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Improved shear design rules of cold-formed steel beams

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ABSTRACT

Light gauge cold-formed steel sections have been developed as more economical building solutions to the alternative heavier hot-rolled sections in the commercial and residential markets. Cold-formed lipped channel beams (LCB), LiteSteel Beams (LSB) and Triangular Hollow Flange Beams (THFB) are commonly used as flexural members such as floor joists and bearers while Rectangular Hollow Flange Beams (RHFB) are used in small scale housing developments through to large building structures. However, their shear capacities are determined based on conservative design rules. For the shear design of cold-formed steel beams, their elastic shear buckling strength and the potential post-buckling strength must be determined accurately. Hence experimental and numerical studies were conducted to investigate the shear behaviour and strength of LCBs, LSBs, THFBs and RHFBs. Improved shear design rules including the direct strength method (DSM) based design equations were developed to determine the ultimate shear capacities of these open and hollow flange steel beams. An improved equation for the higher elastic shear buckling coefficient of cold-formed steel beams was proposed based on finite element analysis results and included in the design equations. A new post-buckling coefficient was also introduced in the design equations to include the available post-buckling strength of cold-formed steel beams. This paper presents the details of this study on cold-formed steel beams subject to shear, and the results. It proposes generalised and improved shear design rules that can be used for any type of cold-formed steel beam.

1. Introduction

In recent times cold-formed steel members have become an increasingly integral part of the construction and building industries. They have many advantages over other construction materials including their light weight, high strength, high quality, protection, cost effective fabrication and non-combustibility. They are used in applications such as building frames, roof trusses, purlins and girts, floor framing and many other load bearing components.

Since early 1990s, Australian companies such as OneSteel Australian Tube Mills [1] have produced innovative cold-formed hollow flange sections known as the doubly symmetric Triangular Hollow Flange Beams (THFB) and the monosymmetric LiteSteel Beams (LSB) with rectangular hollow flanges (see Fig. 1). The development of these sections was based on improving the structural efficiency by adopting torsionally rigid hollow flanges, minimising local buckling of plate elements by eliminating free edges, distributing material away from the neutral axis to afford greater bending stiffness than conventional cold-formed sections, and optimising manufacturing efficiency. These hollow flange sections were produced from a single steel strip using a combined dual electric resistance welding and automated continuous roll-forming process. This manufacturing process produces higher yield strengths for the sections' plate elements, in particular for flange elements.

Rectangular Hollow Flange Beams (RHFB) are also new steel members, consisting of cold-formed rectangular hollow sections for both the top and bottom flanges welded to a flat web plate (see Fig. 1). They can also be cold-formed and welded or screw/rivet fastened along the web-flange juncture. The doubly symmetric RHFBs can be used as long spanning flexural members in various applications. Fig. 1 shows the hollow flange sections (THFB, LSB and RHFB) and one of the commonly used open cold-formed sections known as lipped channel beam (LCB). It also includes a monosymmetric THFB section.

In steel building systems, LCBs, LSBs, THFBs and RHFBs can be used as flexural members, for example, floor joists and bearers. For these cold-formed steel beams to be used as flexural members, their flexural and shear capacities must be known accurately including the potential post-buckling strength. In relation to shear capacity calculations, the elastic shear buckling coefficients of web panels are determined by assuming conservatively that the web panels are simply supported at the junction between the flange and web elements, and ignoring any post-buckling strength. In

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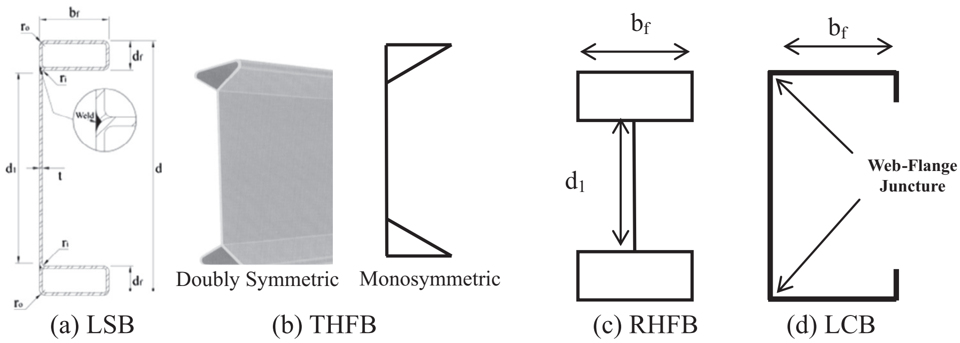

