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EXPERIMENTAL INVESTIGATION ON SHEAR CAPACITY OF LIPPED CHANNEL BEAMS WITH NON-CIRCULAR WEB OPENINGS

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Abstract: Cold-formed steel members are increasingly used around the world due to the availability of thin and high strength steel and advanced steel technologies. Sri Lanka as a fast growing economy in Asia requires new technologies to suit the rapid construction. Cold-formed steel is a viable material for fast and easy construction. This paper presents the results of an experimental study on shear behaviour and strength of cold-formed steel Lipped Channel Beams (LCB) having non-circular web openings. The study included fifty three (53) full scale shear tests of LCBs including square, rectangular, and elliptical web openings tested under simply supported end conditions. The grades of steel are G350 and G450 with thickness 2 mm. The test results were compared with the predictions from the current design rules given in the Australian cold-formed steel design standards AS/NZS 4600 to verify its applicability to LCBs with non-circular web openings. The results show that the predictions of shear capacity reduction due to non-circular web opening by AS/NZS 4600 are conservative in general. The comparison was also done with the other existing shear design equations. The predictions given by Shan et. al. are too conservative and the predictions given by Keerthan and Mahendran are un-conservative in general.

Keywords: Cold-formed steel, Shear capacity, Lipped channel beam, web openings.

1. Introduction

In compare to conventional hot-rolled steel (HRS), the cold-formed steel (CFS) structural members are catching the attention in modern steel construction extensively nowadays due to many advantages they can offer. The CFS members are relatively thin and have a greater width-to-thickness ratio for the flat elements. The advantages associated with CFS are high strength to weight ratio, light weight, easy fabrication, easy erection, ability produce in mass scale etc. which could create cost saving in the construction. The CFS products are being widely used as purlins, girts, portal frames and steel framed housing. The availability of advanced technologies, very thin steels even less than 1 mm, and high strength steels over 550MPa, has made the cold-forming process simple, efficient, economical and environmentally friendly, with the ability of producing a variety of efficient sections compared to the conventional and more expensive hot-rolled sections.

The traditional way of designing the steel beams was with the solid webs, but current practice is to include openings in the web of floor joist or bearers. Sometimes the service engineer who visit the site long after require to make openings in the web to provide ducts and pipelines for various services. Hence the provision of beams with web openings has become an acceptable practice, which eliminates the service engineer cutting holes in an inappropriate location. However, the use of web openings in cold-formed steel beams significantly reduces their shear capacities due to reduced web area. Many parameters affect the shear capacity of cold-formed steel beams with web openings. They are the shape, size and location of the web openings and also the slenderness of the web element. Past researches [1,2] 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 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.

This paper presents the details of an experimental study on shear behavior and design of LCBs with unreinforced non-circular web openings located centrally within their web height. Shear capacities obtained from the experiments were compared with the predicted shear capacities using the current design rules given in the AS/NZS 4600 [3] and the North American Specifications, AISI S100 [4], and based on the comparison, recommendations are given for shear design rules for cold-formed steel channel sections with non-circular web openings.

2. Review of Existing Design Rules

Shear design rules for cold-formed steel beams with web openings are based on a shear reduction factor (qs) at present and it is defined as the ratio of the nominal shear capacity with web openings (Vnl) to the nominal shear capacity of without web openings (Vv). Hence the shear capacity of LCBs with web openings (Vnl) is depended on two parameters Vv and qs and this section discusses the currently available design rules on those parameters.

Current shear design equations for nominal shear capacity Vv given in AISI S100 (AISI, 2012) and AS/NZS 4600 (SA, 2005) are based on LaBoube and Yu [5] recommendations. The shear capacity equations (Vv) given in these codes are based on simply supported conditions at the web-flange juncture and also without including the post buckling strength. Eqs. 1-3 given in AS/NZS 4600 [3] to calculate Vv are as follows:

$$V_v = 0.64 f_y d_1 t_w \quad \text{for} \quad d_1/t_w \leq \sqrt{Ek_v/f_y} \qquad (1)$$

$$V_v = 0.64 t_w^2 \sqrt{Ek_v/f_y} \qquad (2)$$

for $\sqrt{Ek_v/f_y} \leq d_1/t_w \leq 1.415\sqrt{Ek_v/f_y}$

$$V_v = \frac{0.905 E k_v t_w^3}{d_1} \qquad (3)$$

$d_1/t_w \geq 1.415\sqrt{Ek_v/f_y}$

Where d_1 – depth of the flat portion of the web measured along the plane of the web, t_w – thickness of the web, k_v – shear buckling coefficient determine as follows

