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EXPERIMENTAL INVESTIGATION OF HIGH STRENGTH COLD-FORMED SUPACEE® SECTIONS IN SHEAR

Cao Hung Pham * and Gregory J. Hancock*

* School of Civil Engineering, the University of Sydney, Australia
e-mails: caohung.pham@sydney.edu.au, gregory.hancock@sydney.edu.au

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***Abstract**. The paper will describe tests of SupaCee® Sections in Shear. These high strength (450 MPa) C-profile steel sections contain additional return lips and web stiffeners which enhance the bending and shear capacity of the sections.They are used widely in Australia as purlins in roof and wall systems. Design methods for these sections are normally specified in the Australian/New Zealand Standard for Cold-Formed Steel Structures [1] or the North American Specification for Cold-Formed Steel Structural Members [2]. Both the Effective Width Method (EWM) and the Direct Strength Method (DSM) can be used for the design of C-sections although rules for the DSM in shear are not provided in either standard/specification. The paper summarises shear tests on SupaCee® sections performed at the University of Sydney and compares the results with the EWM rules. The paper also demonstrates tension field action in the sections tested leading to post-buckling strength which is included in newly proposed DSM rules for Shear.*

1 INTRODUCTION

High strength cold-formed steel sections are commonly used in a wide range of applications which include lipped C and Z-purlin sections in roof and wall systems. Sections are normally made from high strength steel up to 550 MPa yield stress. With the resulting reduction of thicknesses of high strength steel, the failure modes of such sections are mainly due to instabilities such as local, distortional and flexural-torsional buckling modes or the interaction between them. SupaCee® sections [3] are another type of purlin section which can increase buckling capacity and ultimate strength of thin-walled channel sections by introducing multiple longitudinal web stiffeners and return lips. For compression of columns and bending for beams, the actions causing buckling such as flexural, flexural-torsional, distortional or local buckling, are well understood.

For shear, the traditional approach has been to investigate shear plate buckling in the web alone and to ignore the behaviour of the whole section including the flanges. There does not appear to be any consistent theoretical or experimental investigation of the whole section buckling of thin-walled sections under shear. Recently, Pham and Hancock provided solutions to the shear buckling of complete channel sections [4] and plain C- lipped sections with an intermediate web stiffener [5] loaded in pure shear parallel with the web by using a spline finite strip analysis [6].

As sections become more complex with additional multiple longitudinal web stiffeners and return lips as designed on SupaCee® sections, the computation of the effective widths becomes more complex. For the EWM, the calculation of effective widths of the numerous sub-elements leads to severe complications with decreased accuracy. In some special cases, no design approach is even available for such a section using the EWM. The DSM appears to be more beneficial and simpler by using the elastic buckling stresses of the whole complex channel sections such as SupaCee® section.

In order to further understand the DSM in shear, an experimental program has been recently performed at the University of Sydney for SupaCee® sections. The tests, which are described as predominantly shear test series (*V*-series) in this paper, consist of two different commercially available depths and three different thicknesses of SupaCee®. The basic design of the test rig was developed by LaBoube and Yu [7]. The test results are plotted and compared with the existing EWM rules for shear. Experimental results are also utilized to recommend new design rules for the DSM of design in shear. New DSM shear curves excluding and including tension field action are proposed.

2 EXPERIMENTAL INVESTIGATION

2.1 Test series

The experimental program comprised a total of twelve tests conducted in the J. W. Roderick Laboratory for Materials and Structures at the University of Sydney. All tests were performed in the 2000 kN capacity DARTEC testing machine, using a servo-controlled hydraulic ram. Two different commercially available SupaCee® sections of 150 mm and 200 mm depths were chosen with three different thicknesses of 1.2 mm, 1.5 mm and 2.4 mm. Although the tests described in LaBoube and Yu [7] contained straps at the loading points as described later, tests both with and without straps are included in the test program described in this paper.

