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TECHNICAL ARTICLE—PEER-REVIEWED

Optimization Assessment of a Jib Crane Beam with Variable Web Corrugations Using Finite Element Analysis

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Abstract In construction industries, cranes are often used for lifting and transporting loads from one place to other. One of the simplest types of these cranes is a Jib crane which is used on a wide scale in construction industries. The integral part of the jib crane contains a hoisting mechanism that helps in raising and lowering loads, while trolley motions move loads horizontally. It must be ensured that the crane beam must be designed properly as per norms to get sufficient stiffness and strength to withstand the applied loads. Beams of these types of cranes are usually I-shaped in cross section, and lateral torsional buckling plays a critical role in determining the overall stability of the crane. In this study, finite element analysis of a cantilever, I beam S10@25.4 lb/ft of span 2.54 m is done to determine the buckling behavior when it is subjected to vertical load at its free end in addition to its self-weight. Models of these beams were made on AutoCAD and then analyzed on finite element modeling software ANSYS using a load multiplier. Moreover, a new design approach is proposed to study the lateral torsional behavior of the crane I beam under similar loading conditions by introducing trapezoidal corrugations in the web. For this analysis, 32 models having trapezoidal corrugations in the web with different variations in the angles, thickness and widths were proposed, and then the buckling capacity of the beam was determined to see its effects. From the finite element analysis results, it is observed that the corrugation angles of the plate substantially influence the buckling. Also, in this study, a comparative and cost-benefit analysis is done comparing a conventional beam without corrugation to a corrugated beam. It is found that corrugated beam is more economical, having lesser weight and higher buckling load capacity than the conventional flat beam.

Keywords Jib cranes · Lateral torsional buckling · Finite element analysis

Introduction

Modern construction industries demand cost-effective and highly efficient equipment for handling and transporting materials from one place to another [1]. If properly designed, this equipment saves considerable time and money, thereby increasing productivity. A jib crane is mostly used in these industries to lift and move the materials. They are also used in transportation industries for loading and unloading of freight. One of the major advantages of a jib crane is that it has three degrees of freedom, i.e., vertical, radial, and rotary [2]. The lifting capacities of these cranes may vary from 0.5 tons to 200 tons [3]. In summary, the jib crane includes all such cranes that have a rotating boom [4] and which are attached to a vertical mast. These cranes are classified as per their load-carrying capacities. Crane Manufacturers Associates of America (CMAA) classified cranes in various classes from class A to F as per their intended duty Cycle. Further, each of the jib cranes is also customized and modified for serving specific purposes. For circular coverage area wall mounted jib cranes allow 270° rotation and requires no floor space for operation. The force transmitted to buildings columns by these cranes is low. As a result these cranes can be used and installed practically on any wall or columns

