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Improved shear design rules for lipped channel beams with web openings

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ABSTRACT

Cold-formed steel Lipped Channel Beams (LCB) with web openings are commonly used as floor joists and bearers in building structures. The shear behaviour of these LCBs with web openings is complicated and their shear capacities are considerably reduced by the presence of web openings. However, limited research has been undertaken on the shear behaviour and strength of LCBs with web openings. Hence a detailed numerical study was undertaken to investigate the shear behaviour and strength of LCBs with unreinforced 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 comparing their results with test results. They were then used in a detailed parametric study to investigate the effects of various influential parameters. Experimental and numerical results showed that the current design rules in cold-formed steel structures design codes are very conservative. Improved design equations were therefore proposed for the shear strength of LCBs with web openings based on both experimental and numerical results. This paper presents the details of finite element modelling of LCBs with unreinforced circular web openings, validation of finite element models, and the development of improved shear design rules. The proposed shear design rules in this paper can be considered for inclusion in the future versions of cold-formed steel design codes.

1. Introduction

Until recently, steel construction has recognized hot-rolled steel members as the most popular and widely used structural steel member type. However, over the past couple of decades, the use of cold-formed high strength steel members has been progressively integrated in steel construction as primary load bearing components. 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 structural members such as the 'C', 'Z' or tubular sections are commonly used in floor and roof framing systems (i.e. purlins, joists and bearers), wall and truss systems and many other load bearing systems. The increasing use of cold-formed steel sections has led to greater interest in the design and efficiency of cold-formed steel members. Among them, lipped channel sections are commonly used due to their high strength-to-weight ratio, economy of transportation and handling, ease of fabrication, simple erection and installation. Fig. 1(b) shows the use of lipped channel beams (LCB) in floor systems. Many applications in steel floor systems include openings in the web of joists or bearers so that building services can be located within them as shown in Fig. 1 (b). Although different shapes can be used for these web openings, the most common shape used in floor systems is circular while these openings are commonly used as unreinforced (Fig. 1 (a)). Pokharel and Mahendran's [1] study based on finite element analyses also recommended the use of circular unreinforced web openings for cold-formed steel beams such as LiteSteel beams [2].

Past research on the shear behaviour and strength of cold-formed steel sections containing web openings has been limited to 'C' sections [3–5]. Shan et al. [4] recommended that the nominal shear capacity of cold-formed lipped channel beams with web openings can be calculated using a reduction factor (q_s) applied to the solid web strength of the shear element. Eiler [5] extended Shan et al.'s [4] work to include the behaviour of web elements with openings subjected to linearly varying shear force. In Eiler's tests, cold-formed steel beams with web openings were subjected to a uniform load (not constant shear). Eiler [5] also proposed suitable design equations for the shear strength of cold-formed steel beams with web openings. These shear strength equations have been adopted in AISI S100 [6] and AS/NZS 4600 [7] design standards for cold-formed steel structures.

The use of web openings in cold-formed steel beams such as lipped channel beams significantly reduces their shear capacities due to the reduced web area. 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 also the slenderness of the web element. The main aim of this research is to investigate the effect of unreinforced circular web openings of varying diameters on the shear capacities of LCB sections using detailed finite element analyses (FEA) and experiments,

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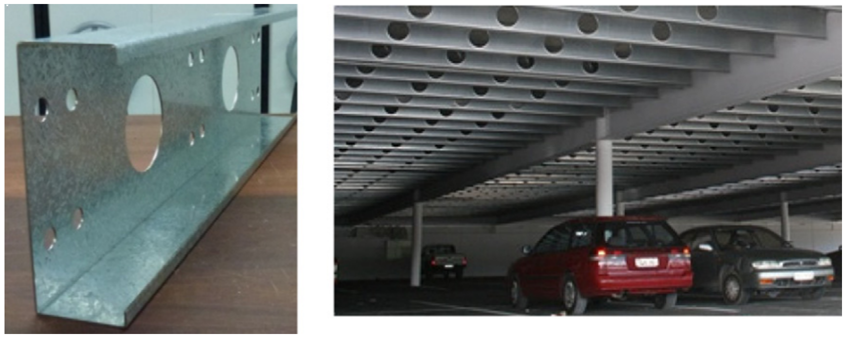

a) LCB with Web Openings b) Applications of LCBs

Fig. 1. LCBs with web openings.

and to investigate the accuracy of currently available design rules. This paper presents the details of the numerical study into the shear behaviour and design of LCBs with unreinforced circular web openings located centrally within their web height. Shear capacities from FEA and experiments are compared with the predicted shear capacities using the current design rules in AS/NZS 4600 [7] and the North American Specification [6], based on which improved shear design rules are proposed.

