Journal of Constructional Steel Research 129 (2017) 185–194

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Elastic critical moment of beams with sinusoidally corrugated webs

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ARTICLE INFO

Article history:
Received 20 June 2016
Received in revised form 10 October 2016
Accepted 4 November 2016
Available online xxxx

Keywords:
Steel structures
Corrugated web beams
Lateral-torsional buckling
Elastic critical moment

ABSTRACT

This paper approaches the elastic critical moment of web-corrugated beams (WCB), either subjected to a uniform bending moment, gradient bending moments, or a uniformly distributed load. Previous research on the subject of lateral-torsional buckling (LTB) of WCB is presented and critically reviewed. Based on earlier studies on the cross-section properties of beams with trapezoidal corrugations, a new method is proposed to obtain the warping or torsional constant of WCB with sinusoidal corrugation. Furthermore, based on an extensive numerical study for a wide range of different corrugation profiles and lengths, it is demonstrated that the present design formulae for the moment modification factor for flat web beams (FWB) could be improved, in order to predict satisfactorily the buckling capacities of WCB under non-uniform bending distributions. Therefore, a new closed-form expression for the moment modification factor is proposed and successfully verified. Finally, by comparing the analytical results with those obtained from a linear buckling analysis (LBA) carried out using shell finite elements, it is demonstrated that the proposed modifications lead to an accurate prediction of the buckling strength of WCB.

1. Introduction

The use of web-corrugated beams (WCB) has been increasing considerably during the last years for various structural applications, especially in industrial/commercial buildings and bridges, due to their high load-carrying capacity in relation to the material usage. The major asset of this structural solution lies in taking advantage of the increase of rigidity provided by the corrugated web, that leads to an higher resistance against local buckling and to an improved shear capacity, combined with a weight reduction up to 30% [1], when compared to beams with flat webs. Furthermore, due to their intrinsic properties, it is possible to achieve adequate out-of-plane stiffness and lateral torsional buckling (LTB) resistance without the need to increase the thickness of the web plate [1] or the need to use additional transversal and/or longitudinal stiffeners.

Since the first developments of WCB, especially in Germany and Austria in the 1990's, a considerable number of researchers have performed experimental, analytical and numerical studies on the behaviour of these beams under different loading conditions to investigate their response against shear, bending and compressive patch loads. Concerning the flexural and torsional behaviour of WCB, the most cited studies could be summarized as follows; Elgaaly et al. [3], found that the web could be neglected in the calculation of the bending resistance and that the load-carrying capacity should be based on the flange yield strength. Abbas et al. [4,5], stated that the flexural capacity of WCB cannot be analysed by the conventional beam theory alone, since under in-plane loading an additional torsional moment is produced resulting in an out-of-plane twist simultaneously with the in-plane deflection. Lindner [6], based on the study of the lateral-torsional behaviour of these beams, has developed a formula to calculate the warping constant of WCB, letting the remain cross-sectional constants considered equal to those used for flat web beams (FWB). In the same publication, it was concluded that, for such conditions, the interaction between local plate buckling and overall LTB needs to be taken into account. Moon et al. [7], have proposed approximated methods for locating the shear centre and calculating the warping constant; Nguyen et al. [2,8] proposed new general formulae for the cross-sectional properties (moments and product of inertia), also for locating the shear centre and to calculate the warping constant, as well as for the determination of the moment modification factors of WCB under moment gradients.

Since the corrugated web is not supposed to resist axial forces due to the so-called *accordion effect* [7], WCB subjected to bending are designed considering that only the flanges resist to the bending moment. On the other hand, such beams have a considerably higher LTB capacity than that of FWB, owing to an increased rigidity, which translates into a higher elastic critical moment for lateral-torsional buckling, M_{cr}. However, Eurocode 3 [9,10] does not provide information on how to compute M_{cr}, only stating that it should be based on the gross cross-sectional properties and take into account the loading conditions, the real moment distribution and the lateral restraints without further reference for WCB. Therefore, it is paramount to find an analytical expression to predict the buckling strength of WCB. In this context, the main difference in the existing expressions to calculate M_{cr} for I-beams with flat webs, is the influence of the torsion and warping constants, which

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http://dx.doi.org/10.1016/j.jcsr.2016.11.005
0143-974X/

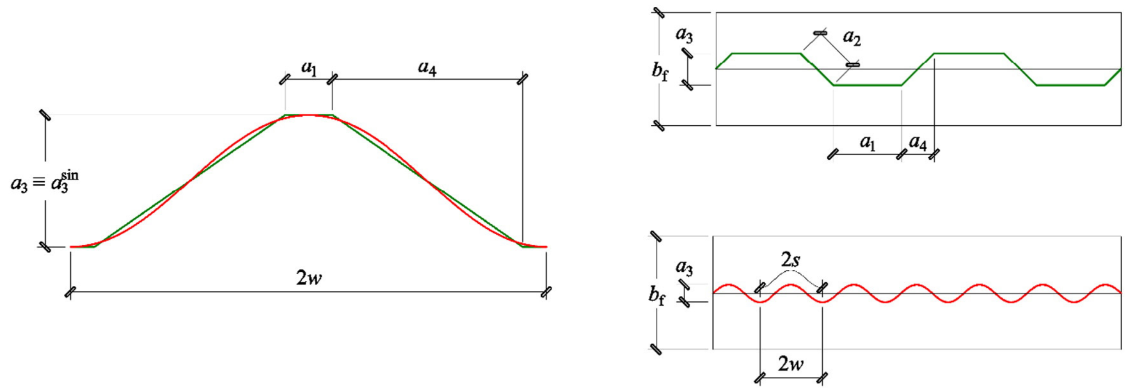

Fig. 1. Scheme of the simplified method to convert the sinusoidal corrugation shape into an equivalent idealized trapezoidal corrugation (geometric notations from the Annex D of EN1993-1-5 [10]).

are not well established for beams with corrugated webs. According to Lindner [6], the increased resistance against lateral-torsional buckling provided by the corrugated web, should be attributed only to an increased warping constant, I_w. However, by studying the torsional response of girders with trapezoidally corrugated webs, Larsson and Persson [11] stated that the extra stiffness should instead be attributed to an increased torsion constant, I_t.