2.2 Specimen Nomenclature and Dimensions

The test specimens were labeled in order to express the series, test number, channel section, depth and thickness. Typical test label "V1-SC15012" is defined as follows:

- V indicates the predominantly shear test series.
- "1" indicates the test "with" straps and "w" expresses the test "without" straps adjacent to loading points.
- "SC150" indicates a SupaCee® section (SC-SupaCee Section) with the web width of 150 mm (alternatively "SC200").
- "12" is the thickness times 10 in mm (alternatively "15" and "24").

The average measured dimensions for the *V*-series are shown in Fig. 1 and in Table 1 respectively. The Young's modulus of elasticity (E) was also calculated from stress-strain curves. The calculated mean value of the Young's modulus of elasticity is 206.6 GPa.

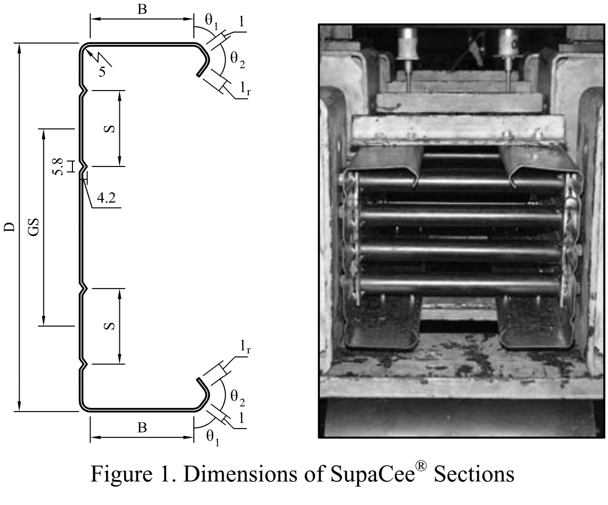


Figure 1. Dimensions of SupaCee® Sections

Table 1. *V*-Series Specimen Dimension and Properties

Test	**Section**	**t (mm)**	**D (mm)**	**B (mm)**	**l (mm)**	**l_r (mm)**	**GS (mm)**	**S (mm)**	**θ_1 (^{0})**	**θ_2 (^{0})**	**f_y (MPa)**
V1	SC15012	1.2	153.56	41.87	5.09	6.22	63.85	41.37	55.5	84.5	589.71
Vw	SC15012	1.2	153.89	42.05	5.83	6.27	63.44	40.79	53.5	84.5	589.71
V1	SC15015	1.5	152.64	42.49	4.78	5.83	63.48	41.28	55.5	81.5	533.88
Vw	SC15015	1.5	153.65	42.48	4.74	5.99	64.68	42.33	54.0	80.5	533.88
V1	SC15024	2.4	153.66	44.49	4.81	4.99	60.84	42.19	51.5	81.5	513.68
Vw	SC15024	2.4	153.63	43.77	5.31	5.56	60.93	42.57	51.5	82.0	513.68
V1	SC20012	1.2	205.45	54.61	6.96	6.15	109.43	42.54	55.5	84.0	593.30
Vw	SC20012	1.2	205.69	54.58	7.08	6.54	109.53	42.06	54.5	86.0	593.30
V1	SC20015	1.5	203.77	54.19	7.28	6.88	109.46	42.41	54.5	87.5	532.03
Vw	SC20015	1.5	203.88	54.34	7.36	6.91	109.24	42.13	54.5	85.5	532.03
V1	SC20024	2.4	204.16	54.67	6.57	8.35	111.48	41.36	55.0	85.5	504.99
Vw	SC20024	2.4	203.25	54.34	6.59	8.64	111.28	41.49	54.0	84.0	504.99

Internal Radius r = 5 mm

2.3 Coupon Tests

Eighteen coupons were taken longitudinally from the centre of the web of each channel section member. The tensile coupon dimensions conformed to the Australian Standard AS 1391 (Standards Australia 1991) for the tensile testing of metals using 12.5 wide coupons with gauge length 50 mm. Full details of the coupon tests are given in Pham and Hancock [8].