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[5]. Floor mounted jib cranes offer high capacities and longer span with 360° and 270° rotation covering area. But these cranes require special foundation for proper mounting. Articulating jib cranes has an inner arm allowing a rotation of 270° and 360° rotation by the outer arm help in moving loads around corners as a result can reach at any point [5]. Jib cranes require maintenance for most of the year, especially in case of the cantilevers I- type beam. Due to lateral torsional buckling beams of these cranes get damaged. Applied load causes lateral displacement and twisting of the beam members. Lateral torsional buckling is a major design aspect of flexural members having their walled I- girder. In such cases, a load approaches its critical value. Out-of-the-plane bending may occur due to insufficient lateral bracing. Lateral torsional buckling is a common failure mode for laterally unrestrained beams [6]. The smallest critical load causing lateral-torsional buckling is a hard problem to solve [7]. In such of laterally unrestrained beams the use of corrugated webs increases the out-of-the-plane stiffness and shear buckling resistance. Hence studies are still going on which help in controlling lateral-torsional buckling using the corrugated web. These stability analyses of jib cranes are essentially required to avoid accidents that can result in failure of the beam of a jib crane [8]. Although very limited literatures are available on the application of corrugated web, these corrugations allow the use of thin plates without stiffeners for design of cranes used in buildings and bridge constructions [2]. There is a considerable reduction in the weight of the beam and cost because the use of larger thicknesses and stiffeners get eliminated [8]. In this paper, a web with trapezoidal corrugation is used to analyze the lateral-torsional buckling of the jib crane beam. A comparative study is done in this research work by developing FEM models of a plane web and comparing the results obtained with a corrugated web. Although jib crane analysis has been conducted by many researchers in the recent past, there is still a lacuna where in-depth finite element analysis has not been carried out. Fatimah et al. [9] used 3D finite element model using LUSAS 14.3. They analyzed triangular web-shaped steel beams for shear buckling behavior in corrugation thickness of the web. Dhanusha and Reddy [10] used CERO software to model a floor-mounted jib crane. They compared the results obtained for stresses developed in the case of two different plates of steel. A comparative study of manual design and FEM analysis was conducted by Gerdemeli et al. [11]. They concluded that FEM analysis gives more acceptable values with fewer error margins. Rajmane and Jadhav [12], in their research work analyzed a column-mounted jib crane using FEM software. Their study was mainly focused on the calculation of Von Misses stresses. They varied the web thickness to increase the Von Misses stresses. Fatimah et al. [9] studied the lateral-torsional buckling behavior of a steel beam having a trapezoidal web. They used Eigen values buckling analysis to determine the critical buckling load and found that higher corrugation thickness develops higher lateral torsional buckling resistance due to increase in moment of inertia. Amreeta and Singh [13] studied stress analysis of a single wall mounted jib crane girder. They performed FEM analysis on different beam section. They found that I-section has lesser stresses and deformation when compared to rectangular section. Chaudhary and Khan [1] also performed software analysis to determine shear capacity and lateral torsional buckling of cantilever beam of a jib crane. They proposed different cantilever beams with different web shapes. Their main study was focused on infill length of corrugated plate. Moon et al. [14] studied FEA of I girder under uniform bending. They proposed an approximate method to locate the shear center and wrapping constant of I girder with web corrugation. They compared their results with flat webs and found that wrapping constants of I girder with corrugated web is larger than that of flat webs [15]. Khetra et al. [16] designed the boom of a rotatory jib crane on solid works and analyzed for stresses and displacements using COSMOS software. They compared their results using static stress analysis. Kiranalli and Patil [17] discussed twisting anxieties of cantilever steel beams with tapered web. They used ANSYS software to perform finite element analysis of a 200 × 100 mm cantilever beam of a span 5 m subjected to a live load of 500 kg. They concluded that flat webs are more liable to lateral torsional buckling when compared to flat webs. They also proposed a suitable taper ratio of 3:2. Wan and Mahendran [18] studied the behavior of hollow flange channel beam when subjected to mid span eccentric load. They performed experimental tests and compared their results using FEA software. In order to investigate the effects of the location and eccentricity of the applied load, finite element models of lite steel beams were validated. They used special test rig to simulate different loading eccentricities and boundary conditions. Stefano et al. [19] studied the effect of shear stress and strains of symmetrical tapered cantilever beam using mathematical modeling and constitutive equations. Lee et al. [20] studied the lateral torsional buckling of a composite beam using 1D Finite element model they found that transverse load on a beam affect the lateral torsional buckling capacity due to fiber orientation and maximum buckling load occurs at a fiber angle of 45°. Trahair [21] also performed FEM analysis on tapered and mono symmetric I cross-sectional members using numerical methods. He also developed a MATLAB programming which he used further for analyzing tapered cantilever and built in beams under various loading and boundary conditions. Lateral torsional buckling of Non prismatic I beam was studied by Gupta et al. [22] using

finite element program. Their study was mainly confined on the use of increase in number of spans on buckling loads of non-prismatic beams. They found that there is increase in buckling load from single span to double span beams [23]. However beyond two spans change in the buckling capacity was very minimal.

Methodology

First of all, in this study, research objectives were formulated after a rigorous literature survey followed by finding research gaps. In order to study the lateral-torsional buckling behavior of an I beam of a Jib crane subjected to vertical load at the free end and self-weight finite element modeling and analysis were done. In this study, two different types of sections were taken for the purpose of analysis. Firstly a conventional I beam was analyzed for lateral-torsional buckling behavior and was compared with an I beam having trapezoidal corrugations under similar loading conditions. In this study, in place of conventional I beam having a flat web, a trapezoidal web corridor is proposed. This new design approach is proposed to predict the buckling behavior of the beam having web corrugation and how this new design approach affects the overall economy of the section. Firstly, different models of I beams with web corrugations were modeled on Auto CAD software, and then these models were analyzed using ANSYS workbench 15.0 software. For this study, insert mounted FS 350 Gorbel Crane was chosen to have parameters as shown in Table 1.

As per previous literatures and analysis done by past researchers, I beam S10@25.4 lb/ft is chosen for analysis whose section properties are given in Table 2.

Load Calculation

A jib crane is subjected to different combinations of loading cases, as discussed below and depicted in Fig. 1a

Trolley weight The weight of the trolley and equipment attached to the trolley.

Dead load The self-weight of the beam.

Hoist load The working load and the weight of the lifting devices.

Vertical inertia forces Dead Load Factor + Hoist Load Factor. According to CMAA [24], Dead load factor equals 1.2 and Hoist load factor equals 0.15.

