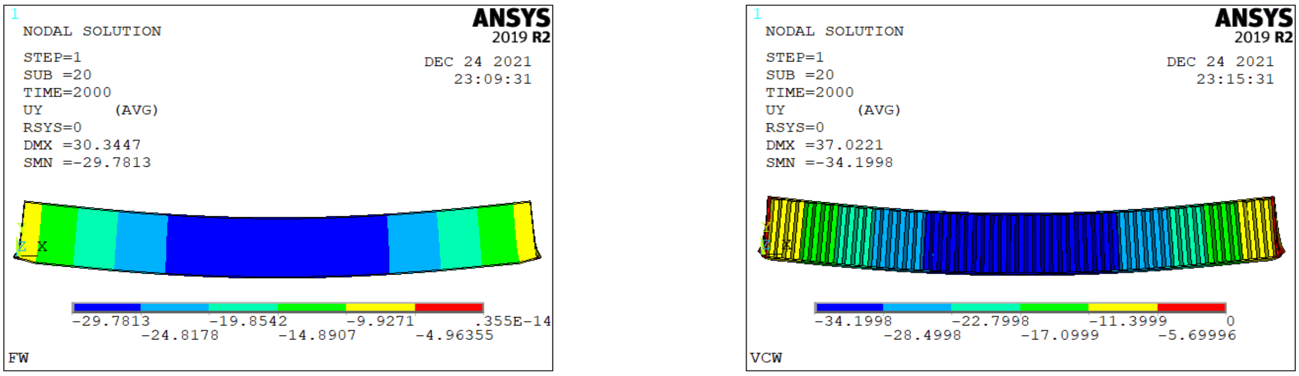
Table 4 Comparison between the behaviors of different profiles under point load

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	7.52	1.00	40.95	1.00
VCW	9.52	0.80	50.86	0.81
ICW	14.44	0.52	90.73	0.45
HICW	192.27	0.04	300.29	0.14
VICW	11.95	0.63	184.58	0.22

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

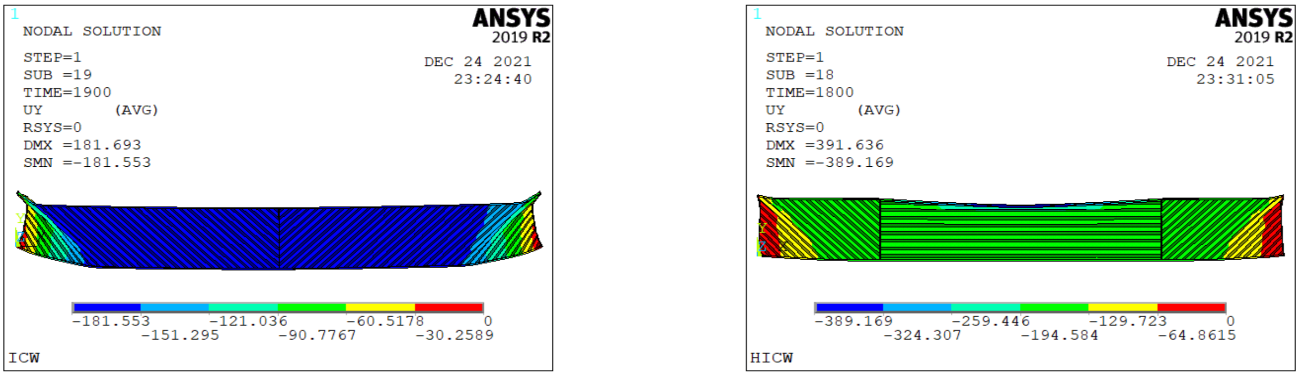
Profile	**Values at Point Load 800 kN**	
	Shear Stress (N/mm^2)	**Shear Stress ration with respect to FW**
FW	18.07	1.00
VCW	5.20	3.48
ICW	4.59	3.94
HICW	6.95	2.60
VICW	1.76	10.27

For the case of uniform load (w), the deflection behavior, bending stresses and shear stresses are collected from the ANSYS models. For example, Figure 15 shows the deflection behavior. The supportive graphs are shown in Figure 16. Results are compared at point of failure of the weakest element as shown in Table 6 and Table 7.



