Thin-Walled Structures 119 (2017) 83–102

Contents lists available at ScienceDirect

Thin-Walled Structures

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

Full length article

Shear behaviour and design of Lipped Channel Beams with non-circular web openings

K.S. Wanniarachchi[a,b], M. Mahendran[a,*], P. Keerthan[a]

[a] Queensland University of Technology (QUT), Brisbane, Australia
[b] Faculty of Engineering, University of Ruhuna, Galle, Sri Lanka

ARTICLE INFO

Keywords:
Cold-formed steel structures
Lipped channel beams
Non-circular web openings
Shear capacity
Finite element analyses
Design rules

ABSTRACT

Cold-formed steel Lipped Channel Beams (LCB) with web openings are commonly used as floor joists and bearers in building structures. Their shear behaviour is influenced by the presence of web openings and the shear capacities are considerably reduced. However, the shear behaviour and capacity of LCBs with non-circular web openings (square, rectangular and elliptical web openings) has not been investigated adequately. Hence a detailed numerical study was conducted to investigate the shear behaviour and capacity of LCBs with non-circular web openings. Finite element models of simply supported LCBs under a mid-span load with aspect ratios of 1.0 and 1.5 were developed and validated by using the available shear test results. They were then used in a detailed parametric study to investigate the effects of various influential parameters. Numerical results showed that the current shear design equations in cold-formed steel structures design standards are conservative or unsafe. New shear design equations were therefore proposed for the accurate prediction of the shear capacity of LCBs with non-circular web openings. This paper presents the details of finite element modelling of LCBs with unreinforced non-circular web openings and the development of new shear design rules. The proposed shear design equations in this paper can be considered for inclusion in the future versions of cold-formed steel design standards. Suitable design equations were also developed under the direct strength method.

1. Introduction

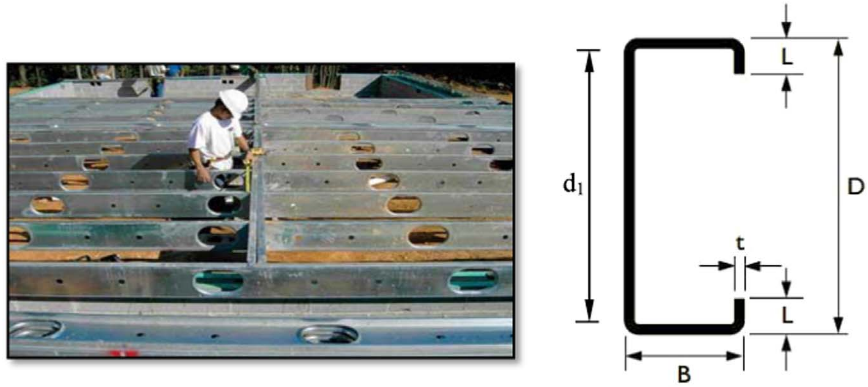
In recent times, cold-formed steel sections are frequently used in residential, commercial and industrial buildings due to their notable strength to weight ratio, ease of fabrication and ease of construction (see Fig. 1). Cold-formed steel sections such as lipped channel and Z-sections are commonly used in floor and roof framing systems, wall and truss systems and many other load bearing systems. Among these sections, lipped channel beam (LCB) sections (Fig. 1b) are commonly used as joists or bearers in floor systems (Fig. 1a). Commonly used LCB section have their section depths in the range of 150–300 mm, section widths in the range of 50–76 mm, and thickness in the range of 1.0–2.4 mm, and are made of steel of nominal yield strengths of 450 and 500 MPa. Many applications in such floor systems include web openings in the joists or bearers in order to include building services within them as shown in Fig. 1(a). Although the most common shape of openings used in floor systems is circular, different shapes such as square, rectangular and elliptical are considered as alternative web opening shapes.

Past research on the shear behaviour and strength of cold-formed steel sections containing web openings has been limited to lipped channel sections [1,2]. Shan et al. [1] recommended the use of a reduction factor (q_s) applied to the solid web strength of the shear element for calculating the shear capacity of cold-formed lipped channel beams with web openings. Eiler [2] extended Shan et al.'s [1] work to include the behaviour of web elements with openings subjected to linearly varying shear force. These shear strength equations have been adopted in AISI S100 [3] and AS/NZS 4600 [4] design standards for cold-formed steel structures. Keerthan and Mahendran [5,6] conducted experimental and finite element analyses to investigate the shear behaviour of lipped channel beams with circular unreinforced web openings and developed improved design equations for the prediction of their shear capacities.

