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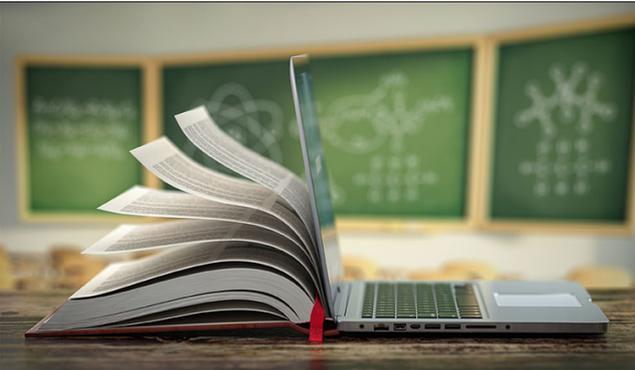
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Lateral-Torsional Buckling Behaviour of Triangularly Tapered Corrugated Web Beam

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Abstract. This paper presents a study of the behaviour of Lateral-Torsional Buckling (LTB) that is one of the common failure modes of large span beams. LTB for non-prismatic I-beams still needs more investigations, due to its sophisticated formulation for cross-section properties. This paper presents the results of numerical (Finite Element Software ABAQUS) and theoretical analysis for LTB of a simply supported I-beam with triangularly tapered corrugated web under concentrated loads. The corrugation densities adopted in this study represent the most commonly used types for such structures in practice of construction. For numerical analysis, the formulas were adopted from the case of a trapezoidal corrugated web, which is successfully verified by different authors. Recommendations of this study are given for simply supported tapered triangularly corrugated web at lateral torsional buckling.

1. Introduction

Tapered or non-prismatic structures have been used principally for bridges and industrial structures. When these kinds of elements are designed with corrugated web that is shown in figure 1, the weight of the structure can be reduced alongside with the improvement in the structure's stability. Although tapered (non-prismatic) beams are not so common and less common is the usage of triangularly corrugated web (TCW) beams for such structures.

The typical types of web used in steel structures are sinusoidal and trapezoidal web, in otherwise TCW is not so common to use in construction despite of all the advantages it has over the others, for example, the web could be thicker than others and have at the same time the better bearing capacity. This is especially important for heavy operating conditions that are characterized by aggressive environment and large values of loads on the structures. Due to its profiled form, corrugated web exhibits enhanced shear stability and therefore eliminate the need for additional transverse stiffeners or thicker web plates [1].

The first detailed studies about LTB of non-prismatic I-girders with flat webs were carried out by Kitipornchai and Trahair (1972) [2], Zhang Lei and Tong Geng Shu [3] have more recent studies about statically determined beams or cantilevers. Elgaaly (1996) was focused on the vertically trapezoidal corrugation. The studies found that the failure of beams under shear loading is due to local buckling of the web for coarse corrugation and global buckling on the web for dense corrugation [4].

There are limited studies about the LTB phenomenon of non-prismatic I-girders even with flat webs have been carried out, as well as the research studies on TCW at such conditions are very limited too. A numerical analysis is carried out by Sayed-Ahmed (2005) shows that resistance to lateral torsion-flexure buckling of such girders is from 15% to 37% higher than the resistance of plate girders with traditional plane webs [5].



Hasan, Denan and Keong (2015) presented experimental study of the buckling moment resistance ($M_{b,Rd}$) of triangular web profile (TWP), which was determined on the basis of the LTB experimental values of the TWP steel section. The main conclusion was that the section properties such as width, depth, flange thickness, web thickness and corrugation shape of web profile affect the buckling moment resistance, $M_{b,Rd}$, of the steel section. The larger section properties of steel sections increase moment buckling resistance [6].

In recent research, Kudryavtsev (2018) presented an investigation into the behaviour and design of triangularly corrugated steel web beams with web openings. He recommended that it is possible to make openings in corrugated web beams in areas of pure bending or in areas with minimal shear stresses. In this case, it is generally possible to avoid additional reinforcement of the opening [7]. Also, Kudryavtsev (2019) investigated LTB behaviour of prismatic triangularly corrugated web beam and proposed a design recommendation for simple supported case accordance with numeral results [8].

