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Elastic critical moment of continuous composite beams with a sinusoidal-web steel profile for lateral-torsional buckling

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ABSTRACT

Lateral-torsional buckling (LTB) is an ultimate limit state that can occur in the hogging moment regions of continuous composite steel and concrete beams. This limit state is characterised by the buckling of the steel profile compressed flange (bottom flange) about the minor axis, together with a distortion of the steel profile web. The European Standard EN 1994-1-1:2004 provides an approximate procedure for LTB design that is applicable to continuous composite beams, but only those with a plane web steel profile. The most important step of this procedure is the determination of the elastic critical moment. In this paper, a finite element analysis (FEA) model was developed using the software ANSYS to determine the elastic critical moments of continuous composite steel and concrete beams with corrugated sinusoidal-web steel profiles, which were evaluated against numerical data from the literature. Ultimately, a study involving 45 models was conducted based on FEA modelling, and a procedure for predicting the elastic critical moment of composite beams with sinusoidal-web steel profiles was proposed.
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1. Introduction

1.1. Lateral-torsional buckling of continuous composite beams

Currently, continuous composite steel and concrete beams are often used in bridges and buildings for larger spans. Due to moment redistribution, it is possible for these beams to use the lightest steel profile, which makes them an attractive structural option. However, continuous beams are subjected to hogging moments at the internal supports, and are susceptible to an ultimate limit state called lateral-torsional buckling [1] (in the following LTB). This failure mode is also referred to as lateral distortional buckling (LDB) or restrained distortional buckling (RDB) in current literature.

Lateral-torsional buckling is characterised by the buckling of the steel profile compressed flange (bottom flange) about the minor axis, together with a distortion of the steel profile web (the bottom flange presents a lateral displacement accompanied by torsion) and has been well described by several researchers, including Johnson [2] (Fig. 1).

1.2. Procedures for LTB design for plane web steel profiles

European Standard EN 1994-1-1:2004 [1] provides an approximate procedure for LTB design (the Brazilian Standard ABNT NBR 8800:2008 [3] adopts the same procedure) for the case in which the same slab is attached to one or more parallel supporting steel members, but the procedure is applicable only to continuous composite beams with plane webs. The most important step of the procedure is the determination of the elastic critical moment, M_{cr}, based on the behaviour of the inverted U-frame model, which is formed by two adjacent beams and the supported slab. As shown in Fig. 2, this model assumes that the value of M_{cr} depends on the flexural stiffness of the cracked concrete slab, k_1; the flexural stiffness of the steel profile web (web distortion stiffness), k_2; and the stiffness of the shear connection, k_3. To facilitate the design, the U-frame model can be represented by a steel beam alone, in which the lateral displacement is restrained and a rotational stiffness per unit length, k_s, is used at the level of the top flange; this rotational stiffness can be expressed in terms of k_1, k_2 and k_3 as follows:

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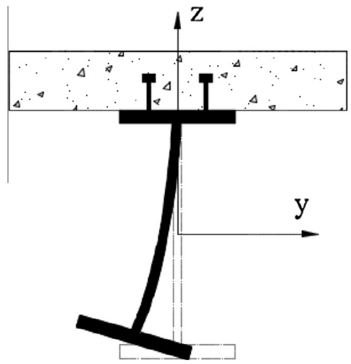

Fig. 1. Lateral-torsional buckling (LTB) of continuous composite beams.

$$k_s = \left(\frac{1}{k_1} + \frac{1}{k_2} + \frac{1}{k_3}\right)^{-1} \quad (1)$$

The stiffnesses k_1 and k_2 are defined as follows:

$$k_1 = \frac{\alpha (EI)_2}{a} \quad (2)$$

$$k_2 = \frac{E_a t_w^3}{4(1 - \nu_a^2) h_s} \quad (3)$$

where α is a coefficient equal to 2 for an edge beam, with or without a cantilever, or 3 for an inner beam (for an inner beam on a floor with four or more similar parallel beams, α equal to 4 may be used); $(EI)_2$ is the cracked flexural stiffness per unit width of the slab; a is the spacing between the parallel beams; E_a is the elasticity modulus of structural steel; t_w is the thickness of the web of the structural steel section; ν_a is the Poisson's ratio of structural steel; and h_s is the distance between the centroids of the flanges of the structural steel section.

The shear connection stiffness, k_3, is not mentioned by EN 1994-1-1:2004 [1], because its value is very high when compared to k_1 and k_2 stiffnesses and it can, thus, be neglected. According to Johnson and Molenstra [4], tests in bridges of composite beams show that the shear connection stiffness affects less than 1% of the total rotational stiffness.