In addition, regardless of the fact that LTB is one of the main design aspects of slender I-beams subjected to bending, studies on this behaviour on WCB are scarce, and their majority focus on the trapezoidal corrugation under uniform bending moment. Therefore, one of the objectives of this paper is to propose a simplified approach to enable the use of the previously developed methods for calculating the cross-sectional constants (torsion and warping), and thus obtain the elastic critical moment of WCB with different types of web configurations and geometrical parameters. Focusing on this aspect, general formulae are proposed for WCB with sinusoidal corrugations to calculate the torsion and warping constants (using the same expressions indicated in [6, 11]), and to obtain the equivalent uniform moment factor, C_1, of WCB with either trapezoidal or sinusoidal corrugations.

The methodologies proposed in this paper result from a parametric study of a finite element analysis (FEA), for which over 2000 numerical simulations were performed for a wide range of corrugated web profiles, using the software Cast3M [12] to carry out linear buckling analyses (LBA) and to obtain the elastic critical moments of WCB. Finally, the accuracy of the presented rules is investigated by comparing them to the obtained numerical results, as well as through comparisons with equivalent methodologies proposed in the literature for WCB with trapezoidal corrugation.

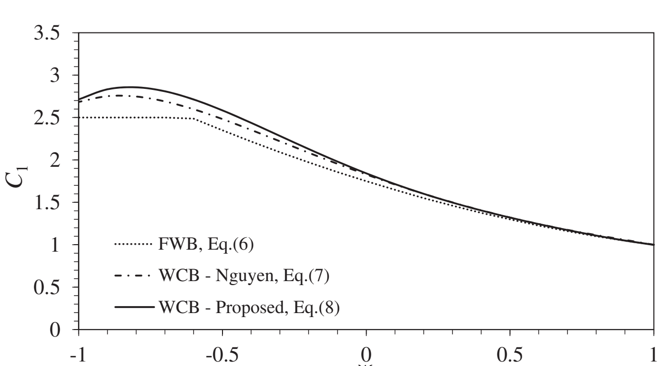

Fig. 2. Comparison between the moment modification factors expressions considered.

2. Design formulae for elastic critical moment

This section provides an overview of the approaches on which the present paper is based. A method to account for the sinusoidal corrugation is proposed, as well as new values for the factor C_1 for WCB.

2.1. Introduction to elastic critical bending moment

The elastic critical bending moment, M_{cr}, is the theoretical maximum bending moment resisted by a beam before the occurrence of LTB in the elastic range, where no residual stresses or initial imperfections are considered. The cross-sectional properties that influence the LTB resistance are: the moment of inertia about the weak axis, I_z, which prevents lateral displacement; the torsion constant, I_t; and the warping constant, I_w, which prevent the rotation of the cross section.

The expression for the elastic critical moment given hereafter only applies to uniform straight members for which the cross-section is symmetric about the bending plane. The restraint conditions at each end are at least: (i) restraint against lateral movement, and (ii) restraint against rotation about the longitudinal axis (i.e., fork supports).

The elastic critical moment may be calculated from the formula stated in Eq. (1), originally derived from the buckling theory by Timoshenko [13], and considering the empirical modification factors (namely the C_1 and C_2 factors) to account for other moment distributions and load applications [14,15]:

$$M_{cr} = C_1 \frac{\pi^2 E I_z}{(k_z L)^2} \left\{ \sqrt{\left(\frac{k_z}{k_w}\right)^2 \frac{I_w}{I_z} + I_t \frac{G L^2}{\pi^2 E I_z} + (C_2 z_g)^2} - C_2 z_g \right\} \tag{1}$$

where E is the Young modulus ($E = 210{,}000$ N/mm^2); G is the shear modulus ($G = 80{,}770$ N/mm^2); I_z is the second moment of area about the weak axis; I_t is the torsion constant; I_w is the warping constant; L is the beam length between points which have lateral restraints; z_g is the distance between the point of load application and the shear centre;

Table 1
Summary of the cases considered (all dimensions in mm).

Web dimensions ($h_w \times t_w$)	Flange dimensions ($b_f \times t_f$)	End moment ratios (ψ)	Corrugation dimensions	
			Sinusoidal	Trapezoidal[a]
1500 × 3 1250 × 3 1000 × 3 750 × 3 500 × 3	400 × 30 300 × 25 280 × 20 240 × 15 200 × 10	1, 0.75, 0.5, 0.25, 0, −0.25, −0.5, −0.75, −1	$2w = 155$ $a_3 = 43$	$a_1 = 15.5$ $a_3 = 43$ $a_4 = 62$

[a] Note: The dimensions shown for the trapezoidal corrugation result from Eq. (5) using the dimensions considered for the sinusoidal corrugation as input values.