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Elastic lateral stability of I-shaped cellular steel beams

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ABSTRACT

In this paper, the lateral stability of cellular steel beams is numerically investigated. The study is carried out using three-dimensional finite element modeling of simply supported I-shaped cellular steel beams with a broad spectrum of cross-sectional dimensions, span lengths and web perforation configurations. Stability analyses are carried out for beams subjected to equal end moments, mid-span concentrated loads and uniformly distributed loads. Finite element results reveal that, unlike the case of conventional beams with solid webs, the moment-gradient coefficient C_b is significantly influenced by the beam geometry and slenderness. In addition, the C_b coefficient of cellular beams depends on the web perforation configuration. Moment-gradient coefficient values that fluctuate closely to those values recommended by design codes are associated with pure elastic lateral torsional buckling (LTB) deformations. As the beam slenderness decreases, the web distortion increases, leading to the lateral distortional buckling (LDB) mode, which is associated with lower C_b values than code-recommended ones. Severe reduction in the C_b coefficient to values less than 1.1 is noticed for shorter-span beams where the response is dominated by non-lateral local buckling modes.

A simplified approach is developed to enable accurate prediction of a moment modification factor κ_{LB} for cellular beams. The proposed κ_{LB} factor is provided by an empirical formula that is derived based on the best fit of the finite element results related to lateral buckling (LTB and LDB) modes only. The proposed approach allows for accurate and conservative evaluation of the critical moment associated with the lateral torsional/distortional buckling of cellular beams. Several numerical examples are worked out to illustrate the application of the proposed procedure.

1. Introduction

Under general loading conditions, the bending moment distribution may vary along the beam span. As a result, the compressive stresses developed in the compression flange of the beam are expected to have variable intensity along the span. Current design codes account for the influence of the moment gradient on the beam moment-carrying capacity through a modification coefficient that is refereed to as the moment-gradient coefficient, C_b. This coefficient relates the nominal moment M_n for a beam subjected to a specific transverse load to the corresponding critical buckling moment $M_{o\text{-}cr}$ of the same beam under a uniform moment:

$$M_n = C_b M_{o\text{-}cr}. \quad (1)$$

Table 1 provides a comparison between various values of moment-gradient coefficients adopted by three major international design codes and standards for beams subjected to mid-span concentrated loads and uniformly distributed loads. Such codes are the American steel construction manual AISC 2005 [1], the new European standards EC3 [2] and the Australian design code SA [3]. As indicated by Eq. (1), all codes assign a C_b value of unity for beams subjected to equal end moments (i.e., uniform moment distribution along the span of the beam). From a practical design standpoint, the tabulated values are very close. It is, however, interesting to note that the European code [2] provides slightly higher estimates of the critical moment for beams subjected to mid-span concentrated loads. Meanwhile, the American code [1] recommends a slightly higher C_b value for beams subjected to uniformly distributed loads.

2. Literature review

I-shaped steel sections are extensively used as main structural elements (e.g., beams and columns) in various building structures. It is advantageous to have web perforations, especially in beam elements, to allow for the passage and installation of piping, ductworks and electrical conduits without increasing the floor-to-floor height (Fig. 1). Besides, web perforations result in a significant reduction in the amount of structural steel used. Two configurations of web perforations are commonly used in engineering practice: hexagonal perforations in castellated beams and circular perforations in cellular beams. Although the former configuration is more common, the latter has recently become widely used in building

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Fig. 1. Practicality of cellular beams in constructing various elements of main structural systems.

construction. Precise manufacturing of cellular sections in an economical way is rather a cumbersome task that involves cutting the web of a solid rolled section and reassembling it by shifting and welding the section components, as depicted by Fig. 2(a) and (b), respectively. However, the current advancement in computer-controlled cutting and welding technology allows for highly precise and cost-effective production of cellular sections. A major architectural advantage of cellular beams is that their appealing aesthetical appearance makes them essential elements in the construction of exposed structures. Despite the fact that the augmentation of the perforated section height enhances the in-plane structural characteristics, the discontinuity in the beam cross-section due to the presence of web openings may have a severe penalty on the load-carrying capacity of cellular beams in the case of failure by lateral–torsional buckling prior to the attainment of their full capacity. Such impact depends mainly on the geometrical configurations of web openings [4–7]. The widespread use of castellated beams as structural elements in multistory buildings, commercial and industrial buildings, stadiums and parking garage structures has prompted several investigations into their structural behavior. However, investigations related to the behavior of cellular beams are quite rare. For both perforation configurations, the non-uniformity in cross-section properties due to the existence of web openings increases the level of complexity of the behavior and