This paper presents a calculation for lateral-torsional buckling on triangularly non-prismatic beam with triangularly corrugated web. The numerical parametric studies analysis is compared with a parametric study of finite element analysis (FEA), which carries out for simply supported beams. This parametric study considered various cases including different type of non-prismatic section, span of the beam and the corrugation density expressed as a ratio between height and length of half-wave of corrugation.

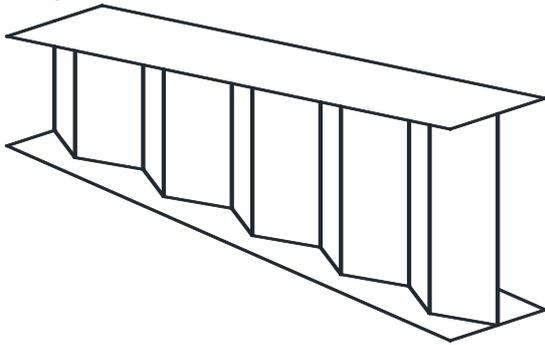


Figure 1. Section of non-prismatic triangularly corrugated web beam.

2. Design of non-prismatic triangularly corrugated web steel beam

The limitations for this study are similar for a steel plate girder with a flat web plate. The destruction of steel beam with a corrugated web may occur for several reasons: due to the exhaustion of the load-bearing capacity of flanges at bending or corrugated web at shear; due to local buckling of compressed flange or at areas of the web; due to overall buckling of the entire structure. In addition, according to the conditions of suitability for normal operation, the maximum vertical deflections of the beam must be limited [8].

Geometrical parameters of the structure and the beam design scheme adopted for this study are shown in figure 2. The AISC Specification [9] covers the design of a doubly symmetric web-tapered I-girder with equal flange. The depth of web varies linearly as follows,

$$h_w = h_{w,\min} \left(1 + \frac{l-z}{l} \xi \right), \quad (1)$$

where ξ is the taper ratio calculated by

$$\xi = \frac{h_{w,\max} - h_{w,\min}}{h_{w,\min}} \leq 0.268 \frac{l}{h_{\min}} \leq 6.0, \quad (2)$$

in which h_w is the web height that variable over the span of the beam l , $h_{w,\min}$ and $h_{w,\max}$ are the web heights at the each ends of the structure, z is position of cross-section from the lower end of the beam.