Table 1 Crane properties

Description	Capacity	Rotation	Span	Mast diameter
Gorbel Crane FS350	500 kg	360°	2.54 m	300 mm

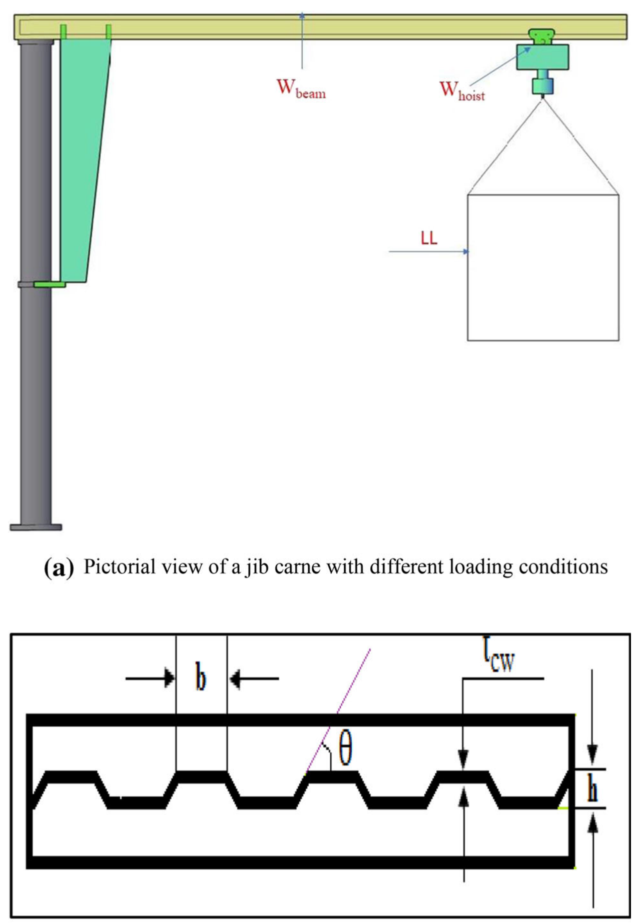
Inertia Forces from drive The inertia forces occur during acceleration or deceleration or crane motions and depend on the driving and braking torques. Inertia forces from drives equals to 2.5% of the vertical load.

Load calculation based on these considerations are presented in Table 3.

Firstly, modeling of a conventional I beam was done on AutoCAD software, and then it was imported to ANSYS software for finite element analysis. Then proposed I beam with trapezoidal corrugation in the web were modeled and analyzed using the same software for comparative study of

Table 2 Section properties of selected beam

Description	Thickness of flange	Thickness of web	Width of flange	Overall depth
S10×25.4	12.5 mm	8 mm	118 mm	254 mm



(a) Pictorial view of a jib carne with different loading conditions

(b) Trapezoidal corrugation of the proposed web of the I beam

Fig. 1 (a) Pictorial view of a jib carne with different loading conditions. (b) Trapezoidal corrugation of the proposed web of the I beam

Table 3 Load calculations

S. No.	Description	Calculation
1	Static load	
	Lift Load (LL)	500 kg × 9.81 = 4.9 kN
	Total weight of the hoist with trolley and jib beam	149.68 × 9.81 = 1.46 kN
2	Dynamic loads with CMAA factors	
	Due to Hoist with trolley and jib beam dead load	1.2 × 1.46 kN = 1.752 kN
	Due to lifted load	LL × (1 + 0.15) = 4.9 × 1.15 = 5.635 kN
	Due to any lateral movement (inertia from drives) 2.5% of total vertical load (LL + hoist load+ dead load of beam)	(2.5/100) (5.635 + 1.752) = 0.183 kN

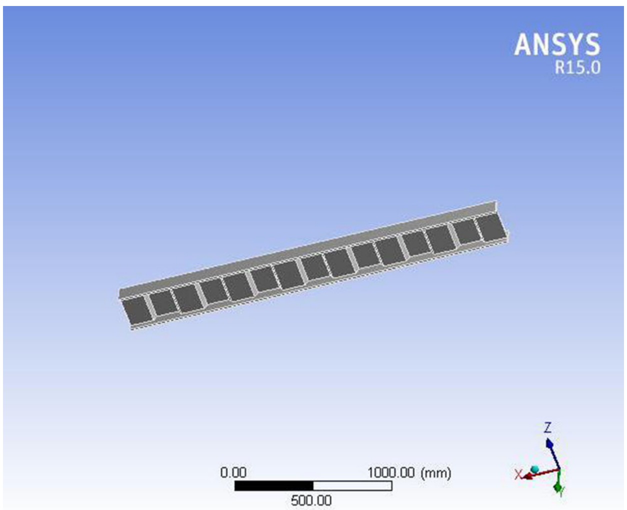


Fig. 2 Trapezoidal corrugation of the proposed web of the I beam

the buckling behavior of the beam. Figure 1b shows the top view of the proposed I beam with a trapezoidal corrugation in the web. 3D view of the same model, when imported to ANSYS software for finite element analysis, is shown in Fig. 2.

For this study, a total of 32 models were prepared and then analyzed using finite element software ANSYS. Table 4 shows the properties of the trapezoidal web taken for analysis purposes. It is shown in Table 4 that two different web thicknesses of 6mm and 8mm were taken having variable corrugation angles.