2. Shear behaviour and design of 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 lipped channel beams considers web shear buckling behaviour in isolation without the effect of flange rigidity. LaBoube and Yu [8] investigated the shear strength of lipped channel beams using single web side plate at the end supports and the loading point. Their proposed shear strength equations are based on simply supported conditions at the web-flange juncture and also without including the post-buckling strength in LCBs. Current shear capacity equations for V_v in AS/NZS 4600 [7] and AISI S100 [6] are based on LaBoube and Yu's research. Pham and Hancock [9,10] 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 (Eqs. (1) to (3)) by including the available post-buckling strength in LCBs and the effect of additional fixity at the web-flange juncture [11]. In these equations based on the direct strength method [6], the nominal shear capacity (V_v) is proposed using V_{cr} (elastic buckling capacity in shear) and V_y (shear yield capacity).

$$V_v = \left[1-0.15\left(\frac{V_{cr}}{V_y}\right)^{0.4}\right]\left(\frac{V_{cr}}{V_y}\right)^{0.4} V_y \tag{1}$$

$$V_y = 0.6A_w f_{yw} \tag{2}$$

$$V_{cr} = \frac{k_v \pi^2 E A_w}{12(1-\upsilon^2)\left(\frac{d_1}{t_w}\right)^2} \tag{3}$$

where k_v is the elastic shear buckling coefficient of the channel section [11].

Keerthan and Mahendran [12] also proposed improved shear strength equations for the new channel sections with two rectangular hollow flanges known as LiteSteel beams (LSB) based on the current shear strength design equations in AISI S100 [6], experimental and finite element analysis results. They then extended their research work to LCBs subjected to primarily shear action. Eqs. (4) to (6) present their proposed shear strength equations, which include the available post-buckling strength in LCBs and the additional fixity at the web-flange juncture. The shear capacity in kN can be obtained by multiplying the shear strength (τ_v) by its web area of $d_1 t_w$. The increased shear buckling coefficient given by Eq. (7) (k_{LCB}) is included to allow for the additional fixity in the web-flange juncture of LCBs [12].

$$\tau_v = \tau_{yw} \quad \text{for} \quad \sqrt{\frac{Ek_{LCB}}{f_{yw}}} < \frac{d_1}{t_w} \le 1.508\sqrt{\frac{Ek_{LCB}}{f_{yw}}} \tag{4}$$

$$\tau_v = \tau_i + 0.2\left(\tau_{yw}-\tau_i\right) \text{for} \quad \sqrt{\frac{Ek_{LCB}}{f_{yw}}} < \frac{d_1}{t_w} \le 1.508\sqrt{\frac{Ek_{LCB}}{f_{yw}}} \tag{5}$$

$$\tau_v = \tau_e + 0.2\left(\tau_{yw}-\tau_e\right) \text{for} \frac{d_1}{t_w} > 1.508\sqrt{\frac{Ek_{LCB}}{f_{yw}}} \tag{6}$$

where

$$\tau_i = 0.6 f_w \qquad \tau_i = \frac{0.6\sqrt{Ek_{LCB} f_{yw}}}{\left[\frac{d_1}{t_w}\right]} \qquad \tau_e = \frac{0.905 E k_{LCB}}{\left[\frac{d_1}{t_w}\right]^2}$$

For LCBs

$$k_{LCB} = k_{ss} + 0.23\left(k_{sf}-k_{ss}\right) \tag{7}$$

$$k_{ss} = 5.34 + \frac{4}{(a/d_1)^2} \quad \text{for} \quad \frac{a}{d_1} \ge 1 \tag{8}$$

$$k_{sf} = 8.98 + \frac{5.61}{(a/d_1)^2} - \frac{1.99}{(a/d_1)^3} \text{for} \frac{a}{d_1} \ge 1 \tag{9}$$

where k_{ss}, k_{sf} = shear buckling coefficients of plates with simple-simple and simple-fixed boundary conditions. a = shear span of web, d_1 = flat portion of clear height of web, and f_{yw} = web yield stress.

Suitable equations for V_v have been given above and now the equations for the shear capacity reduction factor q_s are given. AS/NZS 4600 [7] and AISI S100 [6] present the following design rules for cold-formed steel beams with unreinforced circular openings based on Eiler's [5] research.

$$V_{nl} = q_s V_v \tag{10}$$

$$q_s = 1 \quad \frac{c}{t} > 54 \tag{11}$$

$$q_s = \frac{c}{54t} \quad 5 \le \frac{c}{t} < 54 \tag{12}$$