For unstiffened webs: k_v = 5.34, For beam webs with transverse stiffeners;

$k_v=4.00+[5.34/(a/d_1)^2]$ for $a/d_1 \leq 1.0$

$k_v=5.34+[4.00/(a/d_1)^2]$ for $a/d_1 > 1.0$

Keerthan and Mahendran [6] investigated the elastic shear buckling behavior of cold-formed steel beams known as LiteSteel beams (LSBs) and developed a simple predictive equation for the increased shear buckling coefficient (k_v) due to the presence of higher fixity along the web to flange juncture. Keerthan and Mahendran [7, 8, 9] continued their research using experimental and numerical studies and developed suitable design equations for the shear capacity of hollow flange channel beams (V_v) by including the available post-buckling strength and the increased shear buckling coefficient (k_v).

Pham and Hancock [10] also investigated the elastic buckling of unlipped and lipped channel section members subject to shear using an isoparametric spline finite strip method. They found that flanges can have a significant influence on the shear buckling capacity of thin walled channel sections. Pham and Hancock [11] conducted both experimental and numerical studies to investigate the shear behavior of high strength cold-formed steel lipped channel sections. Pham and Hancock [12] then proposed suitable design equations for the shear capacity of LCBs (Eqs. 4 and 5).

$$V_v = V_y \quad \text{for} \quad d_1/t_w \leq \sqrt{Ek_v/f_{yw}} \qquad (4)$$

$$V_v = \left[1 - 0.15\left(\frac{V_{cr}}{V_y}\right)^{0.4}\right]\left(\frac{V_{cr}}{V_y}\right)^{0.4} V_y \qquad (5)$$

For $\frac{d_1}{t_w} > \sqrt{Ek_v/f_{yw}}$

where shear yielding capacity $V_y = 0.6 f_{yw} d_1 t_w$ and elastic shear buckling capacity $V_{cr} = (0.905 E k k_v t_w^3)/d_1$. Enhanced shear buckling coefficients k_v for channel sections are given in Pham [13].

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). Currently available design rules to predict q_s are discussed next.

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 [14] also proposed improved design equations for shear capacity reduction factor q_s using experimental results. Shear design equations (i.e. Eqs. 6-10) given in AS/NZS 4600 [3] and AISI S100 [4] are based on Eiler's [14] recommendations.

$$V_{nl} = q_s V_v \tag{6}$$

$$q_s = 1 \qquad \frac{c}{t} > 54 \tag{7}$$

$$q_s = \frac{c}{54t} \qquad 5 \leq \frac{c}{t} < 54 \tag{8}$$

$$c = \frac{d_1}{2} - \frac{d_{wh}}{2.83} \text{ circular web openings} \tag{9}$$

$$c = \frac{d_1}{2} - \frac{d_{wh}}{2} \text{ non-circular web openings} \tag{10}$$

where

$$\frac{d_{wh}}{d_1} < 0.7,\ \frac{d_{wh}}{t_w} \leq 200,\quad d_{wh} > 15\,\text{mm},$$

$$d_{wh} \leq 150\,\text{mm}$$

Keerthan and Mahendran [2] also proposed shear capacity reduction factor q_s equations for the LiteSteel beam (LSB) with unreinforced circular web openings based on the ratio of d_{wh}/d_1 in a similar manner to Shan et al. [1].

3. Shear tests of LCBs with non-circular web openings

In the design of this test program, it was important to choose the key parameters carefully. The shear behavior of LCB sections with non-circular web openings can be fully understood if the parameters such as the ratios of the depth of web openings to clear height of web (d_{wh}/d_1) and the clear height of web to web thickness ratio(d_1/t_w) are selected accurately. Following sections describe test specimens, test set-up, and test procedures.

3.1 Test specimens and test set-up

The conference proceedings will be published in standard book (170mm x245 mm) size with two-column layout for text. Diagrams and tables should be in portrait orientation with either one or two column width.

Tests were conducted to investigate the shear behaviour and strength of LCBs with non-circular web openings using a series of full scale shear tests of simply supported LCBs subjected to a mid-span load as shown in Fig. 1.

The test specimens were made by bolting two LCB sections back to back using three T-shaped stiffeners and web side plates located at the end supports and the loading point as shown in Fig. 1. Back to back LCB specimens were used so that it eliminates any torsional loading on test beams. Used of web side plates eradicate possible web crippling of flanges and flange bearing failures. A 30 mm gap between back to back LCBs was introduced to allow the test beams to behave independently but remain together to resist torsional effects. Relatively short test beams were selected based on aspect ratios (i.e. shear span 'a'/clear web height d_1) of 1.0 and 1.5 to simulate predominant shear conditions. Five web opening sizes (d_{wh}) of 60, 80, 100, 125 and150 mm were chosen for two LCB sections (i.e. 200x75x18x2 and 150x65x12x2) giving a total of 53 shear tests. They included four shear tests without web openings, i.e. one test for each section with two aspect ratios.

