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Lateral–distortional buckling of hollow tubular flange plate girders with slender unstiffened webs

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ABSTRACT

In this paper, the lateral–distortional buckling (LDB) of hollow tubular flange plate girders (HTFPGs) with slender unstiffened webs is investigated. Firstly, shell finite element analyses are performed in order (i) to study the elastic buckling behaviour of simply supported HTFPGs under uniform bending and (ii) to compare it with the behaviour of I-section plate girders (IPGs) with unstiffened and stiffened webs. The results show that HTFPGs (without stiffeners) have much higher critical moments than IPGs (with stiffeners). Secondly, the LDB behaviour of HTFPGs is investigated using finite strip analyses and the results show the girder length range in which LDB is relevant. After that, an analytical model to estimate the critical LDB moment is proposed and validated by comparison between analytical and numerical values. Thirdly, the investigation is extended to the inelastic domain and non linear shell finite element analyses are performed to evaluate the ultimate strengths of the HTFPGs. Several remarks regarding the flexural strength of HTFPGs are presented. Finally, the predictions given by Eurocode 3 are compared with the numerical results and it is found that the predictions given by the design equations are unconservative. Therefore, it is recommended to use the European specifications by adopting the proposed expression to estimate the critical LDB moment.

1. Introduction

Members having thin-walled cross-sections are usually very slender, thus being highly susceptible to local, distortional and global buckling. Concerning the local and global (flexural and flexural–torsional) buckling phenomena, there is a huge amount of available formulae to determine the buckling loads and moments. Distortional buckling of thin-walled members was "discovered" due to numerical investigations carried out by Bradford in the 1980s and 1990s [1–5]. Since then, much work has been done by the steel technical/scientific community. One of the buckling modes that involve web distortion in I-sections is known as lateral–distortional buckling (LDB) mode – see Fig. 1a. This mode is due to the simultaneous occurrence of (i) high lateral displacement and rotation of the compressed flange, (ii) low lateral displacement of the tensioned flange and (iii) distortion (transverse bending) of the web. The distortion of the web becomes even more evident if the I-section is attached to stiffer structural components such as concrete slabs in composite girders. In this case, it is designated as restrained-distortional buckling (RDB) – see Fig. 1b.

Both LDB and RDB have been studied during the last twenty years, due to the work of several researchers. To study the RDB of I-sections, Bradford [5] developed a model with three degrees of freedom: the twisting rotations of the restrained and unrestrained flanges and the lateral displacement of the unrestrained flange. Using an energy-based formulation, Bradford defined a 3 × 3 eigenvalue problem and determined its solution (the distortional buckling load). The energy functional comprised three components: the energy stored in the flanges, the energy stored in the web and the energy associated with the elastic twist restraint. The energy stored in the flanges was determined by means of flange geometric properties (EI_f and GJ_f); EI_f and GJ_f are the flexural rigidity and the torsional rigidity of the flange, respectively. For the case of fully restrained I-sections, the twist rotation of the restrained flange is null and the model reduces to two degrees of freedom (the twisting rotation and the lateral displacement of the unrestrained flange) and the eigenvalue problem reduces to 2 × 2 dimension. In the 1980s–1990s, Goltermann and Svensson [6] and Ma and Hughes [7] also proposed analytical and numerical approaches to determine the LDB loads of I-section beams. In recent years, the investigations carried out by Samanta and Kumar [8], Zirakian [9], Silvestre [10], Chen and Ye [11] and Zirakian and Zhang [12] also deserve to be credited. In these works, the authors developed and presented some analytical approaches to calculate the LDB loads of I-beams and showed that the existing design rules generally provide overly conservative strength estimates for the slender-web I-beams.

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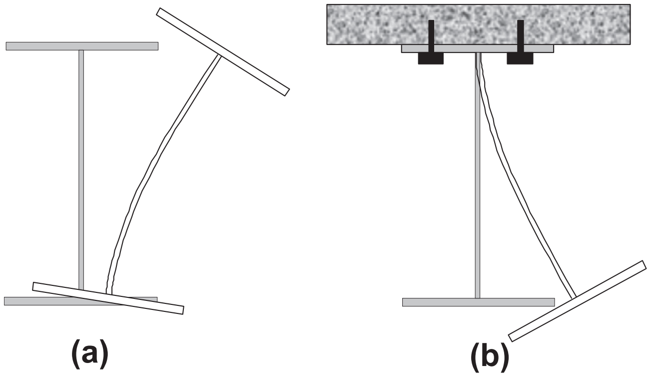

Fig. 1. I-section beam: (a) LDB (positive bending) and (b) RDB (negative bending).

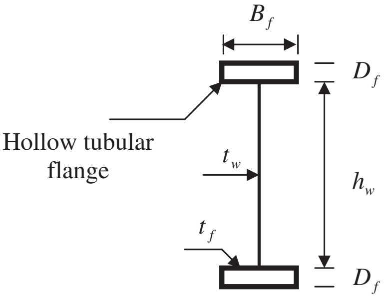

Fig. 2. HTFPG geometry and dimensions.