Although it provides all of the above-described information, the standard EN 1994-1-1:2004 [1] does not offer an expression for the calculation of M_{cr}. However, the old edition of the European Standard, ENV 1994-1-1:1992 [5], prescribed the formulation of Roik *et al.* [6] to calculate this moment. Based on the energy method applied to the steel beam illustrated in Fig. 2, these authors obtained the following equation:

$$M_{cr} = \frac{k_c C_4}{L} \sqrt{\left(G_a I_{at} + \frac{k_s L^2}{\pi^2}\right) E_a I_{afz}} \quad (4)$$

where G_a is the shear modulus of structural steel; L is the length of the beam between points at which the bottom flange of the steel member is laterally restrained; I_{at} is the St. Venant torsion constant of the steel section; I_{afz} is the second moment of area of the bottom flange about the minor axis of the steel member; C_4 is a property associated with the distribution of bending moments; and k_c is a factor related to the geometry of the structural steel section. If the cross-section of the steel member is doubly symmetric, this factor is given by

$$k_c = \frac{h_s I_y / I_{ay}}{\frac{h_s^2/4 + (I_{ay} + I_{az})/A_a}{e} + h_s} \quad (5)$$

with

$$e = \frac{A I_{ay}}{A_a z_c (A - A_a)} \quad (6)$$

where z_c is the distance between the centroid of the steel section and the mid-depth of the slab; A is the area of the equivalent composite section, neglecting concrete in tension; I_y is the second moment of area for major-axis bending of the composite section; I_{ay} and I_{az} are the second moments of area of the structural steel section; and A_a is the area of the structural steel section.

The critical moment is affected by the bending moment diagram and this influence is taken into account by the factor C_4. Roik *et al.* [6] proposed the use of tables to determine the values of this factor for spans of continuous composite beams with plane web steel profiles. Tables 1 and 2 give the values of C_4 for spans with and without transverse loading, respectively.

To obtain the elastic critical moment of continuous composite beams subjected to transverse loading, end moments and torsional moments, Hanswille [7] studied the analogy between the lateral-torsional buckling and compression of a member on an elastic foundation. Through this analogy, similarly to Roik *et al.* [6], Hanswille [7] considered an equivalent system featuring a steel profile with a rigid support that prevented lateral displacement and an elastic torsional support with stiffness k_s; both were continuous and positioned at the top flange of the steel profile (Fig. 3).

Comparing the compression member on an elastic foundation with the lateral-torsional buckling problem, Hanswille [7] obtained the following equation:

$$M_{cr} = \frac{1}{k_z}\left(\frac{\pi^2 E_a J_{w,D}}{(\beta_B L)^2} + G_a J_{T,eff}\right) \quad (7)$$

where L is the length of the span; β_B is a buckling coefficient; $E_a J_{w,D}$ is the warping stiffness; $G_a J_{T,eff}$ is the effective St. Venant torsional stiffness; and k_z is a factor related to the geometry of the structural steel section (see Hanswille [7] for more information about these quantities).

Except for the works that will be cited in Section 1.3, the literature reveals studies on the determination of M_{cr} for continuous composite beams with plane web steel profiles only. The energy method of Roik *et al.* [6] and the equivalent system of Hanswille [7] are usually used in studies on the lateral-torsional buckling of these beams (for example, see Chen and Ye [8] and Ye and Chen [9]).

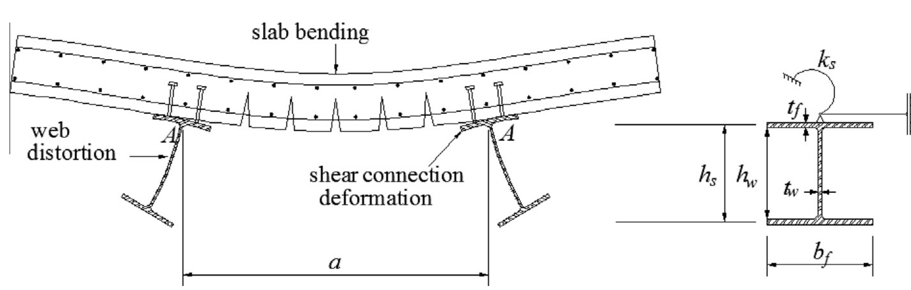

Fig. 2. Deformations of inverted-U frame model and representation of steel beam alone. Adapted from EN 1994-1-1:2004 [1].

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