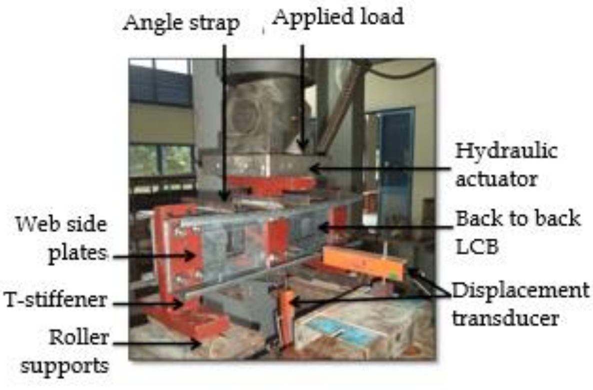


Figure 1: Experimental set-up of back-to-back LCB with non-circular web openings

Moreover, the LCB sections were selected to represent more commonly used LCB sections in the building industry. To steel grades, G350 and G45 were used with 2 mm gauge. Table 1 presents the specimen details of the shear tests. It includes the measured thicknesses (t_w), clear heights (d_1) and yield stresses (f_{yw}), web opening size (d_{wh}), and aspect ratio of the web elements of tested LCBs. The test specimens were also designed to fail in shear prior to reaching other section capacities. Since LCB are open sections, they have an unbalanced shear flow. In order to eliminate the flange distortion due to the presence of this unbalanced shear flows, the flanges of LCBs were restrained by straps. The effect of these straps on the shear behaviour and strength of LCBs having non-circular web openings were also investigated conducting four shear tests without straps.

Load on the LCB sections were applied through the centrally positioned T-shaped stiffener to avoid bearing failures of the flanges. This also has the advantage of applying the load through the shear centre to avoid eccentric loading and web crippling. The T-stiffener was attached to the back to back LCB test beams with two web side plates using four M16 bolts at the mid-span loading point (see Fig. 1). Similar T-shaped stiffeners were also arranged at the supports. The test beam was supported on round sections which ensure simply supported condition at each end. It was observed during the test that the ends of the test beams were freely rotate and therefore simply supported conditions were simulated accurately at the end supports.

The applied load and the deflection at the mid-span of the test beam are important parameters and they were measured during the tests. A displacement gauge was set-up under the loading point on the bottom flange at mid-span of the test beam to measure the vertical deflections (see Fig. 1). Relatively short span test beams were selected based on the aspect ratios of 1.0 and 1.5. However, the loading system adopted in these shear tests was not subjected to pure shear. Some additional bending moment will also be present. However according to the design rules given in AS 4100 for combined shear and bending, it can be assumed that the shear capacity is not affected by this additional bending moment if the ratio of applied moment M_n to the section moment capacity φM_s is less than 0.75.

3.2. Test procedure

Two LCBs were fabricated having non-circular web openings, and their section parameters, specially, the clear web height (d_1) and web thickness (t_w) were measured and recorded (Table 1).

The distance between the centre of inner bolts on the web side plates was taken as the shear span, 'a'. The length of test specimen was calculated based on the aspect ratios 1.0 and 1.5. For example, in the case of 200x75x18x2 LCB with d_1=196 mm, shear span was 294 mm corresponding to an aspect ratio of 1.5 since the aspect ratios =shear span a/clear web height d_1. Hence the specimen length L was 773 mm (i.e. 196x2+45x3+2x25) based on the spacing of bolts in the web side plates of 45 mm and the edge distance of outer bolts of 25 mm.

The test beams were provided with 25 mm overhang at both ends. The effective connections at the loading point and the support points were made by bolting two LCBs, T-stiffener, and web side plates together at each position. The assembled pair of LCB sections with non-circular web openings was positioned accurately in the test rig to ensure that the three-point loading method was achieved.

A displacement transducer was set-up under the point load and it was connected to the data acquisition system to measure the vertical deflection as shown in Fig. 1. A small load was applied first to allow the loading and support systems to settle on bearings evenly. The measuring system was then initialised with zero values and the loading was commenced. The crosshead of the actuator was moved at a constant rate of 0.015 mm/sec until the test beam failed.