2.5 Test Rig Design

Photos of the test set-up are shown in Fig. 2 for the *V*-series with the ratio of span to depth of 1:1. The channel section members were tested in pairs with flanges facing inwards and with a gap between them to ensure inside assembly was possible. At the supports, the test two beam specimens were bolted through the webs by vertical rows of M12 high tensile bolts. These rows of bolts were connected to two channel sections 250x90x6CC with stiffeners. Steel plates of 20 mm thickness were used as load transfer plates which were also bolted through the flanges of the channel sections 250x90x6CC with stiffeners. These load bearing plates rested on the half rounds of the DARTEC supports to simulate a set of simple supports. At each bolt, a nut was located between the SupaCee® and CC sections so that the SupaCee® did not attach directly on the CC thus minimizing restraint to the web.

At the loading point at mid-span, the DARTEC loading ram has a spherical head to ensure that the load is applied uniformly on the bearing plate, and moved at a constant stroke rate of 2 mm/min downwards during testing. The load was transferred to two channel sections 250x90x6CC with stiffeners which were connected to the test beam specimens by two vertical rows of M12 high tensile bolts. The distance between these two vertical rows of bolts is 50 mm. As for the support points, a nut was located on the bolt between the SupaCee® and CC sections. Further, the beam specimens were also connected by four 25x25x5EA equal angle steel straps on each top and bottom flanges adjacent to the loading point and reactions. Self-tapping screws were used to attach these straps to the test specimens. The object of these straps was to prevent section distortion at the loading points. The channel sections 250x90x6CC with stiffeners were introduced to prevent a bearing failure at the loading point and supports which could be caused by using conventional bearing plates. For the 150 mm section, four bolts were used at each support and eight at the load point, and for the 200 mm deep section, five and ten bolts were used respectively.

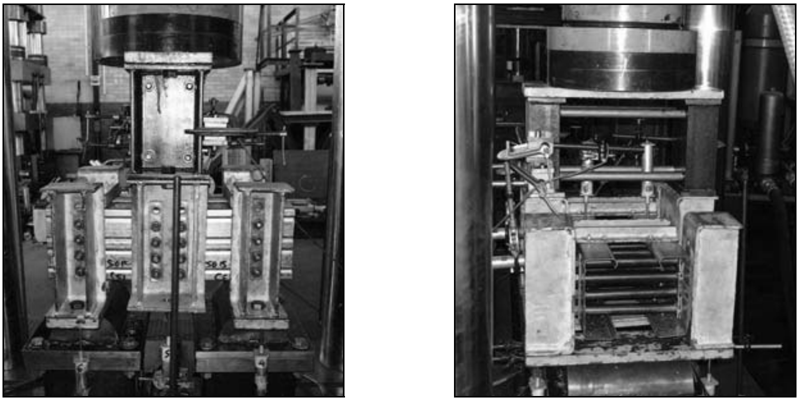
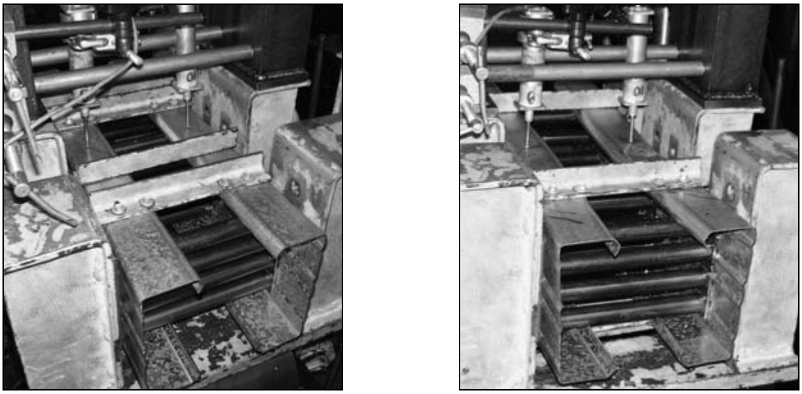