Thirty-two models of corrugated web section of various proposed beams with different variations in their properties for analysis are presented in Table 5.

Conventional I beam with plane web was first modeled on Auto Cad software (Fig. 3a) and then compared with I beam having trapezoidal web with corrugations (Fig. 3b). For finite element analysis, these models were then imported to ANSYS workbench 15.0 and analyzed. In ANSYS software 2D and 3D mesh of given areas or volumes can be done using meshing tools. For meshing, an

Table 4 Selected parameters of the trapezoidal web for finite element analysis

Web Thickness (t_{cw})	Corrugation Angles (θ)	Infill corrugation plate length (b)	Corrugation web width (h)
6, 8 mm	30°, 45°, 60°, 75°	150, 250 mm	25, 35 mm

Table 5 Various Proposed models with variation in their properties

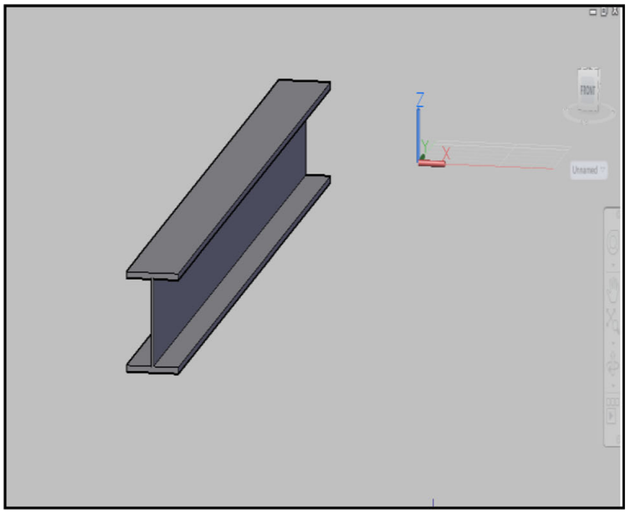
Model No	Web thickness (t_{cw})	Corrugation parameters		
		Angles (θ)	Width (h)	Plate length (b)
1–8	6.8	30°,45°,60°,75°	25	150
9–16	6.8	30°,45°,60°,75°	35	150
17–24	6.8	30°,45°,60°,75°	25	250
25–32	6.8	30°,45°,60°,75°	35	250

element size is taken based on a convergence study. The convergence study done in this paper is shown in Table 6. From this table, it can be observed that after a mesh size of 10 mm, the convergence of displacement is achieved. Hence 10 mm mesh size is used in this analysis for further investigations and design. Graphical interpretation of convergence study is depicted in Fig. 4. The movement of the beam is completely restricted at the left end by providing fixed boundary conditions. Once the boundary conditions are fixed, then a total lift load as calculated earlier is applied at the free end in the transverse direction equally distributed in an area of 118 × 100 mm.

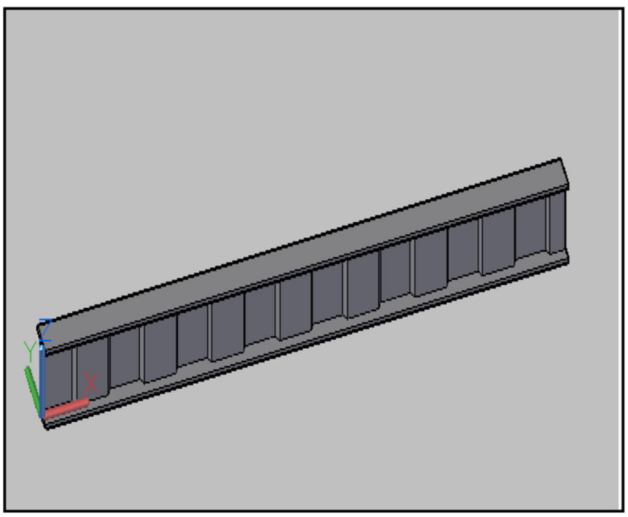
Results and Discussion

FEA Results for a Conventional Beam

First of all, the finite element analysis for a conventional I beam is carried out to find the buckling load, maximum shear stress, and equivalent stresses. The results for the



(a) Modeled Conventional I beam



(b) Modeled I beam with Trapezoidal corrugations in web

Fig. 3 (**a**) Modeled Conventional I beam. (**b**) Modeled I beam with Trapezoidal corrugations in web

Table 6 Convergence study data

Mesh size (mm)	Number of elements	Maximum displacement
70	5598	7.5194
60	5793	7.5176
50	4706	7.4189
40	7763	7.5174
30	13509	7.5077
20	17015	7.4632
10	30536	7.6598
5	121776	7.6599