Fig. 1. Hollow flange and open cold-formed steel beams.

the traditional shear design method of cold-formed steel beams, the web shear buckling performance is considered without the effect of flange rigidity. The shear strength of cold-formed steel LCBs was studied by LaBoube and Yu [2]. They determined the ultimate strengths of LCBs by assuming that the web-flange juncture of LCBs was simply supported. Aswegan and Moen [3] investigated the elastic shear buckling stresses of C- and Z-Sections using hand solutions. Pham and Hancock [4] investigated the elastic buckling behaviour of unlipped and lipped channel section members subject to shear using an isoparametric spline finite strip method. They found that the flanges can have a significant influence on the shear buckling capacity of thin-walled channel sections. However, they did not propose a simple equation to determine the shear buckling coefficients of LCBs.

Pham and Hancock [5] conducted both experimental and numerical studies to investigate the shear behaviour of high strength cold-formed steel lipped channel sections. Suitable design equations for the shear capacity of LCBs (Eqs. (1) and (2)) were then proposed in Pham and Hancock [6]. These shear design equations have also been adopted in AISI S100 [7]. These equations predict the shear strength of LCBs which include their available post-buckling strength and the effect of additional fixity at the web-flange juncture. In these equations the DSM based nominal shear capacity (V_v) is proposed based on V_{cr} (elastic buckling capacity in shear) and V_y (shear yield capacity).

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

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

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

$$V_v = V_{cr} = \frac{k_v \pi^2 E t_w^3}{12(1-\nu^2)d_1} \tag{4}$$

where k_v is the enhanced elastic shear buckling coefficient of channel sections and its values are given in Pham and Hancock [6].

Although various studies have been conducted on LSBs subject to pure bending [8,9], research related to their shear capacities are limited [10,11]. Keerthan and Mahendran [12–14] investigated the elastic shear buckling behaviour of LSBs and LCBs. They proposed simple equations for the determination of elastic shear buckling coefficients of LSBs and LCBs. They found that the realistic support condition of LCB at the web-flange juncture is closer to a simply supported condition while that of LSB is closer to a fixed supported condition. However there are no simple equations to determine the shear buckling coefficients of RHFBs and THFBs. Hence in this research the elastic shear buckling behaviour of RHFBs and THFBs was investigated using finite element analyses (FEA) including the effect of true support conditions at the junction between their flange and web elements. These finite element models included idealized simply supported boundary conditions and a shear flow based loading to prevent any torsional effect. For comparison purposes, a plate girder (PG) was also considered in FEA. The results were then used to develop an equation for the elastic shear buckling coefficient of these beams and determine the corresponding ultimate shear capacity improvement based on the direct strength method (DSM) based shear capacity equations proposed by Keerthan and Mahendran [13].

An increased shear buckling coefficient (k_v) and a post-buckling coefficient (p_n) were also introduced in the DSM based shear capacity equations to allow for the additional fixity in the web-flange juncture instead of k_v assumed as 5.34 in AS/NZS 4600 [15] and include the available post-buckling strength of cold-formed steel beams, respectively. These two coefficients depend on the type of steel beam section. The ultimate shear capacities of any open and hollow flange cold-formed steel beams can be computed using the proposed DSM based shear capacity equations if the relevant elastic shear buckling coefficient (k_v) and post-buckling coefficient (p_n) are known. This paper presents the details of this study including finite element models, shear buckling modes and coefficients and DSM based shear capacity equations including both the increased shear buckling and post-buckling strengths. It also includes the results of LSBs and LCBs based on Keerthan and Mahendran [13,14].

2. Elastic shear buckling analyses

2.1. Model description

This section presents the development of finite element models to investigate the shear behaviour of hollow flange (LSBs, THFBs and RHFBs) and open (LCBs and PG) steel beams including their elastic shear buckling characteristics. For this purpose, a simply supported beam with a mid-span load was considered. A general purpose finite element program ABAQUS [16], which has the capability of undertaking geometric and material non-linear analyses of three dimensional structures, was used. Idealized simply supported boundary conditions were implemented in the beams under a three point loading arrangement. Fig. 2 shows the schematic diagram of the loading set-up used in this research. An aspect ratio (a/d_1) of 1.0 was used to simulate a primarily shear behaviour. ABAQUS has several element types to simulate the shear behaviour of beams. But amongst those, shell element was selected as it has the capability to simulate the shear buckling behaviour of LSBs, LCBs, THFBs, RHFBs and PGs. The shell element available in ABAQUS called S4R was used to model the shear