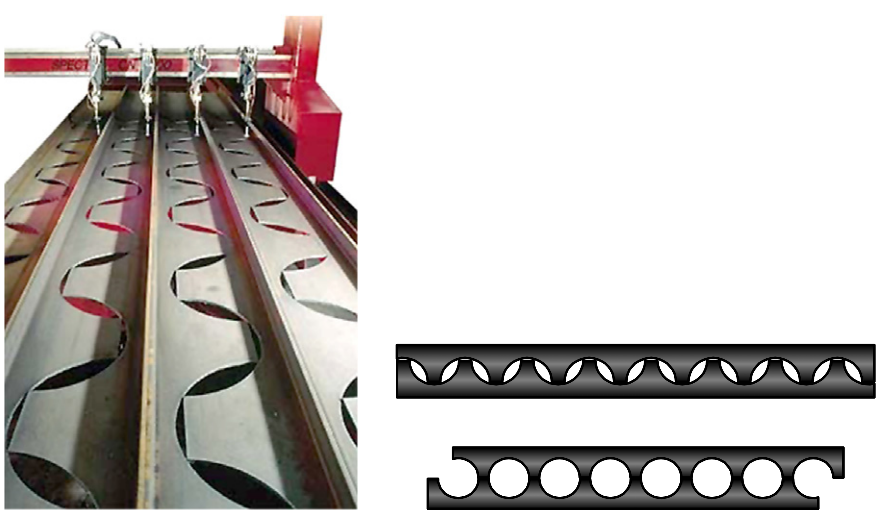
Table 1
Comparison between moment-gradient coefficient values recommended by international design codes.

Case of loading	American code (AISC 2005 [1])	European standards (EC3 [2])	Australian code (AS4100 [3])
Mid-span concentrated load	1.35	1.365	1.32
Uniformly distributed load	1.14	1.132	1.13

the associated potential failure modes. Failure of this special type of beam is controlled by several modes, among which the stability-related ones can be classified as follows [8,9].

1. Lateral–torsional buckling failure.
2. Web post-buckling due to excessive shear stresses.
3. Vertical buckling of web posts.

Experimental studies have been conducted to investigate the behavior and stability of castellated beams by Kerdal and Nethercot [8] and Nethercot and Kerdal [10]. Further numerical investigations have been carried out by Mohebkhah [11] on the inelastic lateral torsional buckling of castellated beams. Such studies provided quantitative data that revealed that the change in the slenderness of castellated beams due to the castellation has a significant influence on the moment-gradient coefficient used in the design of beams subjected to flexure, which in turn affects the strength and stability of such beams. Redwood and Demirdjian [12] and Zaarour and Redwood [13] studied the web buckling of castellated beams both experimentally and theoretically. Recently, experimental investigations of the distortional buckling of castellated beams have been conducted by Zirakian and Showkati [14] and Zirakian [15]. The experimental measurements were then incorporated into several extrapolation techniques to provide more accurate predictions of the critical buckling loads. The previous review reveals that a considerable volume of research has been directed towards investigating the response and behavior of castellated beams. In contrast, very limited studies have been directed to investigating the behavior and response of cellular beams. Chung et al. [9] conducted analytical and numerical analyses to assess the load-carrying capacity of cellular beams related to the Vierendeel failure mechanism. The coupled influence resulting from the combined effect of the moment and shear on steel beams with web openings of various shapes has been also investigated numerically



(a) Computerized cut of the original solid web.

(b) Re-assembly by welding to form a cellular member.

Fig. 2. Manufacturing of cellular beams (http://www.asdwestok.co.uk).