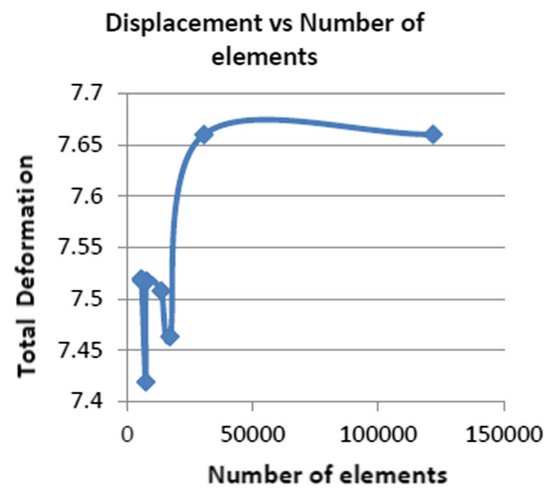


Fig. 4 Convergence study for Finite element analysis

Table 7 Finite element analysis results for conventional beam

Buckling load (kN)	Maximum shear stress (MPa)	Equivalent stress (MPa)	Maximum principal stress (MPa)
81.0	56.86	106.82	160.27

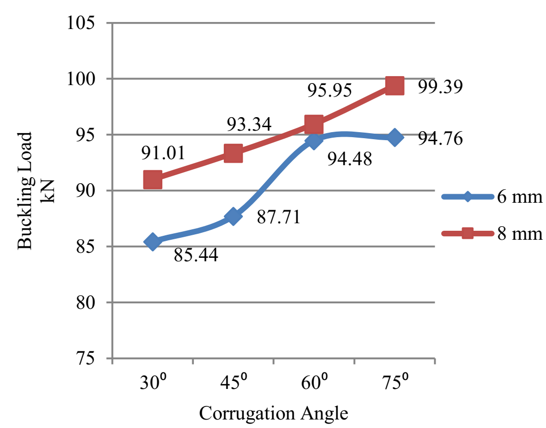


Fig. 5 Buckling load vs corrugation angle for variable web thickness of 150mm plate length and 35 mm web width

same are presented in Table 7. Buckling load is determined only for the first mode by multiplying the load multiplier by the applied load.

FEA Results for Corrugated Beams for Buckling Load and Maximum Shear Stress

In Fig. 5, a comparative study has been plotted between buckling load and corrugation angle for two different web thicknesses with a constant web width of 35 mm and corrugation plate length of 150 mm. An increasing trend in

Table 8 Buckling load and shear stress for 32 models analyzed in FEM software

Corrugation plate length (mm)	Web width (mm)	Web thickness (mm)	Buckling load (KN)				Maximum shear stress (MPa)			
			30°	45°	60°	75°	30°	45°	60°	75°
150	25	6	71.32	84.73	86.48	87.84	64.36	61.32	60.27	60.00
		8	88.25	90.24	92.00	93.82	58.01	57.30	55.59	50.79
	35	6	85.44	87.71	94.48	94.76	61.31	60.93	55.34	53.00
		8	91.01	93.34	95.95	99.39	56.32	55.79	54.54	49.14
250	25	6	70.22	83.22	83.00	83.83	64.64	62.31	60.99	60.64
		8	86.57	88.81	89.80	89.85	58.07	57.33	56.14	55.82
	35	6	84.15	84.00	87.49	87.56	62.18	60.82	60.48	60.00
		8	89.28	90.05	93.45	93.73	57.28	56.64	55.71	54.11

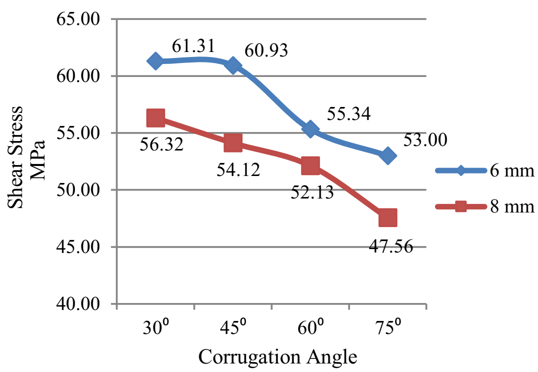


Fig. 6 Shear stress vs corrugation angle for variable web thickness of 150 mm plate length and 35 mm web width

the graph can be observed, showing a maximum buckling load of 99.39 kN when the corrugation angle is 75°.

Table 8 shows the values of the buckling load generated for all the 32 models when analyzed for finite element modeling using ANSYS software. Similarly, shear stress variations for the beam with different corrugation angles are also presented in Table 8.

Figure 6 predicts the graphical interpretation of Table 8 for maximum shear stress. For corrugation plate length of 150 and 35 mm, web width shear stress decreases with an increase in corrugation angles. Equivalent stress (Table 9) for the beam of corrugation plate length 150 mm and web width 35 mm with variable thickness are plotted in Fig. 7. With an increase in corrugation angle, the equivalent stress also decreases.

Other beams with different specifications also show a similar trend and displayed in Table 8. Buckling load behavior for two different corrugation plate lengths was also studied and plotted for comparative study. From Fig. 8, it can be seen that the corrugation plate length of 150 mm shows better results when compared to the 250 mm corrugation length.