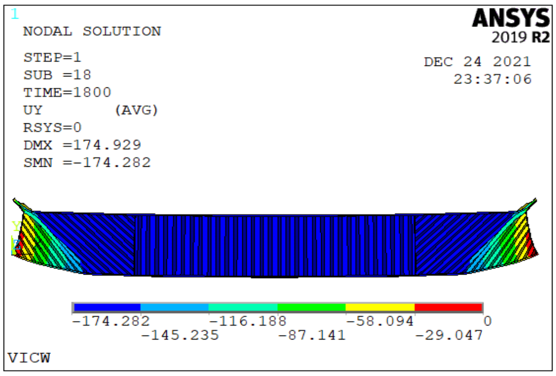
(a) Flat web (FW)

(b) Vertical corrugated web (VCW)



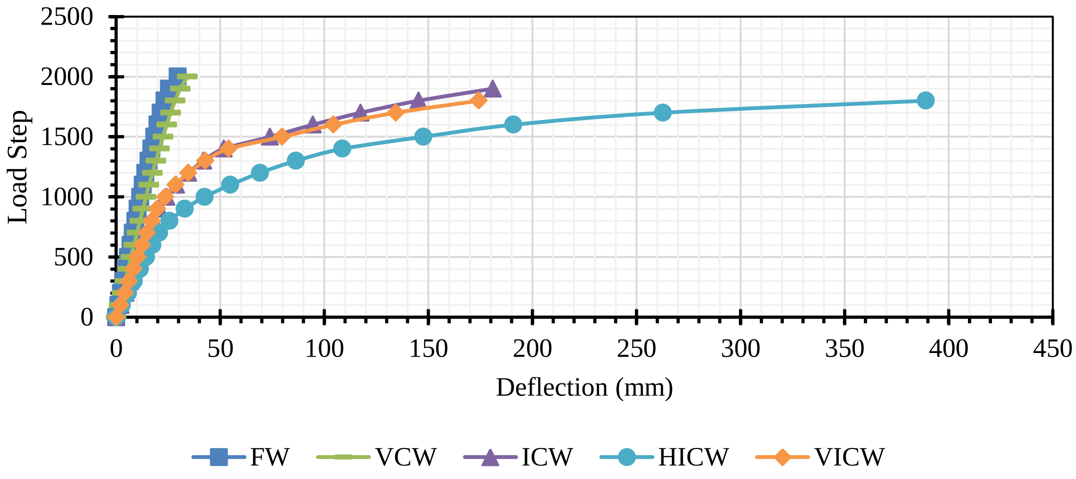
(c) Inclined corrugated web (ICW)

(d) Horizontal & inclined corrugated web (HICW)

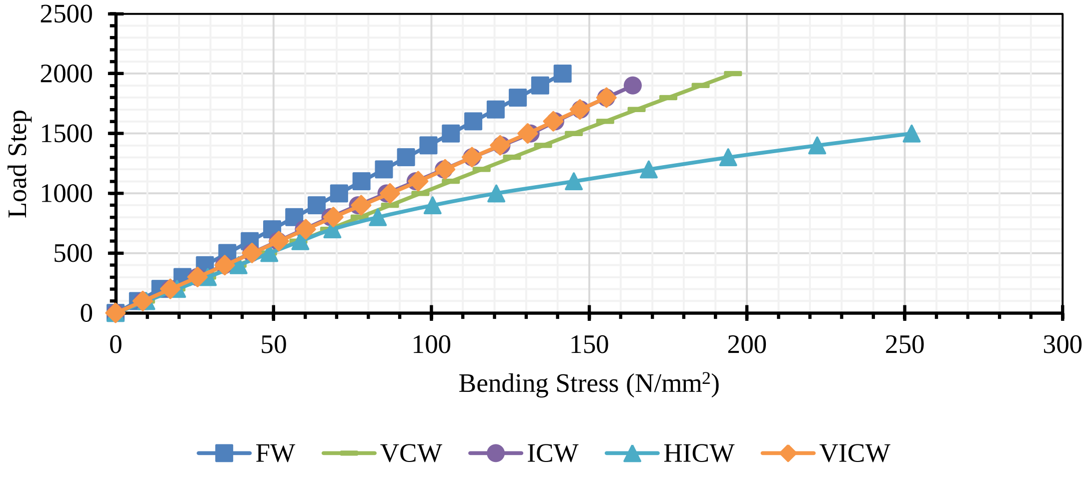


(e) Vertical & inclined corrugated web (VICW)

