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Moment gradient factor of cellular steel beams under inelastic flexure

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ABSTRACT

The flexural capacity of cellular steel beams is influenced by both local and global instabilities. In the current paper, the finite element method is employed to investigate the inelastic behavior of cellular steel beams under combined buckling modes. A three-dimensional non-linear finite element model, that takes into consideration possible interaction between lateral torsional/distortional buckling modes and localized deformations of the cross section is developed and validated against available results in the literature. The study considers simply supported beams subjected to three different load configurations; mid-span load, uniformly distributed load and end moments. An extensive parametric analysis is conducted to assess the impact of various geometrical parameters on the inelastic stability of cellular steel beams. These parameters include the dimensions of the beam cross-section; flange width and thickness, web height and thickness, and hole size and spacing. The moment gradient factors that correspond to various buckling modes experienced by the wide range of dimensions considered in the simulation study are reported. The outcomes of the this study are expected to provide more insight into the behavior of cellular steel beams and enable accurate prediction of the moment gradient factor and consequently the flexural capacity of this special type of steel beams.

1. Introduction

Perforated–web I-shaped non-composite steel sections have been used as structural members since the Second World War in an attempt to enhance the flexural behavior without increasing the cost of the material. In general, two types of web perforations are commonly used in engineering practice; hexagonal and circular. The hexagonal perforation pattern occurs during the typical manufacturing of castellated members by cutting the web of a typical I-shaped member longitudinally in a zigzag pattern and then re-assembling the resulting parts by welding. Cellular beams are the modern style of the traditional castellated beams. The manufacturing process of cellular beams (Fig. 1) increases the overall depth to be up to 1.6 times deeper than that of the root (parent) solid section. The diameter of the openings may reach 80% of the total height of the beam and it is possible to leave only a small distance between the openings which allows for a high level of transparency. The flexural behavior of solid-web I-shaped steel beams is complicated due to its susceptibility to several failure and instability modes. Failure modes include flexural and shear failures while buckling modes comprise local web and local flange instabilities, lateral, torsional and distortional buckling or combination thereof. For the particular case of perforated-web beams, the non-uniformity in the cross section properties due to the existence of web openings increases the level of complexity in the flexural behavior and the associated failure and instability modes.

1.1. Elastic lateral torsional buckling

The critical value of the uniform bending moment, at which elastic lateral torsional buckling (LTB) occurs in an I-shaped beam, is well established [Timoshenko and Gere [22]] and is defined as

$$M_{cr} = \frac{\pi}{L_b}\sqrt{E\,I_y\,G\,J + \left(\frac{\pi E}{L_b}\right)^2 I_y\,C_w} \qquad (1)$$

where L_b is the laterally unbraced length of the beam's compression flange, I_y is the cross-sectional moment of inertia about an axis perpendicular to the axis of bending, J is the torsional moment of inertia of the cross-section, C_w is the warping constant, and G and E are the elastic shear and Young's moduli of the beam's material, respectively.

In practical situations beams are subjected to non-uniform bending moment between the points of lateral supports and, therefore, have greater flexural strength than the value estimated by Eq. (1) for the case of constant bending moment. This is reflected in the

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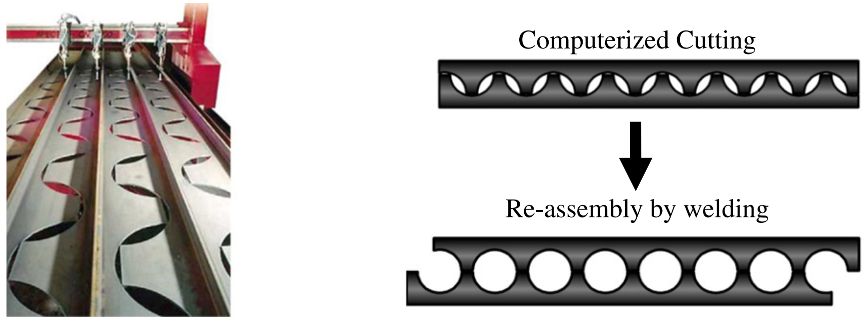

(a) Computerized cut of the web **(b)** Cutting and re-assembly by welding to form a cellular member

Fig. 1. Manufacturing of cellular beams (by permission of Westok Ltd. http://www.asdwestok.co.uk). (a) Computerized cut of the web. (b) Cutting and re-assembly by welding to form a cellular member.

