Journal of Constructional Steel Research 148 (2018) 525–541

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Design procedure for the web-post buckling of steel cellular beams

Lucas Figueiredo Grilo [a,*], Ricardo Hallal Fakury [a],
Ana Lydia Reis de Castro e Silva [a], Gustavo de Souza Veríssimo [b]

[a] *Department of Structural Engineering, Federal University of Minas Gerais, Brazil*
[b] *Department of Civil Engineering, Federal University Viçosa, Brazil*

ARTICLE INFO

Article history:
Received 27 March 2018
Received in revised form 15 June 2018
Accepted 16 June 2018
Available online xxxx

Keywords:
Cellular beam
Web-post buckling
Experimental analysis
Numerical analysis
Steel structures

ABSTRACT

This research presents a study about the structural behavior of steel cellular beams, focused on the web-post buckling. The main objective of this study is to propose a new formulation to calculate the shear resistance of cellular beams for this phenomenon, based on laboratory tests and numerical analysis. Series of tests were performed in this work, with full-scale steel cellular beams. In these experiments, vertical and lateral displacements were measured, as well as web-post deformations. The steel mechanical properties of these beams were determined by tensile testing. A numerical model was proposed, developed in ABAQUS software, to perform parametric analysis. From these numerical models, processing 597 cases, a new formulation to determine the shear resistance in cellular beams for the web-post buckling was proposed, based on resistance curves. The proposed formulation was verified in several situations of geometry and material properties, presenting compatible results with those obtained numerically, and showing better accuracy than those available in the literature.

1. Introduction

The use of steel cellular beams has been increasing due to their economic and aesthetic advantages. Typically, these beams are produced from hot-rolled steel I-sections, and their webs are cut and welded generating higher members with regular circular openings along their length, as shown in Fig. 1 [1–4]. As it can be seen in the figure, d is the depth of the parent section, b_f is the flange width, t_f is the flange thickness, t_w is the web thickness, H is the depth of the cellular section, d_0 is the opening diameter, s and s_0 are, respectively, the pitch and the distance between the openings, s_t is the depth of the tee-section, and y_0 is the distance between the centroid of the tee-section and the cellular cross-section.

The structural behavior of cellular beams under flexure is significantly more complex than the one of regular I-shaped beams. Cellular beams may present the same failure modes of regular beams [1, 4–7] in addition to other cellular beam specific failure modes, such as web-post buckling (WPB), Vierendeel mechanism (VM) [8–11] and rupture of web-post weld [8], that are considered as the dominant failures [12, 13], and also other specific failure modes, such as web-post flexure and tee-section shear [10, 14, 15]. Design manuals that contemplate the major failure modes of cellular beams are available in the literature [16–19]. The focus of this work is the web-post buckling, a kind of collapse caused by shear force, that was initially treated in 1990 by SCI publication 100 [18].

There are some different approaches to design WPB of cellular beam. However, the values of the shear resistance obtained with the different design methodologies present relevant differences when compared among themselves and when compared with laboratory tests. In addition, a satisfactory number of experimental studies of steel cellular beams for this phenomenon is not available in the literature. Besides, there are no resistance curves related do WPB failure that can be used in agreement with beam shear resistance presented in international standards for steel structures design, such as the American ANSI/AISC 360:16 and the European EN 1993-1-1:2005 [20, 21].

In this work, a new procedure is proposed to determine the shear resistance for WPB of steel cellular beams, that is more accurate than the currently ones available in the literature and can be used in accordance to the existing codes. This procedure was determined based on 597 numerical models, which were calibrated with laboratory tests of 14 full-scale steel cellular beams geometrically different and verified with 1948 numerical analyses.

2. Cellular beams

2.1. Existing formulations for web-post buckling

Web-post buckling is the loss of stability of the web-post caused by compression stresses due to the shear force. During this phenomenon, the web-post twists over its vertical axis, assuming the shape shown

* Corresponding author.
E-mail address: lucasfgrilo@gmail.com (L.F. Grilo).

https://doi.org/10.1016/j.jcsr.2018.06.020

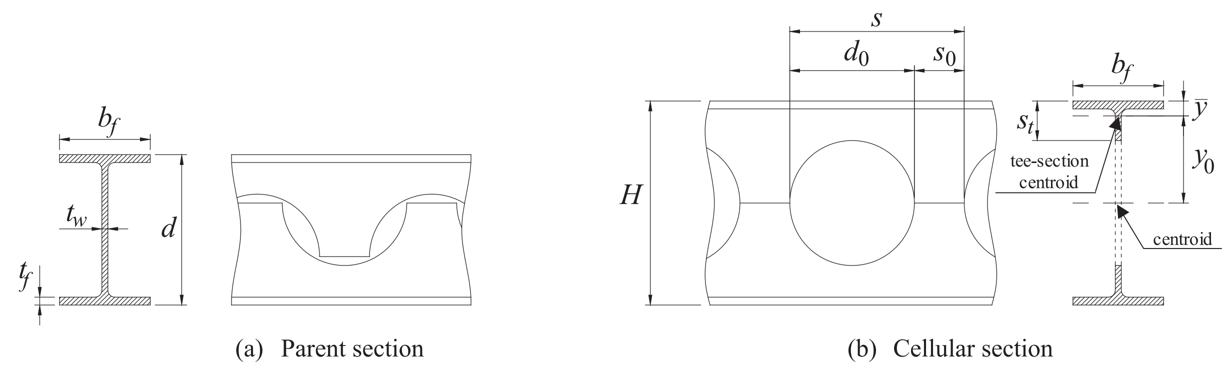

Fig. 1. Cellular beams geometry.

in Fig. 2a and b. The forces equilibrium due to shear is shown in Fig. 2c [17].

