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Lateral torsional buckling strength of unsymmetrical plate girders with corrugated webs

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ABSTRACT

This paper deals with lateral torsional buckling of plate girders with corrugated webs (CWG). The research includes both theoretical and finite element analyses for un-symmetrical plate girders with corrugated webs subjected to uniform moment. A new warping constant for this un-symmetrical cross-section is derived taking into consideration the cross-sectional variation along the girder length. Trapezoidal corrugated web profile is taken into consideration in the derivation. The location of the shear center is determined and a closed form of the warping constant is derived. The un-symmetry of the web-less beam, which agrees with the case of CWG, is considered in the calculation of the lateral torsional buckling strength. The results are verified with those obtained using the finite element technique and gave good agreement. A comparison with different specifications and codes is conducted to investigate the effect of un-symmetry on the plate girder strength. The effect of cross-section geometrical configurations on the lateral torsional buckling strength under uniform moment is investigated and discussed.

1. Introduction

Previous researches and common practices on plate girders with corrugated webs (CWG) indicated that its weight can be much lower, up to 30%, compared with plate girders with flat webs having the same static capacity. As well, using the corrugated webs increases the out-of-plane stiffness and resistance against lateral torsional buckling without the need to add transverse stiffeners or to use thicker web plates. Researchers conducted both analytical and experimental studies on general behavior, bending strength, lateral buckling and lateral torsional buckling capacities of CWG [1–9]. Different types of web configurations and geometrical parameters were investigated.

Many researchers confirmed, both experimentally and analytically, that the contribution of the corrugated web to the ultimate moment capacity can be ignored. Experimentally, the average measured stresses in the flanges, in the elastic range, were close to those obtained using simple bending theory and ignoring the contribution of the web. The longitudinal stresses in the corrugated web, almost all over the web height, were insignificant except very close to the flanges [1]. Ibrahim et al. [2] suggested also that shear deformation of CWG has a considerable contribution and should be added when calculating the vertical deflection of the girder. This is basically because of the accordion effect in the corrugated web longitudinal direction, which gives it high flexibility and hence it might be ignored in the cross-section static calculations.

Till recent, there is no or scarce studies about CWG having unequal top and bottom flanges. Such cross-sections can be used widely in crane tracks girders utilized in the industrial steel buildings. These crane girders are commonly used as un-symmetrical sections and using the corrugated web would improve its lateral torsional buckling capacity, especially for the un-supported compression flange.

In this research, the flexure and torsional rigidities are calculated for un-symmetrical CWG cross section using some basis of the previous studies. The shear center location is determined based on ignoring the corrugated web contribution, due to its high flexibility in the longitudinal direction, as proved before both experimentally and analytically. A new expression for the warping constant of un-symmetrical CWG is derived then the elastic lateral torsional buckling capacity expression for this girder under uniform moment is suggested.

A series of finite element analyses are conducted to verify the proposed equations utilized in this study. Different cross-section geometrical parameters, such as cross section un-symmetry parameter "ρ" and corrugated web parameters a, d and θ as given in Fig. 1(a) are studied to figure their effect on the lateral torsional buckling capacity of the unsymmetrical CWG. The ultimate

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strength is compared with design aspects of the Eurocode and new design suggestions are proposed.

2. Theoretical background

Lindner [6] proposed some empirical formulas for the warping constant of CWG based on tests results. The study confirmed that the torsional section constant may be calculated using the same method as the plate girder with flat web. He also concluded that the interaction between local flange plate buckling and global lateral torsional buckling must be taken into consideration.

Sayed-Ahmed [7] concluded that the resistance of CWG to lateral torsional buckling is higher than those with flat webs, up to 37%. He calculated the lateral torsional buckling strength of the girders using the same conventional equation used for plate girders with flat webs, except using an equivalent web thickness as a function of the corrugated web geometrical configurations.

Ibrahim [8] investigated the lateral torsional buckling capacity of CWG using tubular rectangular flanges. He used the same formula utilized for the elastic capacity of plate girder with flat web but with the modified warping constant suggested by Lindner [6] and using a reduced effective torsional buckling stiffness (GJ_r). It was concluded that this combination of corrugated webs and tubular flanges may result in a higher lateral torsional buckling strength up to 46% than conventional plate girder with flat web having the same cross-sectional area.