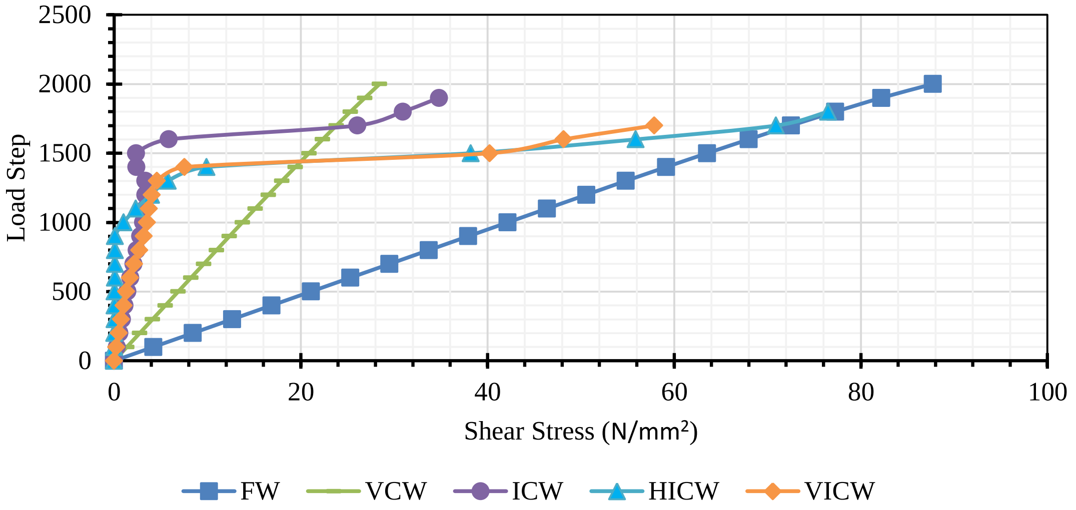
Fig. 15 Deflection Behavior of simple beam (uniform load)



(a) Load-deflection curve at support (uniform load)



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



(c) Shear Stress for simple beams (uniform load)

Fig. 16 Stresses and deflection for simple beams (case of uniform load)

Table 6 Comparison between the behaviors of different profiles under uniform load

Profile	Values at Uniform Load 360 kN/m			
	Deflection (mm)	Deflection ration with respect to FW	Bending Stress (N/mm^2)	Bending Stress ration with respect to FW
FW	23.24	1.00	127.49	1.00
VCW	28.29	0.82	175.19	0.73
ICW	145.31	0.16	155.50	0.82
HICW	389.01	0.06	233.67	0.55
VICW	174.27	0.13	155.61	0.82

Table 7 Comparison between the behaviors of different profiles under uniform load

Profile	Values at Uniform Load 360 kN/m	
	Shear Stress (N/mm^2)	Shear Stress ration with respect to FW
FW	77.26	1.00
VCW	25.31	3.05
ICW	30.92	2.50
HICW	76.51	1.01
VICW	43.17	1.79

Tables 3 through 6 present the capacity values between all profiles and the capacity ratio with respect to the flat web in the case of point load and distributed load, respectively, taking into account the failure of element HICW at point load 800 kN and uniform load 360 kN/m.

The effect of web corrugation varies with respect to the in-plan corrugation angle, as previously demonstrated in the figures and tables. It can be observed that FW and VCW are the most capable of withstanding bending and deflection stresses. On the other hand, HICW is not very resistant to bending and deflection. It can be observed that VCW and ICW have the greatest ability to withstand shear.

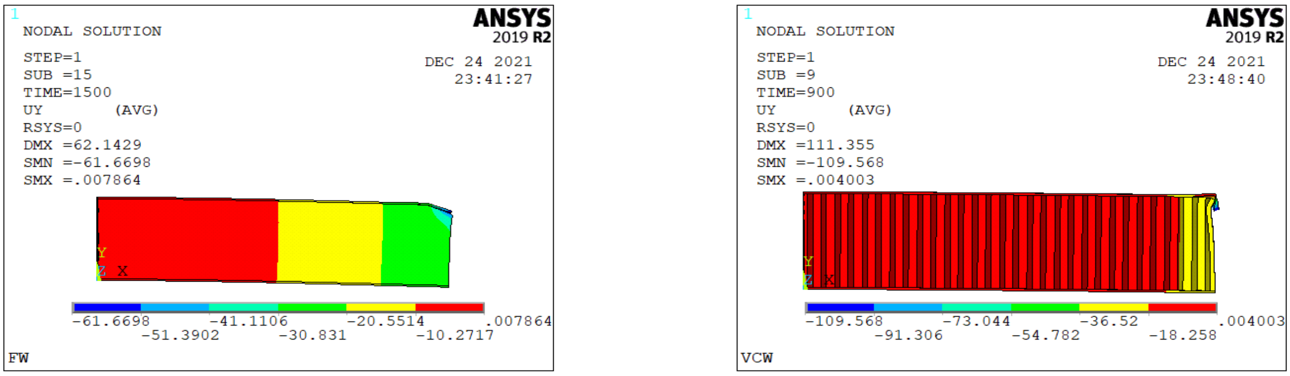
It is observed that the beam's resistance to a point load is lower than its resistance to a uniform load because a point load causes additional damaging stresses to affect the web. By utilising vertical stiffeners at the load location, this can be decreased.