3.3. Test Results

The shear force induced in each LCB section is equal to the ultimate applied load (P) divided by 4 for this back to back LCB test arrangement. Experimental shear capacity reduction factor q_s for each test was calculated as the ratio of applied shear force for a LCB with web opening to the applied shear force without web opening. The experimental results of the ultimate load (P), shear capacity of a LCB, and shear capacity reduction factors for various web opening size and shape are presented in Table 2.

Fig. 3 shows the load deflection curves for the shear test of 150x65x12x2 LCB with 80x80 square web openings. At point 1, the web began to deflect out of plan when shear capacity is 9.5kN (applied load of 38kN/4). Fig. 3 also shows that at point 2 the beam reached the ultimate shear capacity of 12.9kN (applied load of 51.6kN/4). This confirms that LCBs with web openings also have post-buckling strength due to the presence of tension field action.

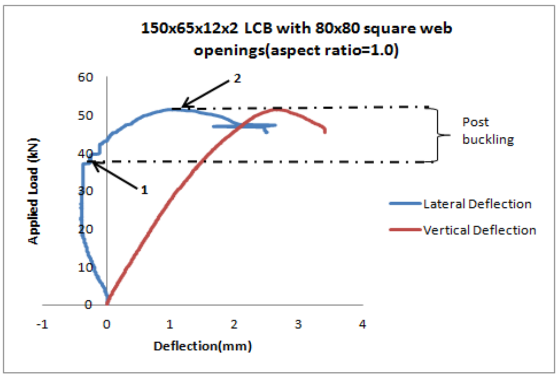
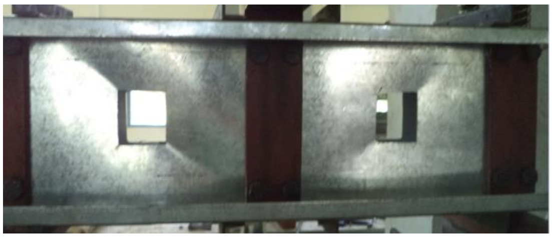
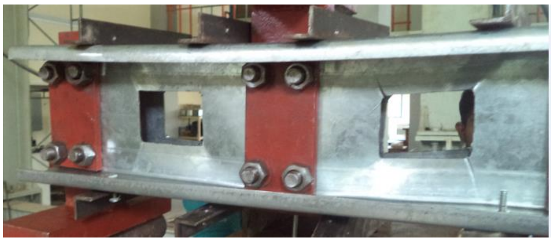


Figure 2: Applied load verses deflection for 150×65×12×2 LCB section

Figs.3 (a)–(c) show the failure modes of shear tests on 200x75x18x2 LCB with 600x60 square web openings (aspect ratio of 1.5), 150x65x12x2 LCB with 80x60 rectangular web opening (aspect ratio 1.5), 200x75x18x2 LCB with 100x60 elliptical web openings (aspect ratio of 1.0), respectively.



(a)



(b)

(c)

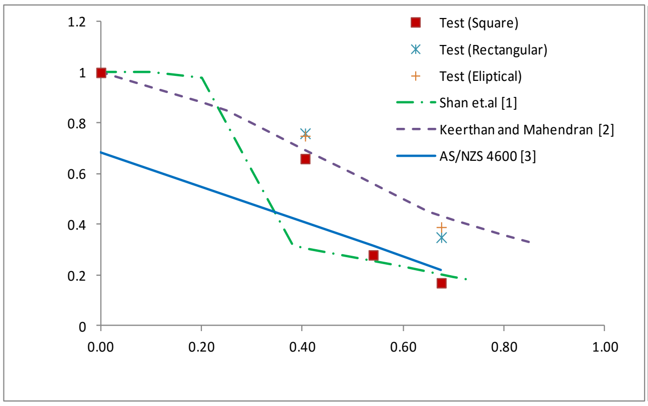
Figure 3: Shear failure modes of LCBs with different web opening shapes and sizes

4. Comparison of shear test results with the existing design rules

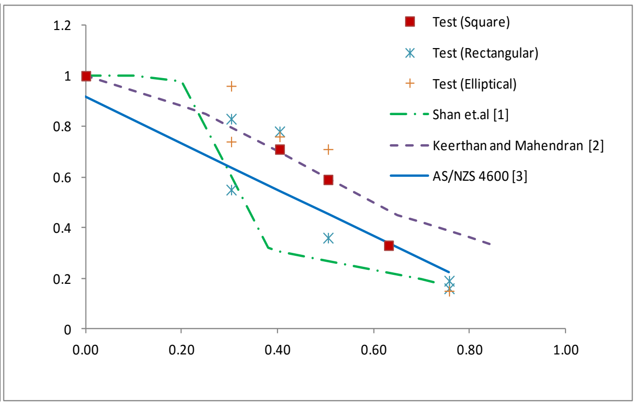
Experimental shear capacity reduction factors obtained from fifty three (53) shear tests were compared with the predictions from the design equations in AS/NZS 4600 [3], Shan et al. [1], Keerthan and Mahendran [2]. The comparison is shown in Table 3. The experimental shear capacities of LCBs without web openings obtained from this study and reported in Table 2 were used as the reference values to determine the shear capacity reduction factor q_s in all cases.

