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Cellular beam design for resistance to inelastic lateral–torsional buckling

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ABSTRACT

To facilitate accurate but conservative design of cellular beams for resistance against lateral–torsional buckling (LTB), this study proposes rational design guidelines based on General method of EC3. The inelastic LTB resistance was the subject of parametric studies using nonlinear finite elements, covering various loading configurations and geometric parameters of practical cellular beams. End moment and shear loadings were considered. The design resistance is slightly conservative in cases with complete LTB behavior that is generally found with non-dimensional slenderness exceeding 2.50. With short beams and shear loads LTB failure may interact with the local failures web-post buckling and web distortional buckling. However, combinations of LTB and Vierendeel failure were not observed. Concentrated stresses in the flange occur with short beams and moment loads, and these can degrade the LTB resistance. Due to interactions of the local failures in short beams, the design resistance requires a correction to ensure it is conservative. The key parameters affecting resistance include load configuration, section ratio, spacing ratio, and slenderness. All these parameters reflect shear effects, but section ratio and slenderness significantly influence the accuracy of the design results. Therefore, a correction factor based on these parameters is proposed, such that improves the EC3 accuracy by minimizing overestimation. The proposed LTB resistance design approach remains mostly conservative relative to both FE simulations and experimental results.

1. Introduction

The flexural behavior of cellular beams is complicated as they are susceptible to several modes of failure and instability. The web openings increase complexity in flexural and shear behavior. The failure modes include flexural failure, shear failure, Vierendeel failure, web-post buckling, lateral–torsional buckling, distortional buckling, and their combinations. Since cellular beams have deeper H or I sections than the parent beams they are made from, they are more susceptible to lateral–torsional buckling (LTB) than their parent sections. An LTB failure occurs when the compressed flange of a steel beam has insufficient lateral support.

LTB failures of cellular beams have been widely found in experiments [1–4]. However, relative to other modes of failure, LTB in cellular beams has been less studied and its understanding is poorly developed. Cellular beams have been investigated for flexural failure, shear failure, Vierendeel failure, and web-post buckling. Various design formulae against these failure modes have been proposed [5–9].

The influence of cellular beam geometry, including web openings, on LTB resistance has been examined in the literature [4,10–12]. Focusing on the elastic lateral stability of cellular beams, Sweedan [10] investigated the influence of web openings numerically. The moment gradient factor was significantly affected by the beam geometry and slenderness. Furthermore, when the beam slenderness decreased, distortion of the web increased leading to lateral distortional buckling (LDB). Under the LDB failure, the moment gradient factor was below the values recommended by design codes. Ellobody [4] examined the effects of beam geometry, span length, and material, on the buckling of cellular beams in non-linear finite element models. The combined effect of web-post buckling and web distortion significantly reduced the load carrying capacity of a cellular beam. Furthermore, it was shown that use of stronger steel could considerably increase the load carrying capacity of a cellular beam with low slenderness, through inelastic flexure. El-Sawy et al. [11] also employed the finite element method to investigate the inelastic behavior of cellular beams under combined buckling modes, i.e. lateral torsional/distortional buckling modes and localized deformations. A parametric analysis was conducted to assess the impacts of various geometric parameters on the inelastic stability of cellular beams. The flexural capacity of cellular beams was found to be influenced

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by both local and global instabilities.

Effects of the residual stresses from cellular beam productions on the LTB behavior have been investigated [4,12]. The production process was found to decrease the buckling resistance with approximately one buckling curve of EC3 [12]. However, the actual residual stresses in cellular beams are hard to determine. Global imperfections of cellular beams with the amplitude $L/500$ have been proposed as a way to cover the influences of residual stresses [2].

To design cellular beams for LTB resistance, most current design guideline proposals are based on the 2T approach [10–12]. On using the 2T approach, the cross-sectional properties calculated at the center of the web opening are used to estimate torsional stiffness and LTB resistance. For elastic lateral stability design of cellular beams, Sweedan's study [10] suggested a formula for the moment modification factor to calculate the LTB resistance. The modification factor gave an accurate and conservative estimate of the critical elastic moment associated with lateral torsional/distortional buckling. The factor was a function of flange width and thickness, opening spacing, web height, and type of loading (uniform moment, mid-span concentrated load, or uniformly distributed load). For the calculation of inelastic LTB resistance, El-lobody [4] found the specification predictions of the Australian Standard generally conservative for LTB failure of cellular beams. The standard provided non-conservative results for cellular beam failure by combined web distortional and web-post buckling. The study by Sonck and Belis [12] proposed a preliminary design approach based on current European guidelines, EC3 [13]. The approach was derived with a modified calculation of the cross-sectional properties and a modified buckling curve selection. However, the study was limited to cellular beams loaded only by a constant bending moment; shear effects on the LTB resistance were not considered. Note that the buckling curve choice for the LTB computation varies between the published proposals [2,12,14].