From graph (Fig. 8), it can be seen that maximum buckling load decreases from 94.76 to 87.56 kN when corrugation length is increased from 150 to 250 mm, keeping web width constant at 6mm.

Shear stress variations for the beam having variable corrugation plate lengths of 150 and 250 mm are shown in Fig. 9. In this case, also 150 mm corrugation length shows better results than 250 mm. The increase in equivalent stress with an increase in plate length is seen. At 75° corrugation angle, equivalent stress for 250 mm corrugation plate length is higher than 150 mm corrugation length (Fig. 10).

Similarly, when web width increases, an increase in buckling load is observed for two different web widths of 25 and 35 mm. In this case, also (Fig. 11) at corrugation angle of 75° maximum buckling load of 94.76 kN is observed for 35 mm web width. In Fig. 12 effect of shear stress on a beam of variable web width is shown when plotted against different corrugation angles. It is evident that minimum shear stress occurs for 35 mm web width. Equivalent stress, when plotted against corrugation angles for different web widths shows a similar pattern (Fig. 13). In this case, the equivalent stress for 35 mm web width is 105.9 MPa when compared to 25 mm web width, which was 108 MPa. When the effect of buckling load with an increase in corrugation angle for variable web thickness of 6mm and 8mm was checked, there was a rise in buckling load capacity when the corrugation plate length was fixed at 150 mm (Fig. 14). In Fig. 15, maximum shear stress is plotted against variable web thickness of 6 and 8 mm when the width of the web was 35 mm with a length of corrugation was 150mm. Although in this case there is a small change in the value but 8mm thickness showed a better result. At last, the equivalent stress was plotted with a change in corrugation angle (Fig. 16) and found to decrease. Again, in this case, for 8 mm thickness of the web, the value of equivalent stress came to be minimum.

Table 9 Equivalent stress and Maximum Principal stress for 32 models analyzed in FEM software

Corrugation plate length (mm)	Web width (mm)	Web thickness (mm)	Equivalent stress (MPa)				Maximum principal stress (MPa)			
			30°	45°	60°	75°	30°	45°	60°	75°
150	25	6	118.50	113.39	111.10	110.90	157.70	157.00	156.70	156.20
		8	109.24	107.81	108.20	108.00	156.50	156.40	155.00	155.00
	35	6	108.42	107.57	106.60	105.90	156.90	156.10	155.00	155.90
		8	107.96	106.81	106.10	105.90	156.40	156.00	154.20	154.80
250	25	6	121.73	115.78	114.60	114.00	158.00	157.90	157.90	156.90
		8	109.99	109.34	109.20	108.70	157.40	156.60	156.10	156.00
	35	6	116.96	115.32	114.00	113.30	157.90	157.40	156.60	156.30
		8	110.32	109.08	108.30	107.20	157.30	157.20	156.10	156.10

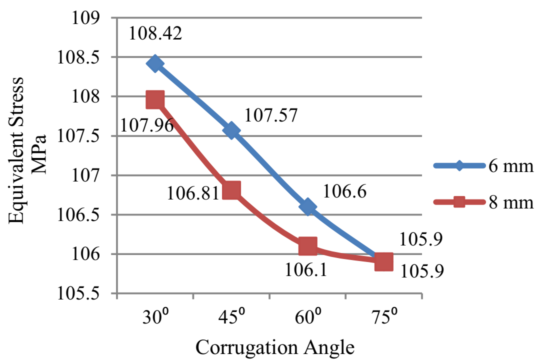


Fig. 7 Equivalent stress vs corrugation angle for variable web thickness of 150 mm plate length and 35 mm web width

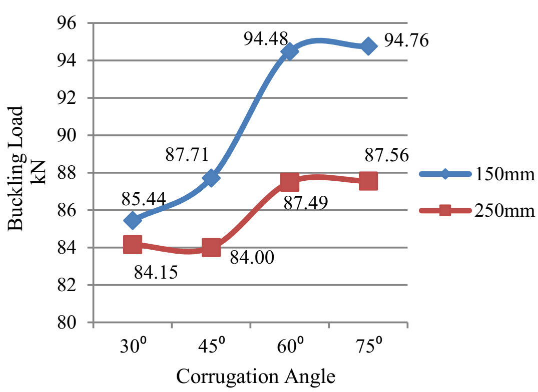


Fig. 8 Buckling load vs corrugation angle for variable Corrugation plate length of 35 mm web width and 6mm web thickness

