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SHEAR CAPACITIES OF RIVET FASTENED RECTANGULAR HOLLOW FLANGE CHANNEL BEAMS

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ABSTRACT

The intermittently rivet fastened Rectangular Hollow Flange Channel Beam (RHFCB) is a new cold-formed hollow section proposed as an alternative to welded hollow flange beams. It is a monosymmetric channel section made by intermittently rivet fastening two torsionally rigid rectangular hollow flanges to a web plate. This method will allow the development of optimum sections by choosing appropriate combinations of web and flange plate widths and thicknesses. RHFCBs can be commonly used as flexural members in buildings. Many experimental and numerical studies have been carried out in the past to investigate the shear behaviour of lipped channel beams. However, no research has been undertaken on the shear behaviour of rivet fastened RHFCBs. Therefore a detailed experimental study involving 19 shear tests was undertaken to investigate the shear behaviour and capacities of rivet fastened RHFCBs. Simply supported test specimens of RHFCB with aspect ratios of 1.0 and 1.5 were loaded at mid-span until failure. Comparison of experimental results with corresponding predictions from the current Australian cold-formed steel design rules showed that the current design rules are very conservative for the shear design of rivet fastened RHFCBs. Significant improvements to web shear buckling occurred due to the presence of rectangular hollow flanges while considerable post-buckling strength was also observed. Appropriate improvements have been proposed for the design rules of shear strength of rivet fastened RHFCBs within the Direct Strength Method format. This paper presents the details of this study and the results.

KEYWORDS

Rivet fastened hollow flange channel beams, cold-formed steel beams, shear capacity, direct strength method and experiments.

INTRODUCTION

Over the past couple of decades cold-formed high strength steel members are increasingly used as primary load bearing components in residential, commercial and industrial buildings. They are used in applications such as building frames, roof trusses, purlins and girts, floor framing and many other load bearing components. The increasing use of cold-formed steel sections has enhanced interest in the design and efficiency of cold-formed steel members.

In 2005, OneSteel Australian Tube Mills (OATM) introduced the “LiteSteel beam” (LSB), a torsionally rigid hollow flange channel section developed primarily for use as flexural members in residential and light commercial/industrial applications (see Figure 1). LSB is manufactured from a single strip of high strength steel using a combined cold-forming and dual electric resistance welding process. The hollow flange sections such as LSBs combine the stability of hot-rolled sections with the high strength to weight ratio of cold-formed sections, and are very efficient as structural beams since they have the hollow flanges away from the centre. In the past, the LSB has been highly researched due to its ability to provide capacities that are more typically associated with hot-rolled, than cold-formed steel (Keerthan and Mahendran, 2010, 2011; Anapayan and Mahendran, 2012). However, the OATM discontinued LSB production in 2012.

Figure 1. LiteSteel Beam

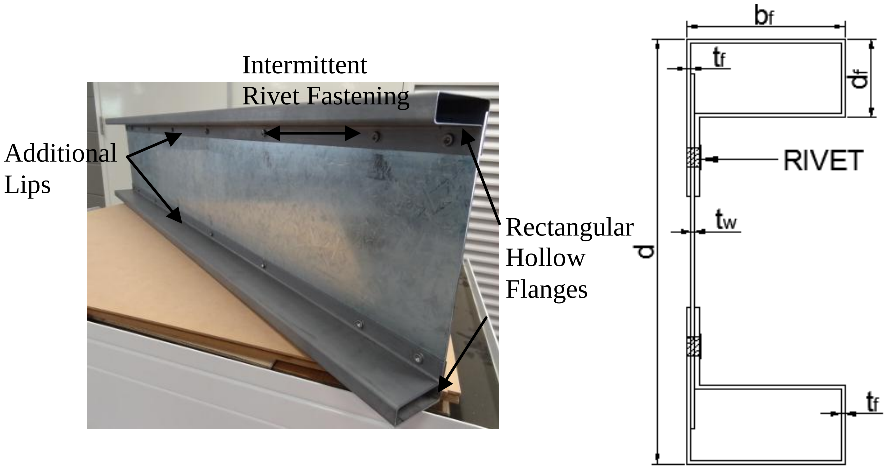


Figure 2. Rivet fastened rectangular hollow flange channel beam

The rivet fastened rectangular hollow flange channel beam (RHFCB) shown in Figure 2 is a new type of cold-formed hollow flange channel beam, proposed as an alternative to the welded hollow flange beams (LSBs). Self-Pierced Riveting (SPR) was proposed instead of self-drilling screws due to the faster manufacturing process in a workshop environment (riveting cycle ranges from 1 to 4 seconds). The proposed simpler and flexible manufacturing process allows the development of mono-symmetric RHFCB while the independent method of joining the web and flange elements of these sections allows the designers to develop optimum sections by choosing the appropriate combinations of web and flange plate thicknesses. For example, the use of thicker web elements will considerably increase the lateral distortional buckling capacity of RHFCB flexural members. Rivet fastened RHFCB also has additional lips, possibly contributing to additional strength. However, only limited research has been undertaken on the structural performance of RHFCBs.