Figs. 4(a)-(d) give a comparison of shear capacity reduction factor q_s versus depth of web opening to clear height of web ratio (d_{wh}/d_1) for the experiment and the current shear design equations for three types of non-circular web opening shapes. According to the comparison shown in Figs. 4(a)-(d), the predicted shear capacities based on AS/NZS4600 [3] are conservative in general for all shapes of non-circular web openings. However, AS/NZS4600 [3] predictions show unconservative results for large openings (i.e. d_{wh}/d_1>0.5) with aspect ratio 1.0. The shear capacity reduction factor given in AS/NZS4600 [3 are directly related to d_{wh}/d_1 and therefore AS/NZS4600 [3] curve varies from section to section.

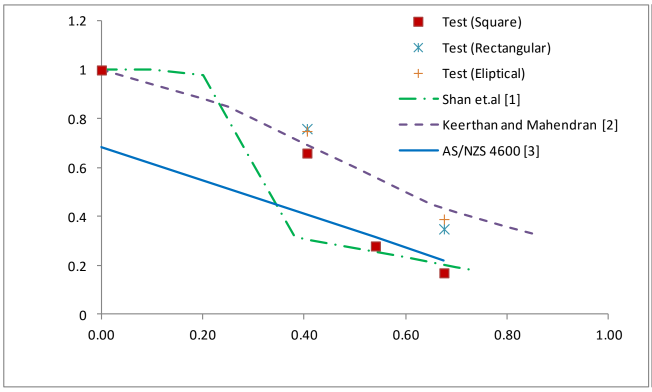
It is clear from these comparisons that the design equations proposed by Shan et al. [1] are too conservative for the shear capacity of LCBs in all types of non-circular web openings. The comparison of test results with the Keerthan and Mahendran [2] design equations showed that they are unconservative in general for the LCB sections with different shapes of non-circular web openings. Therefore none of the existing design rules can predict the shear capacity reduction in LCBs with non-circular web openings and therefore new shear design equations are deemed necessary.



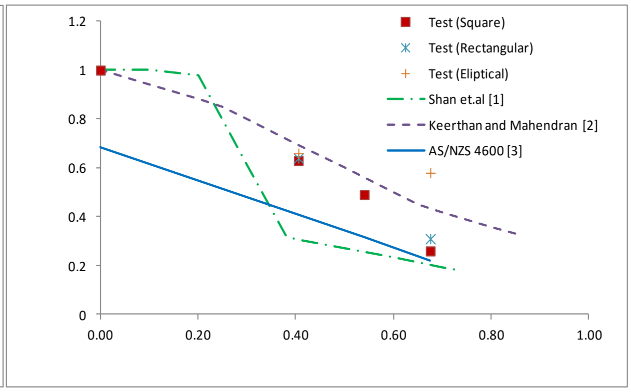
(a)– 200x75x18x2 LCB (aspect ratio 1.0)



(b)– 200x75x18x2 LCB (aspect ratio 1.5)



(c)– 150x65x15x2 LCB (aspect ratio 1.0)



(d) – 150x65x15x2 LCB (aspect ratio 1.5)

Figure 4: Shear capacity reduction factor q_s vs d_{wh}/d_1 for LCBs with non-circular web openings

Table 1: Measured details of LCB test specimens with non-circular web openings

Test no.	LCB section	Shape of opening	Aspect Ratio	f_{yw} (Mpa)	t_w (mm)	d_1 (mm)	d_{wh} (mm)	d_{wh}/d_1
1	200x75x18x2	Square	1	510	2.06	192	0	0.00
2	200x75x18x2	Square	1	510	2.08	194	60	0.31
3	200x75x18x2	Square	1	510	2.16	193	80	0.41
4	200x75x18x2	Square	1	510	2	192	100	0.52