This equilibrium, defining F as the resultant force of a uniform loading acting in the beam and V_h as the horizontal shear force in the web-post, is given by:

$$V_h = \left[V_v + \frac{F}{2}\right] \frac{s}{2\, y_0} \tag{1}$$

with

$$\bar{y} = \frac{b_f t_f^{\,2} + t_w\, s_t^{\,2} - t_w\, t_f^{\,2}}{2(b_f\, t_f + t_w\, s_t - t_w\, t_f)} \tag{2}$$

where V_v is the vertical shear force, M is the moment derived from the force equilibrium, and the other dimensions were presented in Fig. 1.

In 1990, the first international design guide was published that approaches the WPB failure [18], and its design formulation was recently adopted by AISC and republished in [19]. In 2002, Lawson et al. [22] published a different methodology to calculate the shear resistance in which an effective length in the compressed diagonal of the web-post is determined, and the compression stress resistance in this diagonal is calculated using the BS 5950-1:2000 [23] compression resistance formulation. In 2005, Bitar et al. published a paper that presents a methodology to determine the shear resistance, which is used in the cellular beam design software ACB+, but that was not fully explained since some details are confidential [24–27]. In 2013, Veríssimo et al. [13] published an adaptation to cellular beam of Delesques's [28] formulation, which was originally developed for castellated beams. In 2014, Panedpojaman et al. [12] proposed an improvement to Lawson's formulation, changing the effective length so it avoids distortions when in low ratios of opening pitch and opening diameter (s_0/d_0).

2.2. Available experimental results in the literature

Although important for the validation of numerical models, there are not many experimental results of WPB in steel beams available in the literature [8]. Experimental results of cellular beams sufficiently detailed to be reproducible were published in [4, 5, 29–31], and are summarized in Table 1. As it can be seen, eight tests of steel cellular beams that failed by pure WPB were found. Among these eight tests, only three were done with geometrically different beams manufactured by traditional process. In addition, twelve experimental results of composite cellular beams, with concrete slab, are available in the literature [3, 32, 33]. The structural behavior of composite beams is different from the steel beams and were not considered in this work.

The production process of cellular members influences the already present residual stresses in the parent sections. In 2014, Sonck et al. [34] published a paper that presents the residual stresses measurement of two pair of castellated members and one pair of cellular members. However, the cellular members studied by Sonck et al. [34] were manufactured by a post welding process, and the measured residual stresses are probably different from the ones found in cellular members ordinarily manufactured.

An important factor in the WPB behavior is the web-post initial imperfection, and there is no specific international code for the manufacturing tolerance for cellular beams. However, the ArcelorMittal cellular beams catalog defines web-post initial crookedness (δ_w) tolerance equal to 4 mm for cross-sections with height up to 600 mm and a hundredth of the height to cross-sections with height exceeding 600 mm [35].

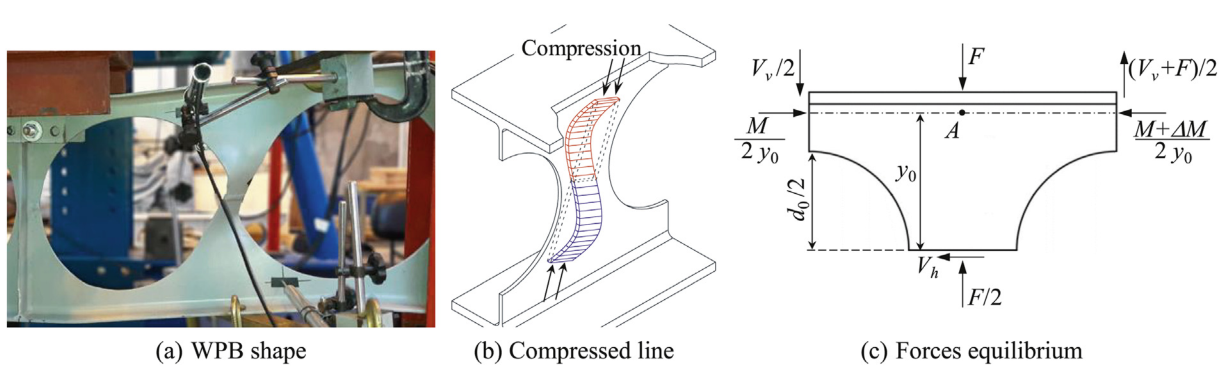

Fig. 2. Web-post buckling phenomena.