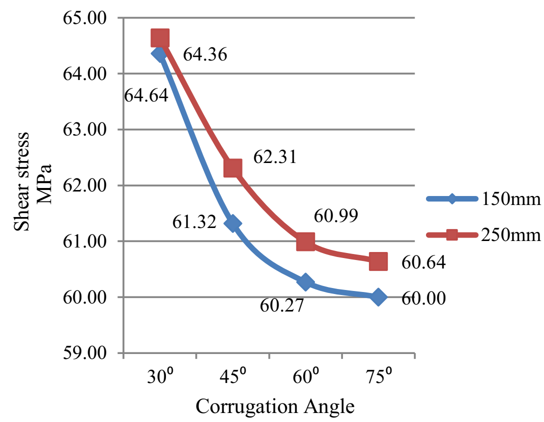


Fig. 9 Shear stress vs corrugation angle for variable Corrugation plate length of 25 mm web width and 6 mm web thickness

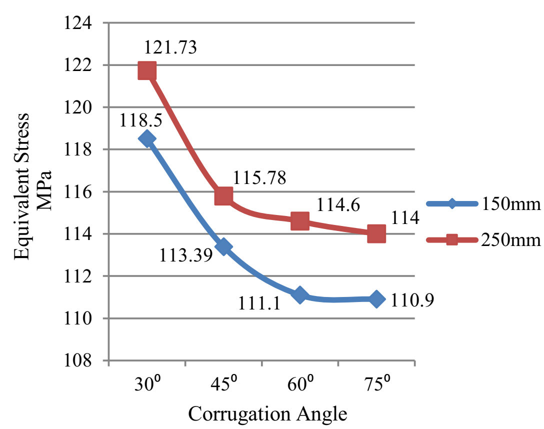


Fig. 10 Equivalent stress vs corrugation angle for variable Corrugation plate length 25 mm web 150 mm plate length and 35 mm web width and 6 mm web thickness

Optimization assessment and comparative study

A conventional I beam without any web corrugations was compared with these 32 models. In order to predict the best suitable model, only weight and buckling load criteria are adopted in this study. The model to be chosen for this comparative study must satisfy the following two conditions.

Condition 1 Proposed I beam should be lightweight when compared to conventional beam

Condition 2 Proposed I beam should have higher buckling load capacity when compared to its conventional counterparts

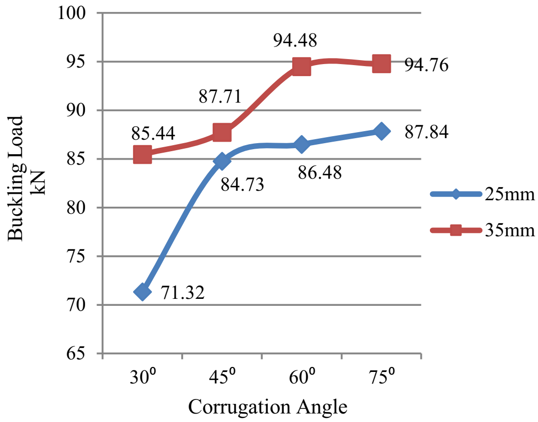


Fig. 11 Buckling load vs. corrugation angle for variable web width of 150 mm plate length and 6 mm web thickness

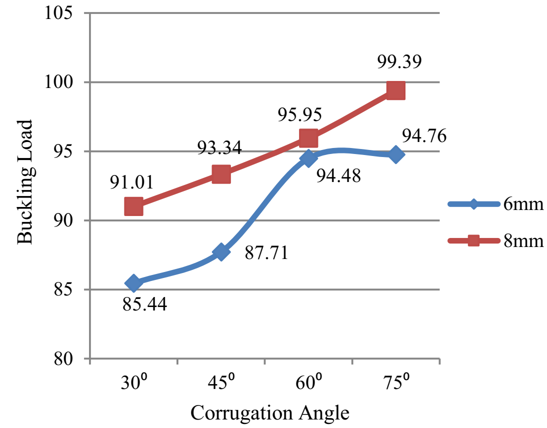


Fig. 14 Buckling load vs. corrugation angle for variable web thickness of 150 mm plate length and 35 mm web width

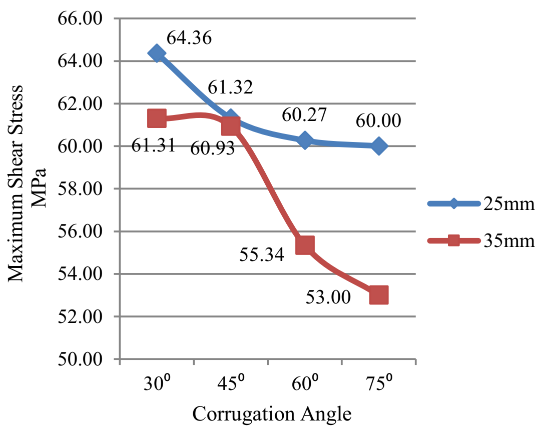


Fig. 12 Shear stress vs. corrugation angle for variable web width of 150 mm plate length and 6 mm web thickness