5	200x75x18x2	Square	1	510	2.08	192	125	0.65
6	200x75x18x2	Square	1	510	2.06	192	150	0.78
7	150x65x12x2	Square	1	482	2.26	142	0	0.00
8	150x65x12x2	Square	1	482	2.2	142	60	0.42
9	150x65x12x2	Square	1	482	2.16	142	80	0.56
10	150x65x12x2	Square	1	482	2.26	142	100	0.70
11	200x75x18x2	Square	1.5	510	2.06	192	0	0.00
12	200x75x18x2	Square	1.5	510	2.16	192	60	0.31
13	200x75x18x2	Square	1.5	510	2.16	192	80	0.42
14	200x75x18x2	Square	1.5	510	2	192	100	0.52
15	200x75x18x2	Square	1.5	510	2.08	192	125	0.65
16	200x75x18x2	Square	1.5	510	2.16	192	150	0.78
17	150x65x12x2	Square	1.5	482	2.2	142	0	0.00
18	150x65x12x2	Square	1.5	482	2.26	141	60	0.43
19	150x65x12x2	Square	1.5	482	2.16	141	80	0.57
20	150x65x12x2	Square	1.5	482	2.26	141	100	0.71
21	150x65x12x2	Square	1.5	482	2.2	141	125	0.89
22	150x65x12x2	Rectangular	1	482	2.26	141	60	0.43
23	150x65x12x2	Rectangular	1	482	2.16	142	100	0.70
24	200x75x18x2	Rectangular	1	510	2.08	193	60	0.31
25	200x75x18x2	Rectangular	1	510	2.16	192	80	0.42
26	200x75x18x2	Rectangular	1	510	2	192	150	0.78
27	200x75x18x2	Rectangular	1	510	2.08	193	60	0.31
28	200x75x18x2	Rectangular	1	510	2.1	192	100	0.52
29	200x75x18x2	Rectangular	1	510	2.08	193	150	0.78
30	150x65x12x2	Rectangular	1.5	482	2.26	142	60	0.42
31	150x65x12x2	Rectangular	1.5	482	2.2	141	100	0.71
32	200x75x18x2	Rectangular	1.5	510	2.16	192	60	0.31
33	200x75x18x2	Rectangular	1.5	510	2.06	192	80	0.42
34	200x75x18x2	Rectangular	1.5	510	2.08	192	150	0.78
35	200x75x18x2	Rectangular	1.5	510	2.06	192	60	0.31
36	200x75x18x2	Rectangular	1.5	510	2.16	192	100	0.52
37	200x75x18x2	Rectangular	1.5	510	2.08	192	150	0.78
38	150x65x12x2	Elliptical	1	482	2.2	141	60	0.43
39	150x65x12x2	Elliptical	1	482	2.16	142	100	0.70
40	200x75x18x2	Elliptical	1	510	2.1	192	60	0.31
41	200x75x18x2	Elliptical	1	510	2.08	192	80	0.42
42	200x75x18x2	Elliptical	1	510	2	194	100	0.52
43	200x75x18x2	Elliptical	1	510	2.16	192	60	0.31
44	200x75x18x2	Elliptical	1	510	2.1	192	100	0.52
45	200x75x18x2	Elliptical	1	510	2.08	192	125	0.65
46	150x65x12x2	Elliptical	1.5	482	2.16	141	60	0.43
47	150x65x12x2	Elliptical	1.5	482	2.2	142	80	0.56
48	200x75x18x2	Elliptical	1.5	510	2	193	60	0.31
49	200x75x18x2	Elliptical	1.5	510	2.16	192	80	0.42
50	200x75x18x2	Elliptical	1.5	510	2.08	194	100	0.52
51	200x75x18x2	Elliptical	1.5	510	2.06	192	60	0.31
52	200x75x18x2	Elliptical	1.5	510	2.16	193	100	0.52
53	200x75x18x2	Elliptical	1.5	510	2.08	192	125	0.65