To prevent a debilitating stress effect, Table 8 displays the maximum deflection at a section 1500 mm away from the mid-span. Because of the normal distribution of stresses, values of deflection have naturally decreased in the majority of sections. The lack of the crippling stresses effect results in a noticeable decrease in the values of deflection, particularly in the HICW sections.

Table 8: Comparison between the deflection of different profiles under crippling effect

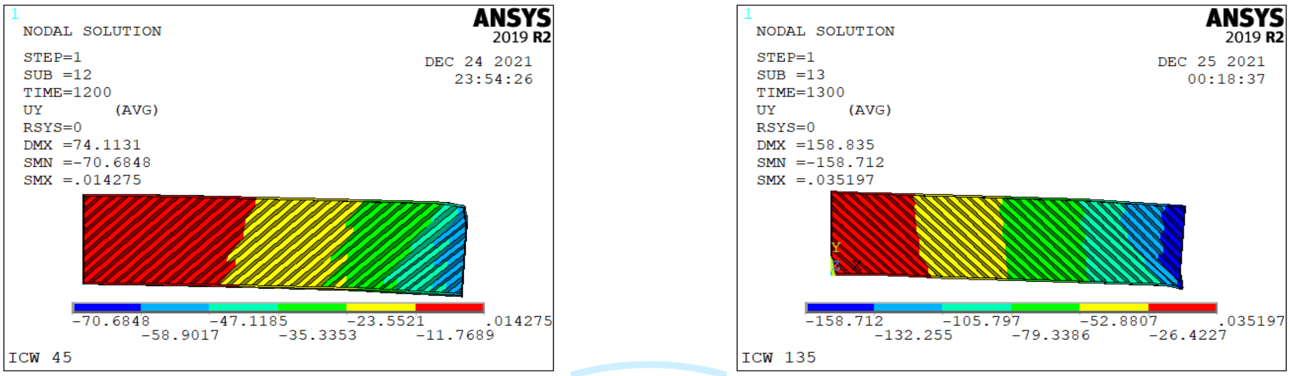
Profile	Deflection at mid-span (mm)	Deflection at 1500 mm away from middle (mm)
FW	7.52	5.77
VCW	9.52	8.61
ICW	14.44	11.37
HICW	192.27	74.12
VICW	11.95	10.11

Regarding cantilever beams for the case of point load (P), the deflection behavior, bending stresses and shear stresses are collected from the ANSYS models. For example, Figure 17 shows the deflection behavior. The supportive graphs are shown in Figure 18. Results are compared at point of failure of the weakest element as shown in Table 9 and Table 10.



(a) Flat web (FW)

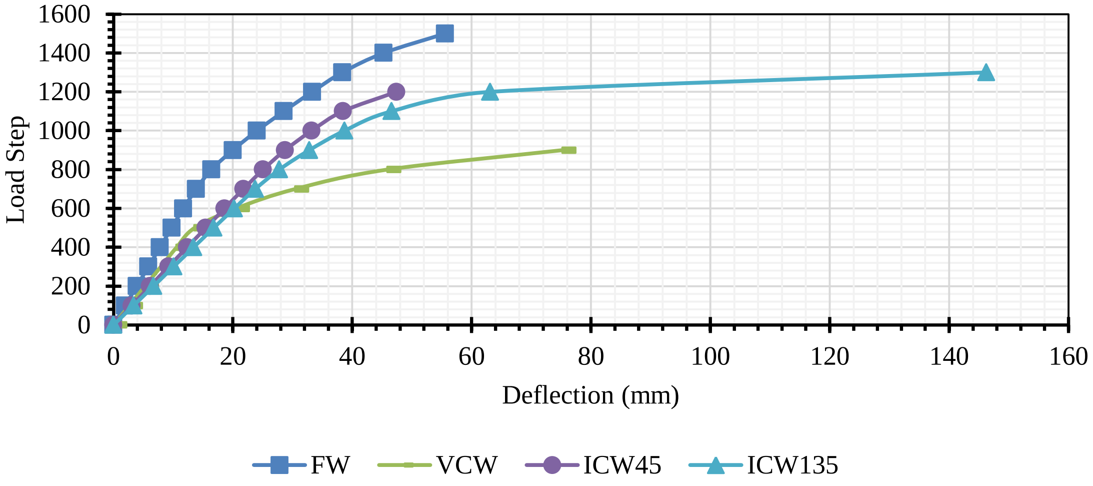
(b) Vertical corrugated web (VCW)