In the conventional shear design method of lipped channel beams (LCBs), the web shear buckling behavior is considered in isolation without considering the effect of flange rigidity. LaBoube and Yu (1978) obtained the ultimate strengths of LCBs by assuming that the web-flange juncture of LCB is simply supported. However, Keerthan and Mahendran (2013) found that the web-flange juncture in LSBs and LCBs has some fixity. In steel building systems, rivet fastened RHFCBs can be commonly used as flexural members, for example, floor joists and bearers. For rivet fastened RHFCB to be used as flexural members, their flexural and shear capacities must be known. In this research the shear behaviour and strength of rivet fastened RHFCB was investigated using experimental studies. The results were then used to develop suitable design equations to determine their ultimate shear capacities.

SHEAR TESTS

In order to fully investigate the shear behaviour and strength of rivet fastened RHFCBs suitable parameters such as the aspect ratio (Shear span (a)/clear height of web (d_1)) and the clear height of web to thickness of web ratios (d_1/t_w) must be selected. Nineteen RHFCB test specimens with overall heights of 150, 200 and 250 mm were fabricated by rivet fastening two rectangular hollow flanges of 51 mm (width) x 15 mm (height) to a web plate at 100 mm spacing. Different flange and web thicknesses were used as seen in Table 1. Such selections gave specimens with varying d_1/t_w ratios. In order to simulate a primarily shear condition, relatively short test beams of span based on two aspect ratios of 1.0 and 1.5 were selected.

All the rivet fastened RHFCB specimens were tested using an Instron testing machine. The shear test set-up used in this study is shown in Figure 3. Two fastened RHFCB sections were bolted back to back using three T-shaped stiffeners and web side plates located at the end supports and the loading point in order to eliminate any torsional loading of test beams and possible web crippling of flanges and flange bearing failures. A 30 mm gap was included between the two fastened RHFCB sections (see Figure 3) to allow the test beams to behave independently while remaining together to resist torsional effects. Flanges were restrained by straps to eliminate any flange distortion due to distortional buckling or unbalanced shear flow. The measuring system was set-up to record the applied load and associated test beam deflections. Two laser displacement transducers were located on the test beam under the loading point and web panel to measure the vertical and lateral deflections, respectively. The cross-head of the testing machine was moved at a constant rate of 0.7 mm/minute until the test beam failed. Table 1 shows the details of test specimens used in this experimental study and the shear capacity results from tests. In this table, RHFCB specimens are specified by their overall depth d x flange width b x flange thickness t_f x web thickness t_w.