In order to improve the twisting strength of beams with open sections and decrease their sensitivity to lateral–torsional buckling (LTB), the flat single-plated flanges have been replaced by hollow flanges. Thus, the hollow flange (HF) sections are torsionally very stiff but remain sensitive to LDB because the minor axis second moment of area of their hollow flanges slightly increases. To the authors' knowledge, the pioneering works devoted to LDB of HF beams are due to Dempsey [13], Heldt and Mahendran [14] and Pi and Trahair [15]. The latter studied the LDB of cold-formed steel beams with triangular HFs, often designated as "dog-bone section". Since then, few works have been devoted to LDB of HF beams. The exception is the intense research carried out by Mahendran and colleagues at the Queensland University of Technology. They studied the structural behaviour and ultimate strength of LiteSteel beam, which is a new cold-formed steel section with C shape but with rectangular HFs. In particular, they investigated the LDB of LiteSteel beams using both numerical FE models [16] and experimental tests [17].

Nowadays, other HF beams are being studied. One of these types is the hollow tubular flange plate girder (HTFPG) with slender web shown in Fig. 2. The shear strength of homogenous and hybrid HTFPGs was investigated by Hassanein and Kharoob [18,19]. More recently, the influence of square opening sizes on the shear behaviour of HTFPGs was investigated [20]. The results of these works [18–20] indicated mainly two significant remarks (beside others); namely that (1) using the HTFPGs instead of IPGs is a powerful tool not only to increase the shear strength of the girders provided by the additional anchorage to the tension field, but also to save considerable weight; and (2) replacing the IPGs with HTFPGs provides a high performance solution for the drop in shear capacity due to the presence of web openings. These results inspired the current authors to investigate this type of girders under bending focusing mainly on its buckling behaviour. Hence, the LTB of hollow tubular flange plate girders (HTFPGs) with slender stiffened webs was recently presented [21]. Nevertheless, and to the authors' best knowledge, the LDB of HTFPGs under bending has never been studied nor addressed in design standards.

The main objective of this paper was to investigate the LDB behaviour and ultimate strength of hollow tubular flange plate girders (HTFPGs) with slender unstiffened webs. Shell finite element models were used to study the elastic buckling behaviour of both (i) HTFPGs with unstiffened webs and (ii) I-section plate girders (IPGs) with unstiffened and stiffened webs. Then, finite strip analyses were performed to determine the length range for which the LDB behaviour of HTFPGs is relevant. After that, an analytical model to calculate the critical LDB moment was proposed and validated. Finally, nonlinear shell finite element analyses were performed to evaluate the ultimate strength of HTFPGs. The numerical results were compared with the predictions given by Eurocode 3 and several remarks were drawn concerning the use of the design equations to estimate the ultimate strength of HTFPGs.

2. Preliminary analysis

In this section, a preliminary finite element (FE) analysis is conducted, following the same modelling technique used in [18–20,22], to generate HTFPGs and IPGs. A series of elastic buckling analyses using ABAQUS computer package [23] is carried out to identify the flexural–torsional buckling mode as well as the critical moment value for each IPG and HTFPG model. First, a comparison is made between HTFPGs and IPGs with slender unstiffened webs. Second, a comparison is made between a HTFPG with unstiffened web and an IPG with different stiffened webs.

2.1. Cross-section selection

Based upon the flexural strength predictions of the AISC [24], the most important parameters that affect the strength of IPGs with slender webs are the section modulus (S_y) and radius of gyration of compression flange (r_z); the orientation of axes can be seen in Fig. 3. Detailed discussion regarding these parameters is provided in [21]. Accordingly, to allow the comparison between the HTFPGs and IPGs to take place, two cross-sections, one of each type, having the same section modulus (S_y) as well as the same radius of gyration of compression flange (r_z) were modelled.

Table 1 provides the cross-sectional dimensions of the HTFPGs and IPGs considered in the current preliminary analysis. The cross-sectional dimensions of the HTFPG, with compact tubular flanges according to [22] and a slender web following [25], were firstly assumed. The section modulus and the radius of gyration

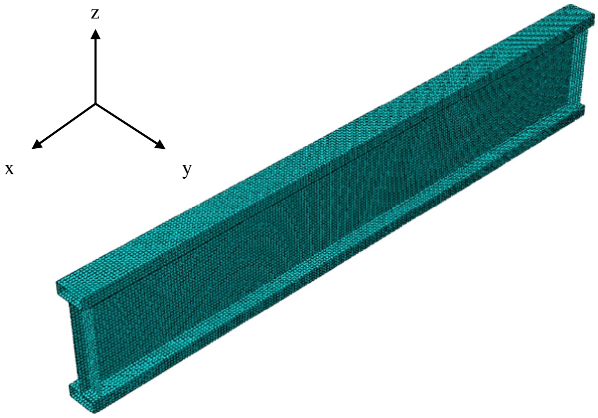

Fig. 3. Finite element mesh of a typical girder.