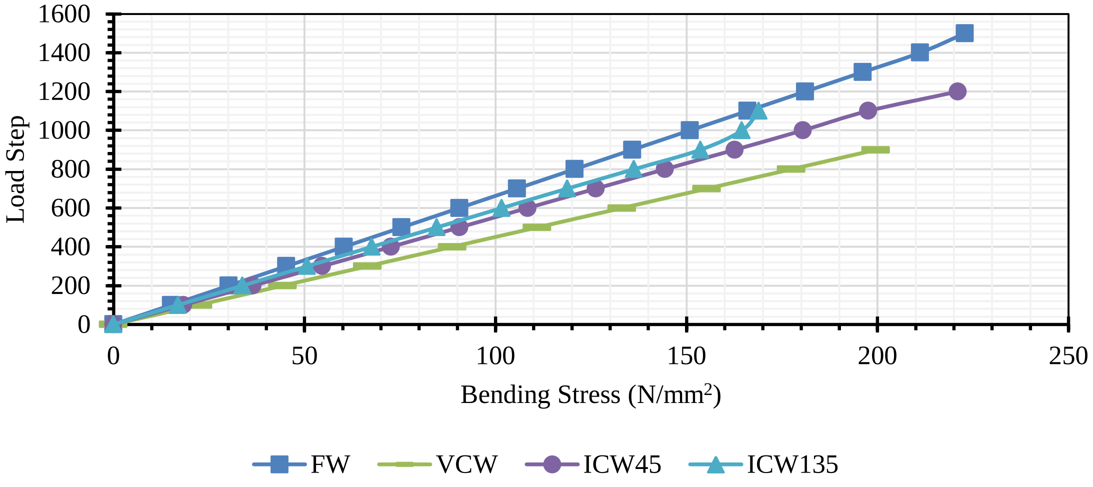
(c) Inclined corrugated web (ICW45)

(d) Inclined corrugated web (ICW135)

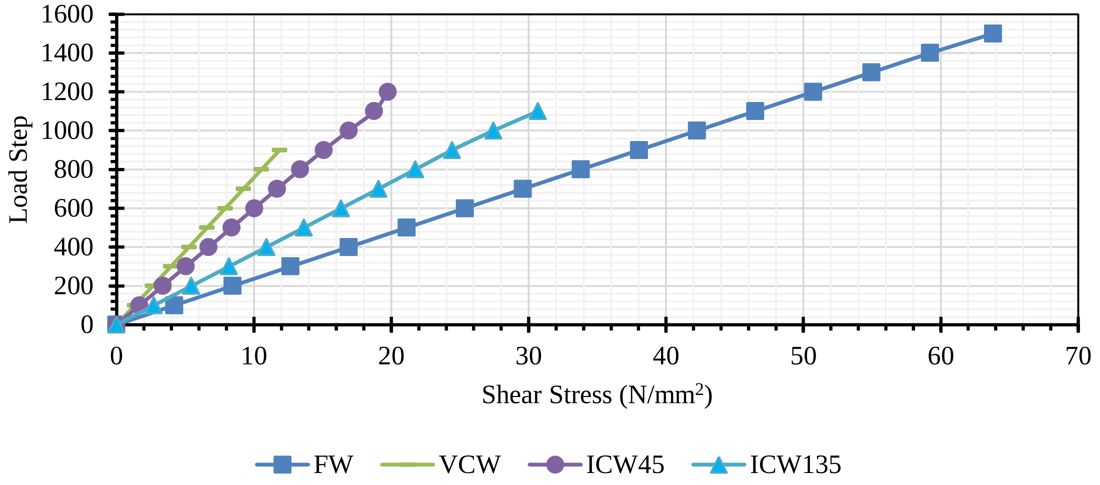
Figure 17: Deflection behavior of cantilever beam (case of point load)