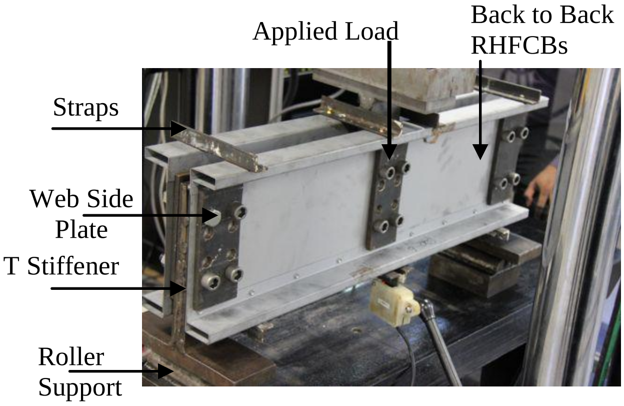


Figure 3. Test set-up

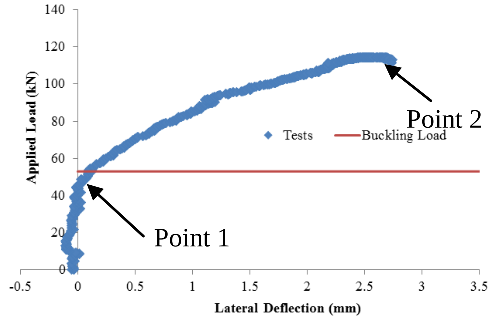
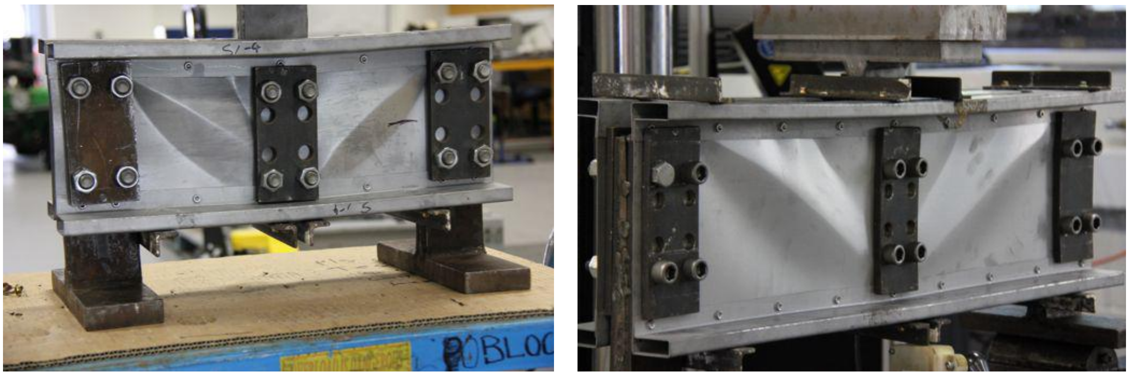


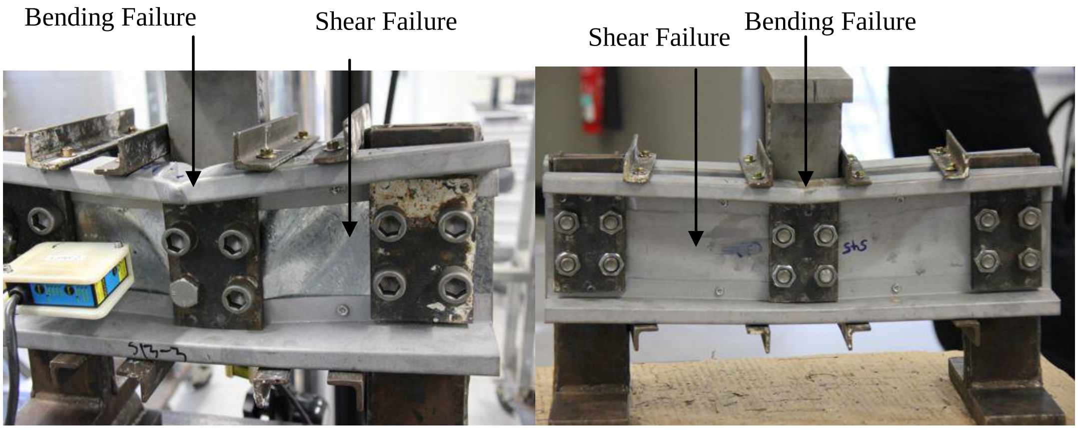
Figure 4. Plot of applied load versus lateral deflection (250x51x 1.15x1.15 RHFCB, Aspect ratio = 1.0)

Figure 4 shows the load-deflection curve for the shear test of 250x51x1.15x1.15 RHFCB (Aspect ratio = 1.0). At Point 1, the web began to deflect out of plane and the beam reached the ultimate shear capacity of 28.5 kN (applied load of 114 kN/4) at Point 2. This confirms that slender rivet fastened RHFCBs have significant post-buckling capacity. Figures 5 (a) and (b) show the typical shear failure modes of 200x1.15x0.95 RHFCB with an aspect ratio (AR) of 1.0 and 250x51x1.15x0.95 RHFCB with an aspect ratio of 1.5, respectively. Test Specimens 4, 5, 12 and 18 failed by combined bending and shear actions. Figures 6 (a) and (b) show the combined bending and shear failure modes of 150x51x1.15x1.50 RHFCB with an aspect ratio of 1.0 and 150x51x1.15x1.15 RHFCB with an aspect ratio of 1.5, respectively. These results were not considered further in this paper.



(a) 200x51x1.15x0.95 RHFCB (Test 8, AR of 1.0) (b) 250x51x1.15x0.95 RHFCB (Test 19, AR of 1.5)

Figure 5. Shear failure modes of rivet fastened RHFCBs



(a) 150x1.15x1.50 RHFCB (Test 4, ASP of 1.0) (b) 150x1.15x1.15 RHFCB (Test 12, ASP of 1.5)