value of the moment gradient factor C_b (greater than unity) which is defined as

$$C_b = \frac{M_{cr} \text{ for case of nonuniform bending moment profile}}{M_{cr} \text{ for case of uniform bending moment profile}}. \tag{2}$$

As such, the nominal elastic critical moment M_{n-el} can be expressed in accordance with Eqs. (1) and (2) as

$$M_{n-el} = C_b\, M_{cr} = \frac{C_b \pi}{L_b} \sqrt{E I_y G J + \left(\frac{\pi E}{L_b}\right)^2 I_y C_w} \;\le\; M_P \tag{3}$$

where M_p is the plastic moment (or maximum flexural strength) that can be carried by the cross-section. Table 1 summarizes the various values of moment gradient factors adopted by four international design codes and standards (AISC 360–10 [2], EC3 [9], AS4100 [19] and BS5950-1 [4]) for steel beams subjected to mid-span concentrated load and uniformly distributed load with lateral restraints being provided at the beam end points only.

The main objective of this paper is to investigate the influence of buckling modes interaction on the inelastic flexural strength of steel beams with circular web openings. Non-dimensional charts are developed to provide a modified moment gradient factor, C_b, that enables accurate estimation of the inelastic flexural strength of cellular beams undergoing combined buckling modes. The research work presented herein is triggered by the lack of information related to stability of non-composite cellular steel beams; especially the instability pertaining to inelastic lateral torsional buckling (LTB) and the associated moment gradient factor C_b.

2. Literature review

Research on cellular beams with circular web openings is very limited and is less developed than castellated beams which may be attributed to the fact that cellular beams are more complicated to analyze due to their continuously changing section properties around the cell. This section presents a brief review of relevant research devoted to cellular steel beams with circular web perforations that started in 1963 when Barbarito [3] used photoelasticity to investigate stress concentrations in cellular beams in pure bending as a function of varying diameters and spacing. He recommended a ratio of hole diameter to beam depth not exceeding 0.5 to maintain the flexural capacity of the beam nearly unchanged from its solid web counterpart. Lawson [13], Darwin [8], Knowles [12], and Redwood and Cho [15] studied the strength of beams with circular web openings and proposed some formulae for the strength design of such beams. Ward [23] concluded that the load carrying capacity of a cellular beam is the smallest of its overall strength in flexure and lateral torsional buckling, and the local strength of the web-posts and the upper and lower tees. Surtees and Liu [20] conducted a series of experimental tests on seven cellular beams to examine the various failure modes of beams subjected to two-point loads. The majority of the tests were carried out on beams without web stiffeners to trigger the web-post buckling mode. The tested beams were provided with several lateral supports at short intervals to avoid lateral torsional buckling effects. Test results revealed that the use of web bearing stiffeners increases the load carrying capacity of cellular beams. Chung et al. [6] conducted analytical and numerical analyses to assess the load carrying capacity of cellular beams related to the Vierendeel failure mechanism. The combined effect of the moment and shear on perforated steel beams with various shapes of web opening has been also investigated numerically by Liu and Chung [14]. The study focused on flexural failure associated with the Vierendeel mechanism along with shear failure. Results of this finite element investigation has been used by Chung et al. [7] to develop a generalized moment–shear interaction curve for determining the load carrying capacities of steel beams with the web openings of various shapes and sizes. An experimental study was carried out by Warren [24] on eight cellular specimens having different geometries, spans and layouts of circular perforation. The aim of the study was to investigate the ultimate load and deflection behavior of cellular beams. Test specimens were designed to avoid the possibility of web-post buckling mechanism. Two loading conditions were adopted including three-point and four-point loading. Seven beams were reported to fail by Vierendeel mechanism while only one specimen experienced web-post buckling failure. Reiter [16] conducted an experimental study to investigate the general flexural behavior of cellular beams. Reiter found that the governing mode of failure for all specimens was due to the combined buckling of the end connection and the first web-post at the connection. Experimental and numerical studies were carried out by Hennessey et al. [11] and Reither et al. [17] to characterize the effect of end connection type on the buckling behavior of cellular beams. In a recent study on the lateral stability of cellular steel beams, Sweedan [21] investigated numerically the influence of cellular

Table 1
Moment gradient factors recommended by international design codes.

Case of loading	American code (AISC 360–10) [2]	European standards (EC3) [9]	Australian code (AS4100) [19]	British standards (BS5950–1) [4]
Mid-span concentrated load	1.32	1.365	1.35	1.18
Uniformly distributed load	1.14	1.132	1.13	1.08