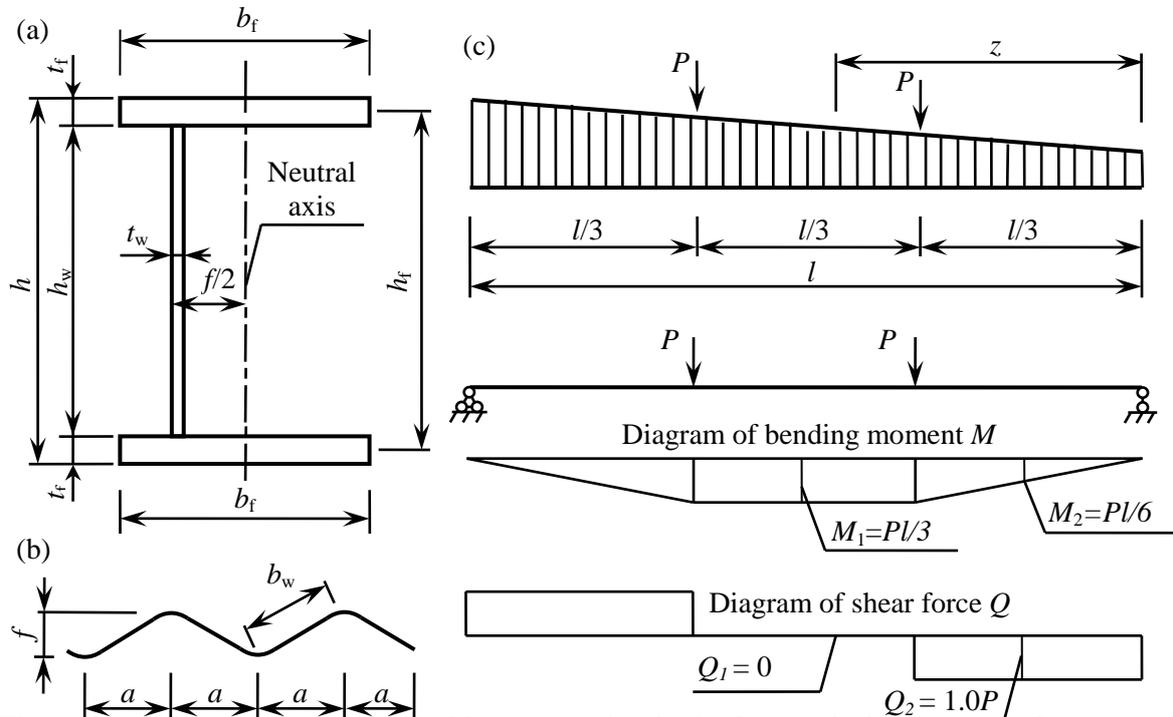


Figure 2. (a) Cross section of beam with corrugated web; (b) Geometrical parameters of corrugated web with triangular shaped corrugations; (c) Considered beam design scheme.

In the study of Samanta and Mukhopadhyay [9] given the formula to calculate the shear modulus G_c for trapezoidal corrugated web that could be adopted for the case of triangularly corrugated web by

$$G_c = \frac{2a}{a + b_w} G, \quad (3)$$

in which $G = 78000MPa$ is shear modulus for steel.

The pure torsional constant I_c of a steel I-beam, according to Lindner [10] could be determined by

$$I_c = \frac{2b_f t_f^3 + h_w t_w^3}{3}. \quad (4)$$

Considering the study of Nguyen [11], the moment of inertia on the weak axis (y axis) $I_{y,c}$ and warping constant of I-beam with trapezoidal web corrugations $C_{w,c}$ are a quadratic function of corrugation height f and varies depending on changing of f from 0 to f_{max} along the beam span. To simplify the expressions for $I_{y,c}$ and $C_{w,c}$ are given like an average values between case with $f = 0$ and case with $f = f_{max}$ as follows:

$$I_{y,c} = \frac{t_f b_f (2t_f b_f^3 + t_w h_w b_f^2 + 12(f/2)^2 t_w h_w)}{6(2t_f b_f + t_w h_w)}, \quad (5)$$

$$C_{w,c} = \frac{h_w^2 t_f b_f (6t_f b_f^3 + t_w h_w b_f^2 + 12(f/2)^2 t_w h_w)}{24(6t_f b_f + t_w h_w)}. \quad (6)$$

Also, Nguyen [11] proposed a formula to evaluate an elastic lateral-torsional buckling strength of an I-beam for a simply supported conditions

$$M_{ocr,c} = \frac{\pi}{l} \cdot \sqrt{EI_{y,c} G_c I_c} \cdot \sqrt{1 + W_c^2}, \quad (7)$$

where $W_c = \frac{\pi}{l} \sqrt{\frac{EC_{wc}}{G_c I_c}}$ represents the effect of warping torsional stiffness.

Nguyen, Nguyen-Van, Han, Choi and Kang [12], adopted formula for I-beam with flat webs according the SSRC Guide [10] to determinate the critical moment of a prismatic I-beam with corrugated webs, warping fixed, lateral bending fixed, and completely fixed end restraint conditions as follow

$$M_{cr,c} = C_{b,c} \frac{\pi^2 EI_{y,c}}{(kl)^2} \cdot \sqrt{\left(\frac{k}{k_w}\right)^2 \frac{C_{w,c}}{I_{y,c}} + \frac{(kl)^2 G_c I_c}{\pi^2 EI_{y,c}}}, \quad (8)$$

where k is the lateral bending coefficient and k_w is the warping coefficient. For free lateral bending $k = 1$. For free warping $k_w = 1$. For lateral bending fixed $k = 0.5$ and for warping fixed $k_w = 0.5$.