The prior investigations into inelastic LTB resistance [4,12] have not clarified the influence of geometry on the design accuracy of LTB resistance. This study aimed to propose rational design guidelines for inelastic LTB resistance, based on EC3. The proposed guidelines derived based on parametric finite element simulations. The geometric parameters investigated were practical cross-section dimensions, span lengths, opening ratios and spacing ratios. Effects of local failures on LTB design accuracy were also examined. The four types of loading were mid-span concentrated load, two-point concentrated load, uniformly distributed load, and end moments.

2. LTB design

In this study, the LTB resistance is designed based on EN 1993-1-1, EC3. Cross-sectional properties of cellular beams are computed at the center of the web opening as in the 2T approach [10–12]. The cross-section geometry is shown in Fig. 1, where b_f and t_f are the flange width and thickness, d_o is the opening diameter, H is the cellular beam height, and h_w and t_w are the web height and thickness.

2.1. Elastic lateral torsional buckling

Consider a symmetric I beam, with simple supports and lateral or torsional support at the beam end, subjected to equal end moments. The critical bending moment capacity at elastic lateral torsional buckling, $M_{cr,0}$, of such beam is defined [15] as

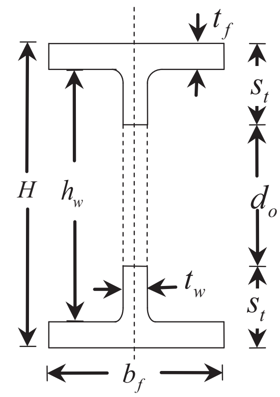

Fig. 1. Cross-section geometry of cellular beams.

$$M_{cr,0} = \frac{\pi}{L_b}\sqrt{EI_yGJ + (\frac{\pi E}{L_b})^2 I_y C_w} \tag{1}$$

where L_b is the laterally unbraced length of the compression flange, G and E are the elastic shear modulus and the elastic Young modulus, respectively, I_y is the moment of inertia about an axis perpendicular to the axis of bending, J is the torsional moment of inertia of the beam cross-section, and C_w is the warping constant of the beam section. The values of the torsional constant J and the warping torsional constant C_w for 2T sections (i.e., sections with a circular opening) can be computed [11,16] as

$$J = \frac{2}{3}b_f t_f^3 + \frac{1}{3}(h_w - d_o)t_w^3 \tag{2}$$

$$C_w = \frac{t_f b_f^3 (h_w + t_f)^2}{24} - \frac{(d_o t_w)^3}{144} \tag{3}$$

Generally, steel beams are subjected to a non-uniform bending moment between the points of lateral support. Therefore, to determine the critical bending moment M_{cr} in this non-uniform case, the critical uniform bending moment in Eq. (1) is modified with the moment gradient factor C_b:

$$M_{cr} = C_b M_{cr,0} \tag{4}$$

Since EC3 does not clearly provide formulas to compute M_{cr} and C_b, the C_b formula of the AISC code [17] shown in Eq. (5) was adopted. This formula is valid for any moment distribution which is a minor modification of the closed form expression proposed in [18].

$$C_b = \frac{12.5M_{\max}}{2.5M_{\max} + 3M_2 + 4M_3 + 3M_4} \tag{5}$$

where $M_{\max}$ is the maximum moment, and M_2, M_3 and M_4 are the values of the moment at $L_b/4$, $L_b/2$ and $3L_b/4$, respectively. Note that all the moments in Eq. (5) are absolute values.

For the case of elastic LTB failure, Sweedan [10] proposed a formula for adjusting the moment gradient coefficient based on the perforation configuration of a cellular beam. However, the suggested formula only very slightly affects the moment gradient coefficient for cellular beams with the opening ratio $d_o/d(0.8–1.2)$ and the spacing ratio $s/d_o(1.1–1.8)$ in their common practical ranges. When a cellular beam fails by pure elastic LTB deformation, the C_b value is found to vary near the recommended design code value. Severely reduced C_b is only observed in the case of a short-span beam with response dominated by local buckling modes, such as web distortion buckling or web-post buckling. Therefore, the C_b values recommended by design codes can generally be used to estimate the elastic critical moment for lateral torsional buckling.