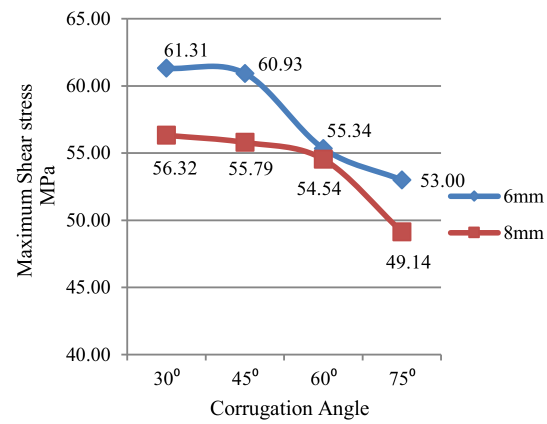


Fig. 15 Maximum shear stress vs. corrugation angle for variable web thickness of 150 mm plate length and 35 mm web width

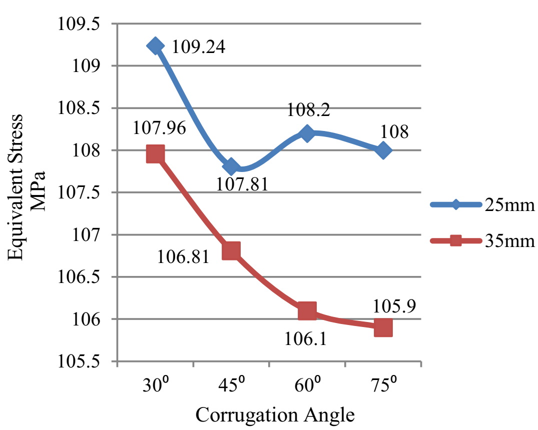


Fig. 13 Equivalent stress vs. corrugation angle for variable web width 150 mm plate length and 8 mm web thickness

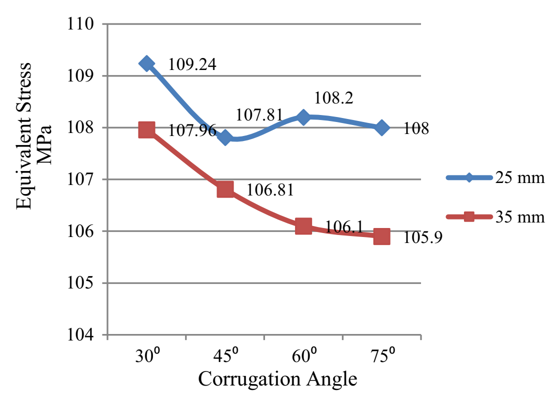


Fig. 16 Equivalent stress vs corrugation angle for variable web thickness 150 mm plate length and 8 mm web thickness

In order to satisfy the above two conditions simultaneously firstly, the weight of all the 32 models was directly taken from ANSYS software. After comparing the above two conditions for all the 32 models, it was found that model number 13 satisfies both conditions simultaneously.

From Table 10, it can be observed that corrugated beam having corrugation angle 60° having web width of 35 mm, web thickness of 6 mm, and corrugation plate length of

Table 10 Weight of the proposed corrugated beams

Corrugation plate length mm	Web width mm	Web thickness mm	Weight (Kg)			
			30°	45°	60°	75°
150	25	6	87.15	87.78	88.56	89.53
		8	96.60	97.43	98.46	99.76
	35	6	74.93	88.24	89.32	90.56
		8	96.96	98.05	99.48	101.17
250	25	6	86.79	87.22	87.61	88.07
		8	96.11	96.69	97.21	97.21
	35	6	87.02	87.51	88.17	88.82
		8	96.42	97.07	97.96	98.82

Table 11 Comparative Results between the flat beam and corrugated beam

Model	Weight (Kg)	Buckling load (kN)	Maximum shear stress (MPa)	Equivalent stress (MPa)	Maximum principal stress (MPa)
Flat beam	95.48	81.00	56.86	106.82	160.27
Corrugated beam	89.32	94.48	55.34	106.61	155.00

150 mm offers high buckling load capacity. Moreover, since the weight of this beam is less than a flat beam, it is lightweight and will be economical. A comparative study done for both cases is presented in Table 11. Only limitation of this study is that it does not take into the consideration substantial increase in labor cost due to beam fabrication with corrugated web versus other conventional beam configurations.

Conclusion

From the above study, the lateral-torsional behavior of the beam when subjected to lift load at the free end and self-weight is analyzed using finite element software, and a new design concept is proposed. From the finite element analysis and comparing the results, following points can be concluded

- Trapezoidal corrugation in the web increases the lateral-torsional buckling capacity when compared to conventional flat beams. As a result, equivalent and principal stresses also get reduced.
- Out of 32 models used for analysis, the beam whose web thickness is 6 mm, corrugation length 150 mm, and width of web 35 mm showed better buckling load capacity. Moreover, this model also has lesser weight than a conventional flat beam and hence will be economical.
- Resistance to lateral-torsional buckling is influenced by the width of corrugated web and web thickness. At 75° of corrugation angle, maximum resistance to lateral-torsional buckling is observed for all the cases.

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