(a) Load-deflection curve at support (point load)



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



(c) Shear stress for cantilever beams (point load)

Fig. 18 Stresses and deflection for cantilever beams (case of point load)

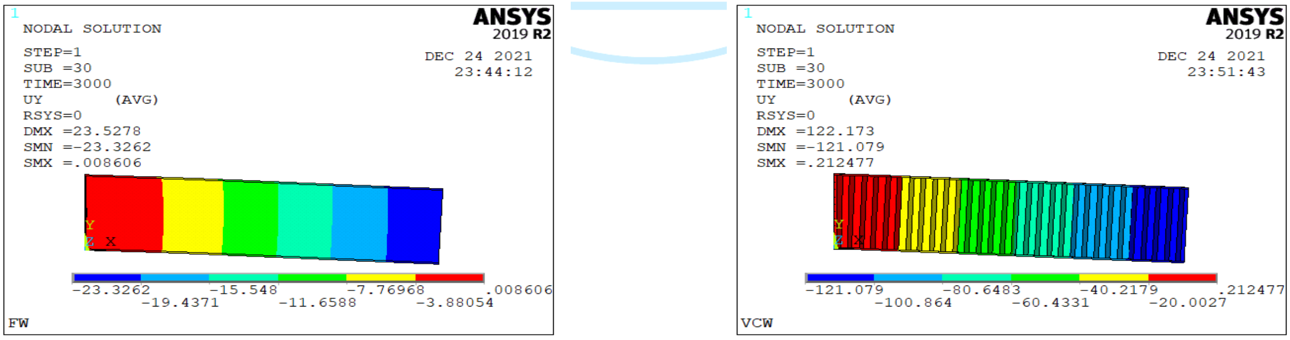
Table 9: Comparison between the behavior of different profiles under point load

Profile	**Values at Point Load 900 kN**			
	Deflection (mm)	**Deflection ration with respect to FW**	**Bending Stress (N/mm^2)**	**Bending Stress ration with respect to FW**
FW	19.99	1.00	135.83	1.00
VCW	75.26	0.27	199.62	0.68
ICW45	28.76	0.70	162.64	0.84
ICW135	32.80	0.61	153.66	0.88

Table 10: Comparison between the behavior of different profiles under point load

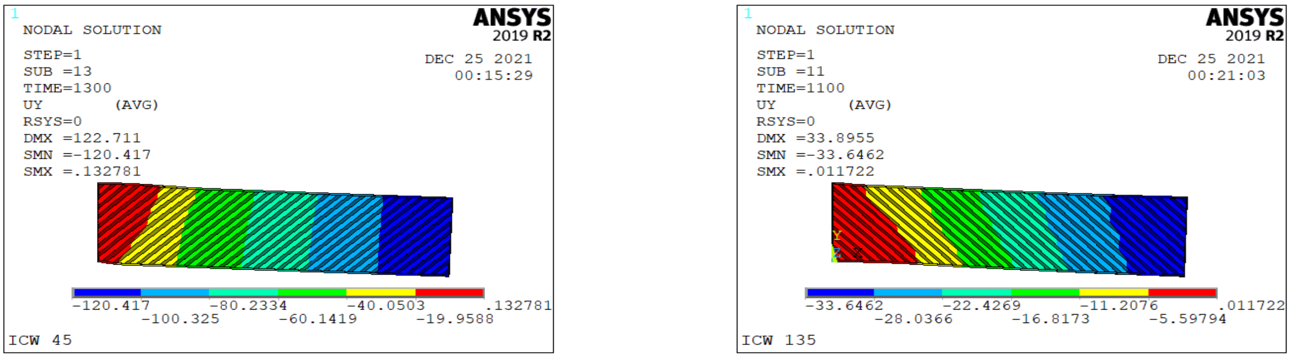
Profile	**Values at Point Load 900 kN**	
	Shear Stress (N/mm^2)	**Shear Stress ration with respect to FW**
FW	38.04	1.00
VCW	11.88	3.20
ICW45	15.10	2.52
ICW135	24.45	1.56

For the case of uniform load (w), the deflection behavior, bending stresses and shear stresses are collected from the ANSYS models. For example, Figure 19 shows the deflection behavior. The supportive graphs are shown in Figure 20. Results are compared at point of failure of the weakest element as shown in Table 11 and Table 12.