Nguyen, Nguyen-Van, Han, Choi and Kang [12] proposed the closed-form expression for moment modification factor $C_{b,c}$ which is applicable for linear and non-linear moment diagrams

$$C_{b,c} = \frac{12.5M_{\max}}{2.5M_{\max} + 3M_A + 4M_B + 3M_C}, \quad (9)$$

where M_{\max} is the absolute maximum moment along the beam span l , and M_A , M_B and M_C are the absolute moments at the quarter, the centre, and the three-quarter point, respectively. Consequently, with any end restraint conditions, the values of $C_{b,c}$ are the same. The values of $C_{b,c}$ for the I-beam with corrugations under moment gradient have not yet been proposed [11]. The values of $C_{b,c}$ are could be written by the next equation for a simply supported beam

$$C_{b,c} = -0.078\alpha^6 - 0.19\alpha^5 - 0.274\alpha^4 - 0.182\alpha^3 + 0.364\alpha^2 + 1.219\alpha + 1.829, \quad (10)$$

where α is the end moment ratio i.e. $-1, 0 \leq \alpha \leq 1, 0$.

3. Numerical parametric study

Typical finite element model adopted for the corrugated web beams are shown in figure 3a. Herein, the study was developed in the software ABAQUS. The models are composed of upper and lower flanges and triangularly corrugated webs with different heights.

Table 1. Geometry data of analysis models.

Model	a , mm	f , mm	b_w , mm	t_w , mm	$h_{w,min}$, mm	$h_{w,max}$, mm	b_f , mm	t_f , mm	l , mm
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
A1	100	50	111.80	4	220	620	200	10	12000
A2	100	50	111.80	4	320	620	200	10	12000
A3	100	50	111.80	4	420	620	200	10	12000
B1	150	60	161.55	6	220	620	200	10	12000
B2	150	60	161.55	6	320	620	200	10	12000
B3	150	60	161.55	6	420	620	200	10	12000
C1	200	70	211.90	8	220	620	200	10	12000
C2	200	70	211.90	8	320	620	200	10	12000
C3	200	70	211.90	8	420	620	200	10	12000

For the web were assumed three different corrugation densities and three different heights. For each density just one beam span was considered. All the dimensions of the models are given in Table 1. All models were loaded by two concentrated loads $P = 1\text{ kN}$ located in the thirds of the upper flange at the centre line of the structure. Boundary conditions were applied on the lower flange and corrugated web simulating simply supported beam. An elastic material was assumed with a yield strength $R_y = 235\text{ MPa}$, modulus of elasticity $E = 210000\text{ MPa}$ and Poisson's ratio 0.3.

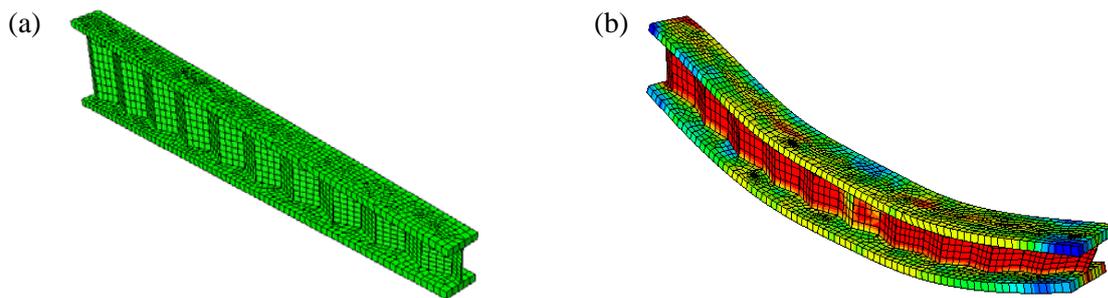


Figure 3. (a) FE model of tapered triangularly corrugated web beam adopted for buckling analysis; (b) Example of the global buckling mode for tapered I-beam with triangularly corrugated web.