Figure 6. Combined bending and shear failure modes of rivet fastened RHFCBs

Table 1. Details of rivet fastened RHFCB specimens and their shear capacities

Test No.	RHFCB Section (d xbx t_f x t_w)	d_1 (mm)	t_w (mm)	f_y (MPa)	a/d_1	Shear capacity (kN)		
						Test	AS/NZS 4600	Eqs. (1) and (2)
1	150x51x1.15x0.70	117	0.70	-	1.0	16.50	-	-
2	150x51x0.95x0.95	117	0.91	290	1.0	17.00	10.89	14.66
3	150x51x1.15x1.15	117	1.10	310	1.0	23.75	18.64	20.48
4	150x51x1.15x1.50	117	1.55	545	1.0	41.25	Combined	Combined
5	150x51x1.15x1.90	117	1.91	480	1.0	35.00	Combined	Combined
6	200x51x0.95x0.95	166	0.91	290	1.0	20.08	7.67	17.37
7	200x51x1.15x1.15	166	1.10	310	1.0	27.00	13.55	24.35
8	200x51x1.15x0.95	166	0.91	290	1.0	21.75	7.67	17.37
9	250x51x1.15x1.15	220	1.10	310	1.0	28.50	10.23	27.85
10	250x51x1.15x0.95	220	0.91	290	1.0	23.25	5.79	19.83
11	150x51x0.95x0.95	117	0.91	290	1.5	14.25	8.30	14.06
12	150x51x1.15x1.15	117	1.10	310	1.5	18.25	Combined	Combined
13	150x51x1.15x0.95	117	0.91	290	1.5	15.00	8.30	14.06
14	150x51x1.15x0.70	117	0.71	-	1.5	13.75	-	-
15	200x51x0.95x0.95	166	0.91	290	1.5	16.25	5.85	16.63
16	200x51x1.15x0.70	166	0.71	-	1.5	15.50	-	-
17	200x51x1.15x0.95	166	0.91	290	1.5	18.80	5.85	16.63
18	250x51x1.15x1.15	220	1.10	310	1.5	24.00	Combined	Combined
19	250x51x1.15x0.95	220	0.91	290	1.5	19.38	4.41	18.96

Note: Yield stress f_y for 0.70 mm steel sheet is not yet available. d = overall height, b = flange width
t_f = flange thickness, t_w = web thickness, a = shear span, d_1 = clear height of web, f_y = web yield stress.

DESIGN EQUATIONS FOR THE SHEAR CAPACITY OF RIVET FASTENED RHFCB

Table 1 compares the shear capacities from tests with those predicted by the current shear design rules in AS/NZS 4600. This comparison showed that the current shear design rules are very conservative. This is because they do not include the observed post-buckling strength and the effects of increased fixity at the web-flange juncture of RHFCBs. Rivet-fastened RHFCB also has additional lips, possibly contributing to additional shear capacity. Therefore new design equations are proposed in this section.

Based on the shear capacity results in Table 1 and test observations, new design equations are proposed for the shear capacity of rivet fastened RHFCBs in a similar manner to those of the section moment capacity of beams subject to local buckling (Equations 1 and 2). In these equations the Direct Strength Method based nominal shear capacity (V_v) is proposed using V_{cr} (elastic buckling capacity in shear) and V_y (shear yield capacity) with a power coefficient of 0.3. As for hot-rolled I-sections, only two regions based on shear yielding, and elastic and inelastic shear buckling were considered.

$$V_v = V_y \quad \lambda \leq 0.72 \tag{1}$$

$$V_v = \left[1 - 0.15\left(\frac{V_{cr}}{V_y}\right)^{0.3}\right]\left(\frac{V_{cr}}{V_y}\right)^{0.3} V_y \quad \lambda > 0.77 \tag{2}$$

Equations (1) and (2) include the experimentally observed post-buckling strength in rivet fastened RHFCBs and the additional fixity at the web-flange juncture. They also include the effects of additional fixity at the web-flange juncture of RHFCBs. This effect can be simulated by the inclusion of an increased shear buckling coefficient (k_{RHFCB}). Finite element analyses were undertaken to obtain the shear buckling coefficient of rivet fasted RHFCBs. For this purpose a 100 mm rivet spacing was considered as used in the shear tests. Equation 5 presents the proposed equation for k_{RHFCB}. Further finite element analyses will be carried out to investigate the effect of rivet spacing on the shear buckling coefficient of RHFCBs.

$$V_y = 0.6 f_y d_1 t_w \tag{3}$$

$$V_{cr} = \frac{k_{LCB}\pi^2 E d_1 t_w}{12(1-\upsilon^2)\left(\frac{d_1}{t_w}\right)^2} \tag{4}$$

$$k_{RHFCB} = k_{ss} + 0.80(k_{sf} - k_{ss}) \tag{5}$$

$$k_{ss} = 5.34 + \frac{4}{(a/d_1)^2} \quad \text{for } \frac{a}{d_1} \geq 1 \tag{6}$$

$$k_{ss} = 4 + \frac{5.34}{(a/d_1)^2} \quad \text{for } \frac{a}{d_1} < 1 \tag{7}$$

$$k_{sf} = \frac{5.34}{(a/d_1)^2} + \frac{2.31}{(a/d_1)} - 3.44 + 8.39(a/d_1) \quad \text{for } \frac{a}{d_1} < 1 \tag{8}$$

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

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 = clear height of web, f_y = web yield stress.

