International Journal of Mechanical Sciences 126 (2017) 255–260

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

journal homepage: www.elsevier.com/locate/ijmecsci

Distortional buckling of perforated cold-formed steel channel-section beams with circular holes in web

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ARTICLE INFO

Keywords:
Perforated
Cold-formed
Channel
Distortional buckling
Web opening
Finite element

ABSTRACT

This paper presents the numerical and analytical investigations on the distortional buckling of perforated cold-formed steel channel-section beams with circular holes in web. The numerical investigation involves the use of finite element methods. In the analytical analysis the distortional buckling model recommended in EN1993-1-3 is employed. The influence of the web holes on the distortional buckling behaviour and corresponding critical stress and moment of perforated cold-formed steel channel-section beams are discussed. Finally, a simple analytical formulation is proposed for evaluating the effect of hole size on the reduction of critical stress and critical moment of the channel-section beams with circular holes in web.

1. Introduction

Thin-walled, perforated cold-formed steel (PCFS) sections are frequently used as structural members in residential buildings and for storage rack constructions. For example, in low and mid-rise building construction holes are pre-punched in structural studs to accommodate the passage of utilities in the walls and ceilings of buildings; whereas in steel storage rack constructions column perforation patterns are provided to allow for variable shelf configurations. The buckling behaviour of PCFS sections is influenced not only by the reduction of cross-sectional properties but also by the stress concentration caused due to perforations. Similar to common cold-formed steel (CFS) sections, PCFS sections may also exhibit local, distortional, and global buckling modes when they are subjected to compressive and/or bending loads. However, because of the wide variety in the size and configuration of perforations, it is rather difficult to directly calculate the critical buckling stresses of PCFS sections [1].

Early work assessed the influence of a single hole on the elastic buckling of rectangular plates under compression [2]. It was found that the hole reduces the bending stiffness of the plate and causes the concentration of the axial stress in the plate strips adjacent to the hole. The work led to the development of approximation of elastic buckling stress for plates with holes by assuming the strips adjacent to the hole to act as unstiffened elements and the concept of effective width for predicting the post-buckling ultimate strength of plates with holes [3,4]. Davies et al. [5] developed a design method for PCFS sections subjected to axial and bending loads by using both experimental and numerical results, taking account of local, distortional and global buckling. Kesti and Mäkeläinen [6] presented a design method for gypsum-sheathed perforated steel wall studs, of which the failure mode was mainly controlled by distortional buckling. Dhanalakshmi and Shanmugam [7] compared the ultimate load-carrying capacities of perforated and non-perforated equal-angle CFS stub columns under axial and eccentric loads. By using both experimental and numerical results a simplified design formula was proposed to determine the ultimate load-carrying capacity of PCFS equal-angle stubs. Szabo and Dubina [8] evaluated an equivalent α imperfection factor for EN buckling curves to adapt them for sections with different perforation patterns. Freitas et al. [9] conducted a material and geometric non-linear analysis using ANSYS for typical sections of perforated stub columns manufactured in Brazil. The numerical results were compared with experimental data obtained by stub column tests. Sputo and Tovar [10], Tovar and Sputo [11] analysed the local and distortional buckling problems of PCFS studs using finite strip method and the critical loads obtained were used to calculate the ultimate strength of the PCFS studs by using the direct strength method. Experiments were carried out by Moen and Schafer [12] to quantify the relationship between the elastic buckling and tested responses of CFS columns with holes. Compression tests were conducted on 24 short and intermediate length CFS columns with and without slotted web holes. For each tested specimen, finite element buckling analysis was also carried out such that the influence of the boundary conditions and the hole on local, distortional, and global elastic buckling responses was examined. It was showed that slotted web holes could modify the local and distortional elastic

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http://dx.doi.org/10.1016/j.ijmecsci.2017.04.001
Received 16 January 2017; Received in revised form 19 March 2017; Accepted 4 April 2017
Available online 05 April 2017
0020-7403/

buckling half-wavelengths, and may also change the critical elastic buckling loads. Experimental work was carried out by Crisan et al. [13] on upright members of two different cross-sections, with and without perforations to determine the ultimate strength for specimens of different lengths corresponding to local, distortional and global buckling. Material tests and imperfection measurements for the tested specimens were also performed. The effects of perforation positions on the load capacity of column members of lipped channel cross-section were investigated by Kulatunga and Macdonald [14] using both experimental and finite element numerical methods. The influence of perforations of various shapes on the buckling behaviour of CFS columns of lipped channel cross-section was examined by Kulatunga et al. [15] using finite element analysis method.