Moon et al. [3] derived an expression, based on the force method, for the warping constant C_w of symmetrical CWG based on ignoring the web contribution. The location of the shear center of cross-section lies at a distance d outside the corrugated web. They calculated the warping constant based on average corrugation depth d_{avr}. They also used a reduced shear modulus proposed by Samanta and Mukhopadhyay [10]. The equation for the modified shear modulus of corrugated plate is as follows

$$G_c = \frac{(a+b)}{(a+c)}\,G \tag{1}$$

where G is the shear modulus of flat plates, $(a + b)$ is the projected length of the folded plate and $(a + c)$ is the actual length of the corrugated plate as shown in Fig. 1(a). Fig. 1(b) shows the geometrical configuration of a singly symmetric CWG and the off-center location of the corrugated web plate. They suggested an average corrugation depth d_{avr}, for simplicity, to take the change in corrugation depth into account as follows

$$d_{avr} = \frac{(2a+b)}{2(a+b)}\,d_{max} \tag{2}$$

The warping constant C_w was evaluated by integrating the normalized unit warping W_n curve across the entire cross-section, and based on ignoring the web due to its accordion effect. The final value of the warping constant was to be calculated by summation of the normalized units warping, but without a final expression given for the warping constant.

The final expression for the warping constant of symmetric CWG is developed in the current research by the author and is adopted in its final form as

$$C_{w(Moon)} = C_{w(flat)} + I_w\, d_{avr}^2 \tag{3a}$$

where $C_{w(flat)}$ is the warping constant of symmetric plate girder with flat web and is given as

$$C_{w(flat)} = \frac{I_{y,c}}{4} h_w^2 \tag{3b}$$

where $I_{y,c}$ is the second moment of inertia of CWG about the weak axis and ignoring the web in the calculation. I_w is the second moment of inertia of web plate and is given as $\frac{h_w^3 t_w}{12}$. By substituting Eq. (2) into Eq. (3a), the warping constant of symmetric CWG based on Moon et al. [3] can be enhanced as a function of both geometrical cross-section and corrugated web parameters as in the following equation

$$C_{w(Moon)} = C_{w(flat)} + I_w \left(\frac{2a+b}{2a+2b}\right)^2 d_{max}^2 \tag{4}$$

They utilized the formula used to calculate the lateral torsional buckling strength of plate girder with flat web using the new warping constant derived in Eq. (4). The elastic lateral torsional buckling of CWG under uniform moment can be expressed as

$$M_{cr} = \frac{\pi}{L_b}\sqrt{EI_{y,c}G_cJ_c}\sqrt{1+W_c^2}, \quad \text{with } W_c = \frac{\pi}{L_b}\sqrt{\frac{EC_w}{G_cJ_c}} \tag{5}$$

where L_b is the lateral buckling length of the CWG and J_c is the pure torsional constant of CWG which is considered the same as the corresponding plate girder with flat web and for symmetrical I-shape cross-section and is given as

$$J_c = \frac{1}{3}\left(2b_f t_f^3 + h_w t_w^3\right) \tag{6}$$

Nguyen et al. [4] used the same approach as Moon et al. [3] but considered the corrugated web to be fully active and taken into consideration in the cross-section static properties calculations. The moments of inertia of symmetric CWG was given as

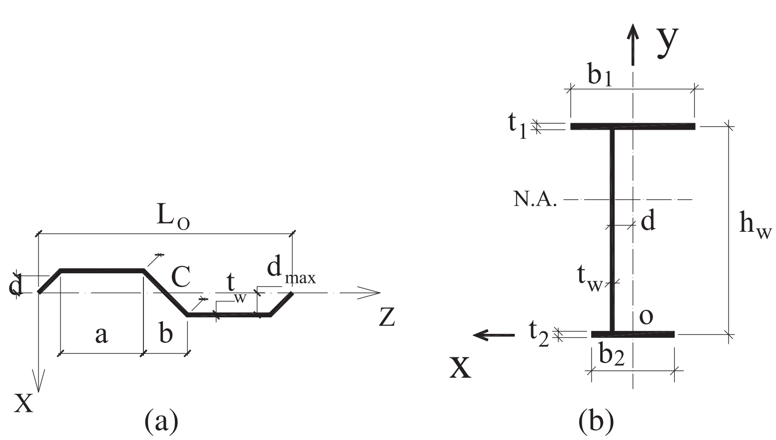

Fig. 1. (a) Trapezoidal corrugated web profile and (b) cross-section of un-symmetric CWG.