The shear capacities predicted by the proposed design equations (Eqs. (1) and (2)) are compared with test shear capacities in Table 1. This shows a good agreement, indicating the accuracy of the developed shear capacity equations. Experimental ultimate shear capacity results were also processed within the DSM format and are shown in Figure 7. Here slenderness (λ) was calculated using Equation 10. Figure 7 shows the non-dimensional shear capacity curve for rivet fastened RHFCBs and compares with experimental results. Equations (1) and (2) appear to predict the shear capacities well as they include the available post-buckling strength and additional fixity at the web-flange juncture.

$$\lambda = \sqrt{\left(\frac{V_y}{V_{cr}}\right)} = 0.815\left(\frac{d_1}{t_w}\right)\sqrt{\left(\frac{f_y}{E k_{RHFCB}}\right)} \tag{10}$$

Due to lack of experimental evidence on the shear capacity of plates without stiffeners, AS/NZS 4600 (SA, 2005) design equations do not include the post-buckling strength in shear, and the design shear stress in webs is therefore limited by the elastic buckling capacity. It was found that AS/NZS 4600 design equation are very conservative for the shear capacity of rivet fastened RHFCBs. Test results in Figure 4 show that there is considerable amount of post-buckling strength for rivet fastened RHFCBs subjected to shear. Hence post-buckling shear strength can be taken into account in the design of rivet fastened RHFCBs with large clear web height to thickness ratios (d_1/t_w).

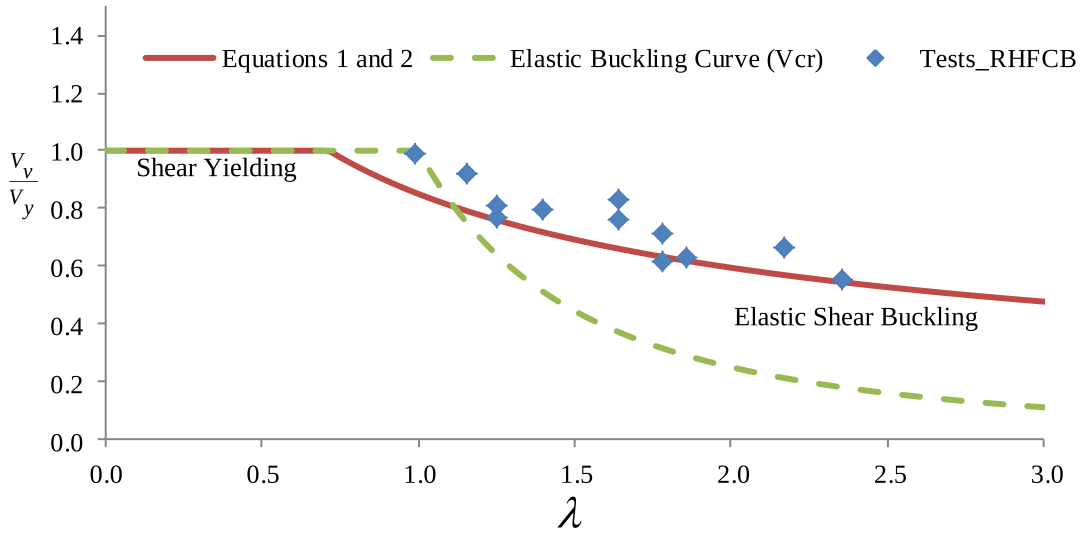


Figure 7. Comparison of experimental shear capacities of rivet fastened RHFCBs with DSM based design equations

CONCLUSIONS

This paper has presented the details of an experimental study of 19 shear tests into the shear behaviour and strength of rivet fastened RHFCBs. Comparison of ultimate shear capacities from tests showed that AS/NZS 4600 (SA, 2005) design equations are very conservative for the shear design of rivet fastened RHFCBs. It was found that there is considerable amount of post-buckling strength for rivet fastened RHFCBs subject to shear. Suitable shear design rules were therefore developed under the direct strength method format. Experimental studies were limited to 100 mm rivet spacing and hence further research is currently underway to investigate the effect rivet spacing on shear capacities.

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