(a) Flat web (FW)

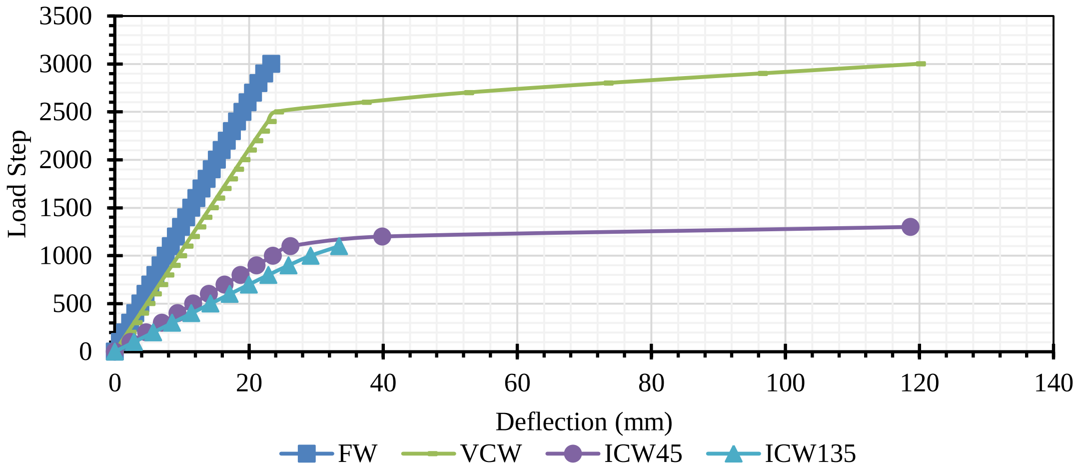
(b) Vertical corrugated web (VCW)



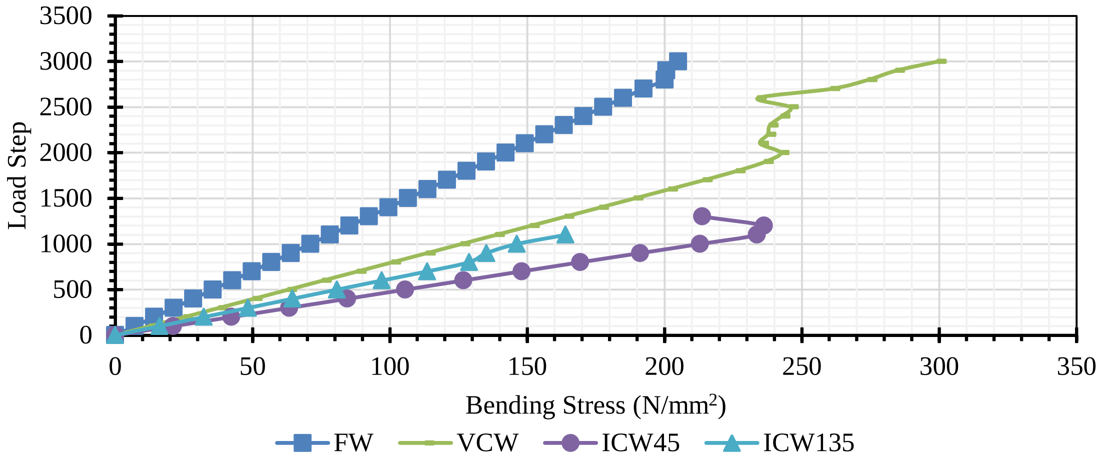
(c) Inclined corrugated web (ICW45)

(d) Inclined corrugated web (ICW135)