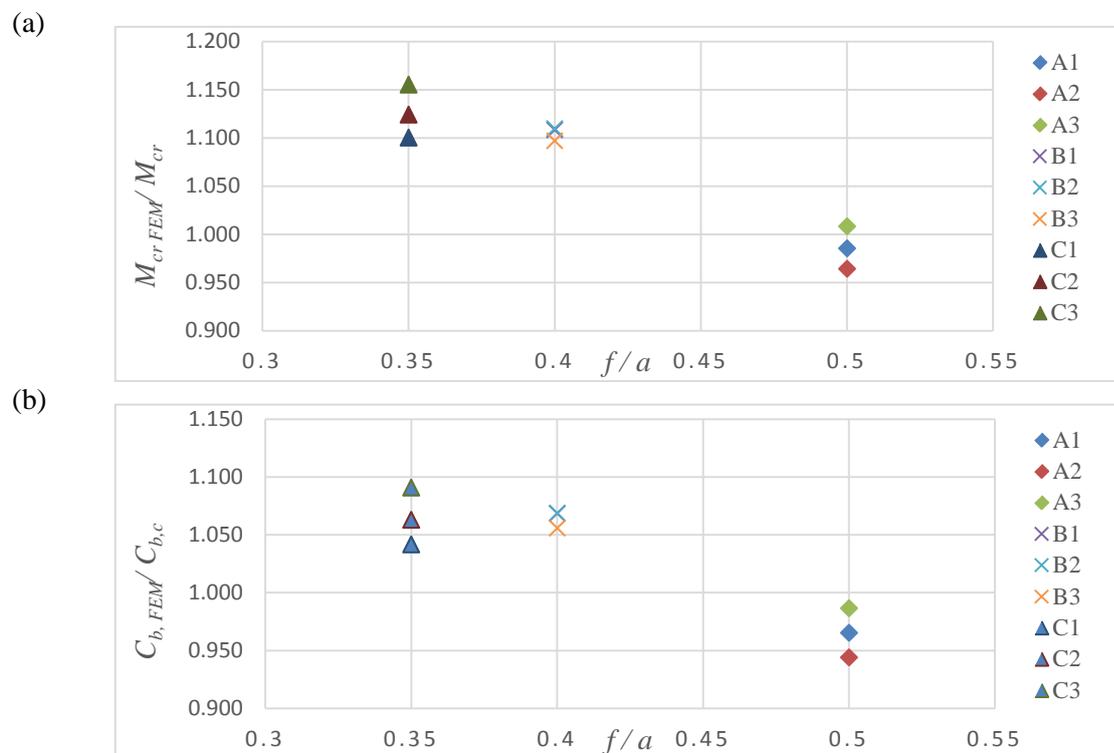


Figure 4. (a) Comparison between $M_{cr,FEM}$ and M_{cr} . (b) Comparison between $C_{b,FEM}$ and $C_{b,c}$.

4. Results of parametric study

In this study, for the tapered I-girder with triangularly corrugated web the critical moment is given by the formula (8). In addition, the values of $C_{b,FEM}$ are calculated as follows

$$C_{b,FEM} = \frac{M_{cr,FEM}}{\frac{\pi^2 EI_{y,c}}{(kl)^2} \sqrt{\left(\frac{k}{k_w}\right)^2 \frac{C_{w,c}}{I_{y,c}} + \frac{(kl)^2 G_c I_c}{\pi^2 EI_{y,c}}}}, \quad (11)$$

in which $M_{cr,FEM}$ is the critical moment of I-beam with tapered triangularly corrugated web at lateral torsional buckling. To calculate $M_{cr,FEM}$, the eigenvalues v derived from the FEA were multiplied by the applied load 1kN, so critical force for LTB is $P_{cr} = 1kN \cdot v$. For case under consideration

$$M_{cr,FEM} = P_{cr} l / 3. \quad (12)$$

Plots with comparisons between $M_{cr,FEM} / M_{cr}$ and $C_{b,FEM} / C_{b,c}$ are given in figure 4 for the different models. The minimum variations are between the models A1, A2 and A3 approximately 3.4%, otherwise the largest discrepancies are found in the models C1, C2 and C3 with approximately 9%, between numerical and analytical analysis.

5. Conclusions

The present study reported the lateral torsional buckling behaviour and design of a triangularly corrugated tapered (non-prismatic) web beams under two concentrated loads on the quarters of the beam. The present work used finite element analysis program to model steel beams with variations in the length and the corrugation web with the same highs for all models.

According to the results, the lateral torsional buckling strength of the non-prismatic I-beam with triangularly corrugated web was determined by using the formulas as the used for a beam with plane web and taking maximum value of M_{cr} with $f = 0$ and $f = f_{max}$. For this reason, it is important to determine modification coefficient for optimal results to the lateral torsional buckling. Undoubtedly, the study of the buckling resistance for such structures requires further investigation considering initial imperfections, type and location of the applied load, the shape of the bending moment, end support conditions and so on.

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