Figure 2. V - Series Configuration (Dimensions for 150 mm Depth SupaCee® Section)

2.5 Test With and Without Straps Configurations

For the predominantly shear *(V)* test series, six of the twelve tests had four 25x25x5EA straps connected by self-tapping screws on each of the top and bottom flanges adjacent to the loading point and reactions as shown in Fig. 3(a). Six remaining tests were tested without the two 25x25x5EA straps adjacent to the loading points on the top flange as shown in Fig. 3(b). The purpose of these two straps is to prevent distortion of the top flanges under compression caused by bending moment. The distortion may be a consequence of unbalanced shear flow or distortional buckling.



(a) With Straps (b) Without Straps

Figure 3. V - Series Configuration with and without Straps adjacent Loading Point

3 EXPERIMENTAL RESULTS AND DIRECT STRENGTH METHOD (DSM) OF DESIGN FOR SHEAR PROPOSALS

3.1 Direct Strength Method based on AISI in DSM Format in Shear without Tension Field Action

The equations in Section 3.2.1 of the North American Specification [2] which are expressed in terms of a nominal shear stress F_v have been changed to DSM format by replacing stresses by loads as follows:

$$\text{For } \lambda_v \le 0.815 \; : \; V_v = V_y \tag{1}$$

$$\text{For } 0.815 < \lambda_v \le 1.231 \; : \; V_v = 0.815\sqrt{V_{cr}V_y} \tag{2}$$

$$\text{For } \lambda_v > 1.231 \; : \; V_v = V_{cr} \tag{3}$$

where $\lambda_v = \sqrt{V_y / V_{cr}}$, V_y = yield load of web = $0.6 A_w f_y$,

V_{cr} = elastic shear buckling force of web = $\dfrac{k_v \pi^2 E A_w}{12\left(1-\nu^2\right)\left(\dfrac{d_1}{t_w}\right)^2}$

d_1 = depth of the flat portion of the web measured along the plane of the web,

t_w = thickness of web, A_w = area of web = $d_1 \times t_w$,

k_v = shear buckling coefficient for whole SupaCee® Sections.

To account for the shear buckling of the whole section rather than simply the web, the shear buckling coefficient k_v can be back-calculated from the shear buckling load V_{cr} of the whole section as described in Pham and Hancock [4] by using the Spline Finite Strip Method.

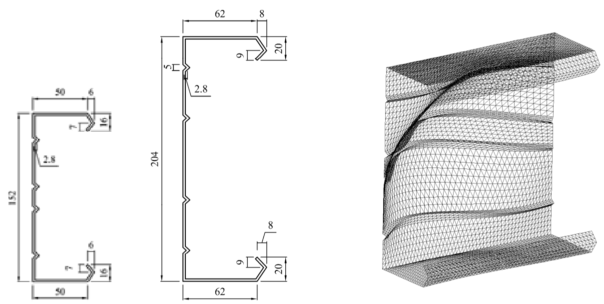


Figure 4. V – Dimensions of 150 mm and 200 mm Depth SupaCee® Sections and Buckling Mode Shape of 150 mm Depth SupaCee® Section

Both 150 mm and 200 mm depth SupaCee® channel sections with the thickness of 2 mm as shown in Fig. 4 are investigated. A shear distribution similar to that which occurs in practice allowing for section shear flow is used for modeling sections in pure shear resulting from a shear force parallel with the web. All edges of the end cross-section are simply supported. The results of the buckling analyses of SupaCee® sections are shown in Table 2 by using the Spline Finite Strip Method. The presence of multiple longitudinal web stiffeners and return lips contribute significantly to the shear elastic buckling capacity of the SupaCee® channel sections. The corresponding buckling mode shape of the 150 mm depth SupaCee® channel section is also shown in Fig. 4.