Table 2: Shear test results for LCB sections with non-circular web openings

Test no.	LCB section	Aspect ratio	f_{yw} (Mpa)	d_{wh}/d_1	Ultimate applied load (kN)	Test shear capacity (kN)	Shear capacity reduction factor, q_s (Eq 1)
1	200x75x18x2	1	510	0.00	210.82	52.71	1.00
2	200x75x18x2	1	510	0.31	155.15	38.79	0.74
3	200x75x18x2	1	510	0.41	130.73	32.68	0.62
4	200x75x18x2	1	510	0.52	95.60	23.90	0.45
5	200x75x18x2	1	510	0.65	56.00	14.00	0.27
6	200x75x18x2	1	510	0.78	27.12	6.78	0.13
7	150x65x12x2	1	482	0.00	185.94	46.49	1.00
8	150x65x12x2	1	482	0.42	123.12	30.78	0.66
9	150x65x12x2	1	482	0.56	51.56	12.89	0.28
10	150x65x12x2	1	482	0.70	31.55	7.89	0.17
11	200x75x18x2	1.5	510	0.00	161.77	40.44	1.00
12	200x75x18x2	1.5	510	0.31	164.84	41.21	1.02
13	200x75x18x2	1.5	510	0.42	114.27	28.57	0.71
14	200x75x18x2	1.5	510	0.52	95.07	23.77	0.59
15	200x75x18x2	1.5	510	0.65	54.02	13.51	0.33
16	200x75x18x2	1.5	510	0.78	9.52	2.38	0.06
17	150x65x12x2	1.5	482	0.00	155.42	38.86	1.00
18	150x65x12x2	1.5	482	0.43	97.86	24.47	0.63
19	150x65x12x2	1.5	482	0.57	76.12	19.03	0.49
20	150x65x12x2	1.5	482	0.71	41.05	10.26	0.26
21	150x65x12x2	1.5	482	0.89	14.77	3.69	0.10
22	150x65x12x2	1	482	0.43	117.61	29.40	0.76
23	150x65x12x2	1	482	0.70	53.64	13.41	0.35
24	200x75x18x2	1	510	0.31	130.73	32.68	0.62
25	200x75x18x2	1	510	0.42	145.81	36.45	0.69
26	200x75x18x2	1	510	0.78	17.21	4.30	0.08
27	200x75x18x2	1	510	0.31	127.92	31.98	0.61
28	200x75x18x2	1	510	0.52	73.53	18.38	0.35
29	200x75x18x2	1	510	0.78	23.02	5.76	0.11
30	150x65x12x2	1.5	482	0.42	99.40	24.85	0.64
31	150x65x12x2	1.5	482	0.71	47.63	11.91	0.31
32	200x75x18x2	1.5	510	0.31	133.61	33.40	0.83
33	200x75x18x2	1.5	510	0.42	126.11	31.53	0.78
34	200x75x18x2	1.5	510	0.78	26.51	6.63	0.16
35	200x75x18x2	1.5	510	0.31	88.83	22.21	0.55
36	200x75x18x2	1.5	510	0.52	58.69	14.67	0.36
37	200x75x18x2	1.5	510	0.78	30.42	7.61	0.19
38	150x65x12x2	1	482	0.43	140.30	35.08	0.75
39	150x65x12x2	1	482	0.70	72.95	18.24	0.39
40	200x75x18x2	1	510	0.31	184.04	46.01	0.87
41	200x75x18x2	1	510	0.42	156.33	39.08	0.74
42	200x75x18x2	1	510	0.52	104.45	26.11	0.50
43	200x75x18x2	1	510	0.31	154.93	38.73	0.73
44	200x75x18x2	1	510	0.52	93.54	23.39	0.44
45	200x75x18x2	1	510	0.65	17.21	4.30	0.08
46	150x65x12x2	1.5	482	0.43	103.05	25.76	0.66
47	150x65x12x2	1.5	482	0.56	89.78	22.45	0.58
48	200x75x18x2	1.5	510	0.31	155.42	38.86	0.96
49	200x75x18x2	1.5	510	0.42	123.73	30.93	0.76

50	200x75x18x2	1.5	510	0.52	86.34	21.59	0.53
51	200x75x18x2	1.5	510	0.31	119.11	29.78	0.74
52	200x75x18x2	1.5	510	0.52	115.06	28.77	0.71
53	200x75x18x2	1.5	510	0.65	24.29	6.07	0.15

Table 3: Comparison of shear capacity reduction factor of test with existing design rules