The use of web openings in cold-formed steel beams causes a significant reduction to their shear capacities. Many parameters affect the shear capacity of cold-formed steel beams containing web openings. They are the shape, size and location of the web openings and the slenderness of the web element. Past research [1,5] has reported that the most influential parameter for the shear capacity of LCBs with web openings is the ratio of the depth of web opening (d_{wh}) to clear height

* Corresponding author.
E-mail address: m.mahendran@qut.edu.au (M. Mahendran).

http://dx.doi.org/10.1016/j.tws.2017.03.035
Received 30 September 2016; Received in revised form 6 March 2017; Accepted 31 March 2017



(a) Applications of LCBs (b) LCB Profile

Fig. 1. LCBs with web openings.

of web (d_1) and thus developed their shear capacity reduction factors in terms of d_{wh}/d_1. However, past research has concentrated on circular web openings.

The primary aim of this research is to investigate the effect of unreinforced non-circular web openings (square, rectangular and elliptical) on the shear capacity of lipped channel beam (LCB) sections using detailed finite element analyses (FEA) and to investigate the accuracy of current design rules. This paper presents the details of this numerical study into the shear behaviour and design of LCBs with unreinforced non-circular web openings located centrally within their web height. Shear capacities from FEA are compared with the predicted shear capacities using the current design rules in AS/NZS 4600 [4] and AISI S100 [3], based on which improved shear design rules are proposed.

2. Current shear design rules for LCBs with web openings

Current shear design rules for cold-formed steel beams with web openings are based on a reduction factor (q_s) defined as the ratio of the nominal shear capacity of LCBs with web openings (V_{nl}) to the nominal shear capacity of LCBs without web openings (V_v). Hence suitable design rules are also needed to predict V_v, and this section presents the currently available design rules for both V_v and q_s.

In general the shear design of LCBs considers web shear buckling behaviour in isolation without the effect of flange rigidity. LaBoube and Yu [7] investigated the shear strength of LCBs using single web side plates at the end supports and the loading point. Their shear strength equations are based on simply supported conditions at the web-flange juncture and do not include the available post-buckling strength in LCBs. Pham and Hancock [8,9] performed both experimental and numerical studies to investigate the shear behaviour of high strength cold-formed steel channel sections. They proposed improved design equations for the shear capacity of channel sections by including the available post-buckling strength in LCBs and the effect of additional fixity at the web-flange juncture (Eq. (1)–(3)). In these equations based on the direct strength method [9], the nominal shear capacity (V_v) is proposed using V_{cr} (elastic buckling capacity in shear) and V_y (shear yield capacity). These shear design equations are now included in AISI S100 [3].

$$V_v = V_y \qquad \text{for} \quad \frac{d_1}{t_w} \le 0.952\sqrt{\frac{Ek_v}{f_{yw}}} \tag{1}$$

$$V_V = \left[1 - 0.15\left(\frac{V_{cr}}{V_y}\right)^{0.4}\right]\left(\frac{V_{cr}}{V_y}\right)^{0.4} V_y \text{ for } \frac{d_1}{t_w} > 0.952\sqrt{\frac{Ek_v}{f_{yw}}} \tag{2}$$

$$V_y = 0.6 f_{yw} d_1 t_w \tag{3a}$$

$$V_{cr} = \frac{k_v \pi^2 E t_w^3}{12(1-\nu^2)d_1} \tag{3b}$$

where V_v = nominal shear strength, d_1 = depth of the flat portion of web, t_w = web thickness, E = elasticity modulus of steel, f_{yw} = design web yield stress, V_y and V_{cr} are given by Eqs. (3a) and (3b), and k_v is the enhanced elastic shear buckling coefficient of channel sections and its values are given in Pham and Hancock [8].

Keerthan and Mahendran [10] also proposed improved shear capacity equations for the LCBs based on their experimental and FEA results. Their shear capacity equations included the available post-buckling capacity in LCBs and the additional fixity at the web-flange juncture. The presence of additional fixity at the web-flange juncture of LCBs is allowed for by including an increased shear buckling coefficient (k_v) equation.

The investigation of cold-formed steel sections containing web openings was undertaken during the 1990s. However, only limited research has been undertaken in relation to LCBs with non-circular web openings. Shan et al. [1] proposed a shear capacity reduction factor q_s to determine the shear capacity of cold-formed steel beams with web openings as a function of the ratio of depth of web opening to clear web height (i.e. d_{wh}/d_1) based on their experimental study. Eiler [2] also proposed improved design equations to determine the shear capacity of cold-formed steel beams with web openings based on q_s using his experimental results. However, the shear capacity reduction factor q_s proposed by Eiler [2] also considers the remaining web area above the openings. Eiler [2] found that the parameter, c/t, was the dominant parameter affecting the shear behaviour of webs with circular and non-circular openings (Fig. 2). As shown in Fig. 2, the parameter c depends on the shape and size of the openings. AS/NZS 4600 [4] and AISI S100 [3] gives identical shear design equations (Eqs. (4)–(8)), which are based on Eiler's [2] recommendations.

$$V_{nl} = q_s V_v \tag{4}$$

$$q_s = 1 \qquad \frac{c}{t} > 54 \tag{5}$$

$$q_s = \frac{c}{54t} \qquad 5 \le \frac{c}{t} < 54 \tag{6}$$