Table 2. Shear Buckling Coefficients of SupaCee® Sections

Sections	**Span : Panel Depth = 1:1**	
	k_v **150 mm Depth Sections**	k_v **200 mm Depth Sections**
SupaCee® Channels	12.204	11.709

3.1 Direct Strength Method based on AISI in DSM Format in Shear with Tension Field Action

All results of tests for the predominantly shear *(V)* test series of SupaCee® sections are summarized in Table 3. Fig. 5 shows all test data and nominal shear capacity curves which include the Tension Field Action (TFA) curve [9], the existing Effective Width Method (EWM) shear curve without TFA (based on AISI), elastic buckling curve (V_{cr}) (Eqs. 1-3) and new DSM proposed curve for shear (V_v) including TFA.

The DSM nominal shear capacity (V_v) is proposed based on the local buckling (M_{sl}) equation where M_{sl}, M_{ol} and M_y are replaced by V_v, V_{cr} and V_y respectively as follows:

$$V_v = \left[1 - 0.15\left(\frac{V_{cr}}{V_y}\right)^{0.4}\right]\left(\frac{V_{cr}}{V_y}\right)^{0.4} V_y \qquad (4)$$

where V_y is yield load of web $V_y = 0.6 A_w f_y$,

V_{cr} is elastic shear buckling force of web $V_{cr} = \dfrac{k_v \pi^2 E A_w}{12\left(1-\nu^2\right)\left(\dfrac{d_1}{t_w}\right)^2}$,

k_v is shear buckling coefficient for the whole channel sections (Table 2).

Fig. 5 shows that all SupaCee® *V*-series tests lie close to the proposed DSM nominal shear capacity with Tension Field Action (see Eq. 4). The DSM proposed shear equation with tension field action therefore gives a good mean fit to the *V*-series tests. They lie well above the AISI in DSM format equations (see Eqs. 1–3) presumably because significant tension field action was developed.

Table 3. *V*-Series Test Results of SupaCee® Sections

Test	**Section**	V_T **(kN)**	V_y**(AISI) (kN)**	V_{cr} **(kN)**	$\lambda_v = \sqrt{\frac{V_y}{V_{cr}}}$	$\frac{V_T}{V_y}$
V1	SC15012	42.13	59.93	27.00	1.490	0.703
Vw	SC15012	39.33	60.08	26.94	1.493	0.655
V1	SC15015	55.58	67.10	53.32	1.122	0.828
Vw	SC15015	51.87	67.58	52.94	1.130	0.768
V1	SC15024	97.99	102.71	219.62	0.684	0.954
Vw	SC15024	92.92	102.69	219.66	0.684	0.905
V1	SC20012	46.48	82.47	18.95	2.086	0.564
Vw	SC20012	45.55	82.57	18.92	2.089	0.552
V1	SC20015	62.07	91.35	37.44	1.562	0.679
Vw	SC20015	61.65	91.40	37.42	1.563	0.675
V1	SC20024	124.21	137.70	154.52	0.944	0.902
Vw	SC20024	117.31	137.04	155.26	0.939	0.856