Test no.	LCB section	Aspect ratio	f_{yw} (Mpa)	d_{wh}/d_1	q_s			
					Test	Shan et al. [1]	Keerthan, Mahendran [2]	AS/NZS 4600 [3]
1	200x75x18x2	1	510	0.00	1.00	1.00	1.00	1.00
2	200x75x18x2	1	510	0.31	0.74	0.58	0.81	0.60
3	200x75x18x2	1	510	0.41	0.62	0.30	0.67	0.48
4	200x75x18x2	1	510	0.52	0.45	0.26	0.53	0.43
5	200x75x18x2	1	510	0.65	0.27	0.21	0.36	0.30
6	200x75x18x2	1	510	0.78	0.13	0.16	0.24	0.19
7	150x65x12x2	1	482	0.00	1.00	1.00	1.00	1.00
8	150x65x12x2	1	482	0.42	0.66	0.30	0.66	0.35
9	150x65x12x2	1	482	0.56	0.28	0.25	0.47	0.27
10	150x65x12x2	1	482	0.70	0.17	0.19	0.29	0.17
11	200x75x18x2	1.5	510	0.00	1.00	1.00	1.00	1.00
12	200x75x18x2	1.5	510	0.31	1.02	0.57	0.80	0.57
13	200x75x18x2	1.5	510	0.42	0.71	0.30	0.67	0.48
14	200x75x18x2	1.5	510	0.52	0.59	0.26	0.53	0.43
15	200x75x18x2	1.5	510	0.65	0.33	0.21	0.36	0.30
16	200x75x18x2	1.5	510	0.78	0.06	0.16	0.24	0.18
17	150x65x12x2	1.5	482	0.00	1.00	1.00	1.00	1.00
18	150x65x12x2	1.5	482	0.43	0.63	0.30	0.66	0.33
19	150x65x12x2	1.5	482	0.57	0.49	0.24	0.47	0.26
20	150x65x12x2	1.5	482	0.71	0.26	0.19	0.28	0.17
22	150x65x12x2	1	482	0.43	0.76	0.30	0.66	0.33
23	150x65x12x2	1	482	0.70	0.35	0.19	0.29	0.18
24	200x75x18x2	1	510	0.31	0.62	0.34	0.81	0.59
25	200x75x18x2	1	510	0.42	0.69	0.30	0.67	0.48
26	200x75x18x2	1	510	0.78	0.08	0.16	0.19	0.19
27	200x75x18x2	1	510	0.31	0.61	0.34	0.81	0.59
28	200x75x18x2	1	510	0.52	0.35	0.26	0.53	0.41
29	200x75x18x2	1	510	0.78	0.11	0.16	0.19	0.19
30	150x65x12x2	1.5	482	0.42	0.64	0.30	0.66	0.34
31	150x65x12x2	1.5	482	0.71	0.31	0.19	0.28	0.17
32	200x75x18x2	1.5	510	0.31	0.83	0.34	0.80	0.57
33	200x75x18x2	1.5	510	0.42	0.78	0.30	0.67	0.50
34	200x75x18x2	1.5	510	0.78	0.16	0.16	0.19	0.19
35	200x75x18x2	1.5	510	0.31	0.55	0.34	0.80	0.59
36	200x75x18x2	1.5	510	0.52	0.36	0.26	0.53	0.39
37	200x75x18x2	1.5	510	0.78	0.19	0.16	0.19	0.19
38	150x65x12x2	1	482	0.43	0.75	0.30	0.66	0.34
39	150x65x12x2	1	482	0.70	0.39	0.19	0.29	0.18
40	200x75x18x2	1	510	0.31	0.87	0.34	0.80	0.58
41	200x75x18x2	1	510	0.42	0.74	0.30	0.67	0.50
42	200x75x18x2	1	510	0.52	0.50	0.26	0.54	0.44
43	200x75x18x2	1	510	0.31	0.73	0.34	0.80	0.57
44	200x75x18x2	1	510	0.52	0.44	0.26	0.53	0.41
45	200x75x18x2	1	510	0.65	0.08	0.21	0.36	0.30
46	150x65x12x2	1.5	482	0.43	0.66	0.30	0.66	0.35
47	150x65x12x2	1.5	482	0.56	0.58	0.25	0.47	0.26
48	200x75x18x2	1.5	510	0.31	0.96	0.34	0.81	0.62
49	200x75x18x2	1.5	510	0.42	0.76	0.30	0.67	0.48

50	200x75x18x2	1.5	510	0.52	0.53	0.26	0.54	0.42
51	200x75x18x2	1.5	510	0.31	0.74	0.34	0.80	0.59
52	200x75x18x2	1.5	510	0.52	0.71	0.26	0.53	0.40
53	200x75x18x2	1.5	510	0.65	0.15	0.21	0.36	0.30

5. Conclusions

This paper presents the results of an experimental study on shear behaviour and strength of cold-formed steel Lipped Channel Beams (LCB) having non-circular web openings. The test results were compared with the predictions from the current design rules given in the Australian cold-formed steel design standards AS/NZS 4600, Shan, et. al., and Keerthan and Mahendran design equations to verify their applicability to LCBs with non-circular web openings. The results show that these existing design rules are either conservative or unconservative or unsafe. Therefore new design equations are deemed necessary to predict the shear capacity reduction due to non-circular web openings in LCB section. A data base developed through a numerical investigation with detailed parametric study can be used to develop new design rule.

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