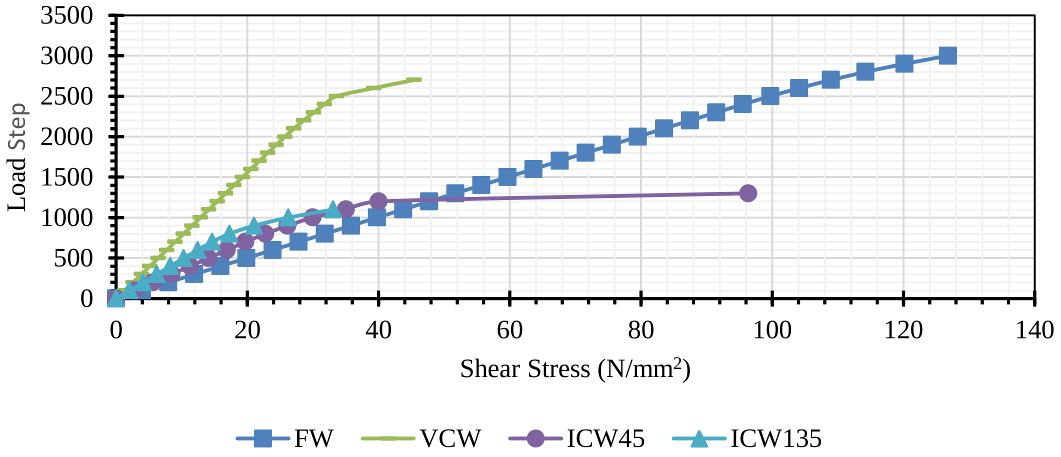
Fig. 19 Deflection Behavior of cantilever beam (uniform load)



(a) Load-deflection curve at support (uniform load)



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



(c) Shear Stress for cantilever beams (uniform load)

Fig. 20 Stresses and deflection for cantilever beams (case of uniform load)

Table 11 Comparison between the behavior of different profiles under uniform load

Profile	Values at Uniform Load 150 kN/m			
	Deflection (mm)	**Deflection ration with respect to FW**	**Bending Stress (N/mm^2)**	**Bending Stress ration with respect to FW**
FW	8.36	1.00	78.20	1.00
VCW	10.40	0.80	138.72	0.56
ICW45	26.20	0.32	233.65	0.33
ICW135	33.45	0.25	164.00	0.48

Table 12: Comparison between the behavior of different profiles under uniform load

Profile	Values at Uniform Load 150 kN/m	
	Shear Stress (N/mm^2)	Shear Stress ration with respect to FW
FW	43.75	1.00
VCW	14.12	3.10
ICW45	35.05	1.25
ICW135	33.08	1.32

Tables 9 through Table 12 present the capacity values between all profiles and the capacity ratio with respect to the flat web in the case of point load and distributed load, respectively, taking into account the failure of element VCW at point load of 90 tonnes and element ICW135 at uniform load of 150 kN/m.

The effect of web corrugation varies with respect to the in-plan corrugation angle, as previously demonstrated in the figures and tables. It is observed that under uniform load conditions, VCW exhibits superior resistance to bending stresses and deflection near FW, whereas under point load conditions, ICW45 and ICW135 demonstrate superior resistance to bending stresses and deflection near FW. When it comes to shear resistance, VCW is observed to be more resilient to shear stresses than other profiles. All things considered; it is evident that resistance to shear rises when web corrugation occurs.

In order to prevent the crippling stress effect, Table 13 displays the maximum deflection at a section 1500 mm away from the mid-span. With the exception of the VCW section, where there is a noticeable reduction in its values of deflection, the value of deflection has naturally decreased in most sections as a result of the normal distribution of stresses.

Table 13: Comparison between the deflection of different profiles under crippling effect

Profile	Deflection at mid-span (mm)	Deflection at 1500 mm away from middle (mm)
FW	19.99	12.07
VCW	75.26	15.68
ICW45	28.76	19.49
ICW135	32.80	20.62

6. Conclusion

This study examined the behaviour of I-section steel beams with a trapezoidal corrugated web, with and without in-plane inclinations in the bending, shear, and deflection stresses, as well as the relationship between the load-carrying capacity of the beam and the corrugation angle in the plane direction. The investigation led to the following conclusions.:

I. Since the beam flanges are primarily in charge of bending resistance, using vertical, horizontal, or inclined corrugated web beams in place of flat web beams does not increase the beam resistance to deflection or bending stresses. Conversely, they strengthen the beam's ability to withstand shear stress.

II. When point loads are applied, the results indicate a minor reduction in beam resistance because of additional concentrated stresses that weaken the web. To lessen web crippling, vertical stiffeners should be used at the point of load.

III. According to shear stresses, in case that the shear stresses govern the element design, it is recommended to use corrugated web beams, this will increase the beam loading capacity.

IV. In both cases of point load and uniform, corrugated web can reduce the shear stress up to 30% as resulted from VCW profile. However, it is also recommended to use vertical stiffeners at point load location to reduce web crippling.

V. More research on this topic is necessary in order to add its code requirements. Further research is needed on this topic in order to determine the necessary ratios that determine the type of section—compact, non-compact, or slender. Ultimately, more research has to be done on how fire, temperature, and fire affect this kind of structure.

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