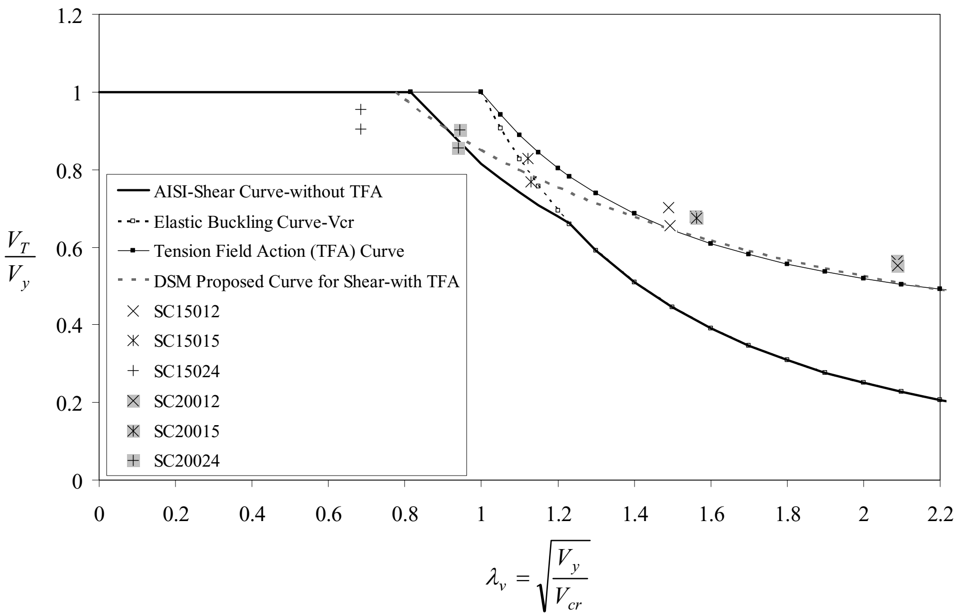
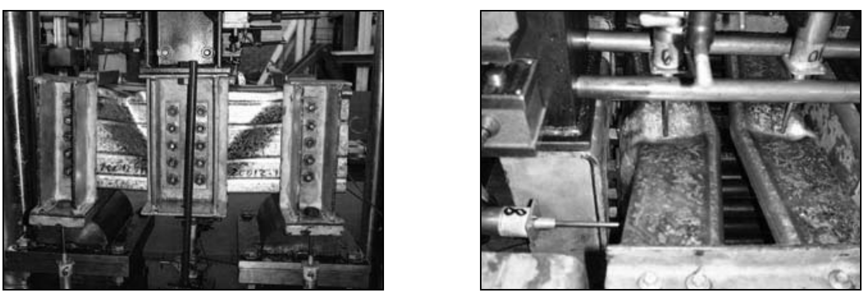


Figure 5. DSM Proposed Nominal Shear Curve and Shear Test Data

The development of tension field action may be a result of the bolts connecting the webs of the channels spanning the full depth of the section for both 150 mm and 200 mm tests. The two vertical rows of bolts have increased the restraints to the web panel and act as web stiffeners. These increased restraints have improved the post-buckling strengths of the web for the *V*-series. It is interesting to note that the slender sections (e.g. SC15012, SC20012 and SC20015) are more conservative than stockier sections. This fact shows that the more slender sections have more tension field action contribution to the ultimate strength of the sections in shear. In tests where full tension field action is not developed**,** the results may lie below Eq. 4. Investigation of other test results such as those from LaBoube and Yu [7] will be required to confirm these design curves for all situations. Figs 6(a) and 6(b) show the corresponding buckling mode shapes of the SupaCee® section members with and without straps respectively for the *V*-series.



(a) With Straps (b) Without Straps

Figure 6. Buckling Mode Shape of SupaCee® Section Members
V-Series – With and Without Straps

3 CONCLUSION

An experimental program was carried out to determine the ultimate strength of high strength SupaCee® cold-formed channel sections subjected to predominantly shear. A total of twelve tests of two different depths and three different thicknesses have been performed at the University of Sydney. While six tests were conducted with straps at the loading points, the remaining tests were tested without straps. The shear capacity, V_v, is based on the DSM proposals with and without tension field action. The shear buckling load, V_{cr}, used in the DSM equations is based on the shear buckling coefficient of the full section and not just the web buckling in shear. The tests show that the DSM proposal curve for shear with tension field action gives a good mean fit to the *V*-series tests and more accurate prediction on post-bucking strength of SupaCee® sections in shear.

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