Finite strip method has been widely used for the buckling analysis of CFS members. The problem with the finite strip method is that holes cannot be easily modelled. In order to apply the finite strip method to PCFS sections, Casafont et al. [16] proposed an approach in which a reduced thickness of the perforated strip is applied to take into account perforations effect. A formulation was proposed for the reduced thickness that has been calibrated with loads obtained in the buckling analysis using finite element method. The accuracy was verified by carrying out analyses on real rack columns with different end conditions. Recently, the flexural behaviour, including the ultimate moment capacities and failure modes, of built-up CFS members with circular web holes was investigated by Wang and Young [17] using experimental methods. A total of 43 beams having ten cross-section sizes with different hole diameters were tested under four-point bending. Different approaches of determining the critical elastic local and distortional buckling moments including the influence of holes for the built-up open and closed sections were compared and discussed. The influence of web opening on the lateral-torsional buckling behaviour of CFS channel-section purlins was also examined by Ling et al. [18] using finite element method. More recently, extensive research has been carried out on the load bearing capacity of rack uprights subjected to combined axial and bending loads using different analysis methods, including design codes [19], experimental [20] and finite element numerical [21–23] methods.

In this paper, the distortional buckling of PCFS channel-section beams with circular holes in web is investigated using finite element method. The influence of the web openings on the critical stress and critical moment of distortional buckling is examined. Finally, according to the EN1993-1-3 distortional buckling model, a simple analytical formulation is proposed for the prediction of critical stress and critical moment of distortional buckling of PCFS channel-section beams with circular holes in web.

2. Finite element analysis of PCFS channel-section beams with circular holes in web

Consider a PCFS channel-section beam with circular holes in web as shown in Fig. 1. The depth of web, flange width, lip length, and thickness of the section are symbolised by h, b, c, and t, respectively. It is assumed that the circular holes of diameter d are equally displaced in the web along the longitudinal direction of the beam. For the convenience of discussion, the beam length is assumed to be $L = n\pi d/2$, where n is an integer, representing the total number of holes in the web. This implies that, in the web strip of openings the total opening area is equal to the total solid area. The beam analysed is assumed to be simply supported at its two ends, and subjected to a pure bending about it major axis. Fig. 2 shows a typical mesh of shell elements used in the analysis for the beam. The displacement boundary conditions are applied to the nodes at the two end sections of the geometrical model. All nodes at both end sections are assumed to have zero lateral displacement, zero transverse displacement, and zero rotational displacement about the longitudinal axis. To avoid the rigid displacement in the longitudinal axial direction a node located at the neutral plane at one of the end sections is assumed to have zero axial displacement. The bending moments loaded at the two end sections are applied by the line distribution forces defined on the web, flange, and lip lines, in which the forces are assumed to be uniformly distributed on the two flange lines ($\sigma_y t$ for upper flange and $-\sigma_y t$ for lower flange), linearly distributed on the web (from $\sigma_y t$ to $-\sigma_y t$) and lip (from $\sigma_y t$ to $\sigma_y t(1\text{-}2c/h)$ for upper lip and from $-\sigma_y t(1\text{-}2c/h)$ to $-\sigma_y t$ for lower lip) lines, as shown in Fig. 2, respectively. The material properties of the beam are assumed as Young's modulus $E = 210$ GPa and Poisson ratio $\nu = 0.3$, yields stress $\sigma_y = 390$ MPa. The linear buckling analysis is performed by using the

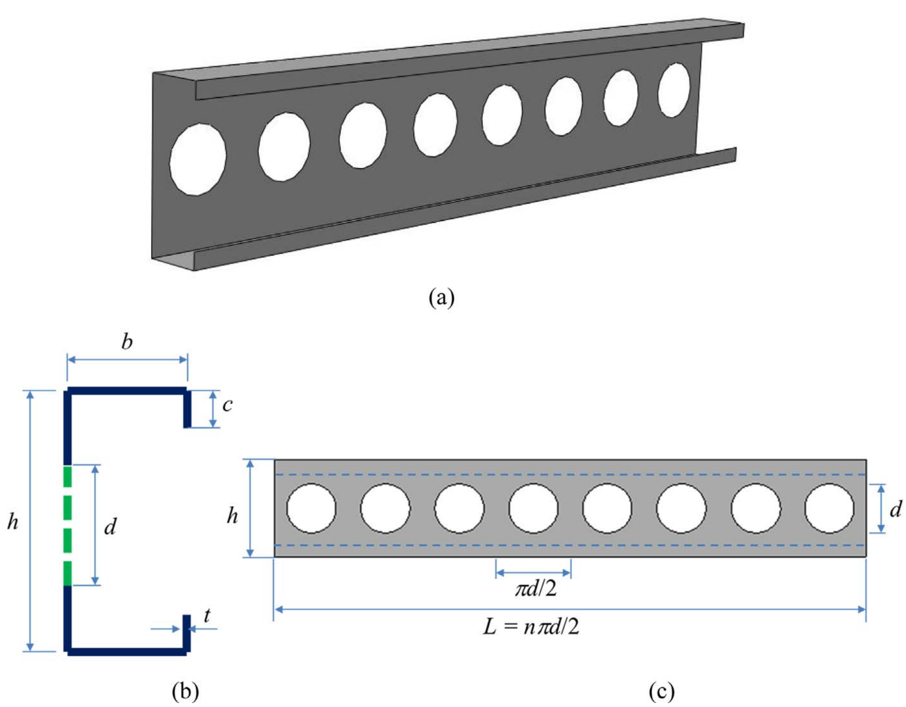

Fig. 1. (a) PCFS channel-section beam. (b) Front view. (c) Side view.