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Direct Strength Design of Cold-Formed C-Sections in Combined Bending and Shear

Cao Hung Pham[1] and Gregory J. Hancock[2]

Abstract

The paper describes a research program including tests on both plain C- and SupaCee® purlin sections in combined bending and shear, and bending only. The high strength SupaCee® 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. The tests were performed at the University of Sydney with and without straps on the flange and thus allowed distortional buckling in the latter case. Design methods for these sections are normally specified in the Australian/New Zealand Standard for Cold-Formed Steel Structures or the North American Specification for Cold-Formed Steel Structural Members. 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 combined bending and shear are not provided in either standard/specification. New DSM design rules for C-sections in shear both with and without tension field action are presented and discussed in a separate paper at this conference. This paper proposes DSM design rules for C-sections in combined bending and shear both with and without the effect of distortional buckling included. Both series of test results are compared with the proposed design rules.

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1. INTRODUCTION

High strength cold-formed steel sections are commonly used in a wide range of applications which include lipped C and Z-purlin plain sections and SupaCee® 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 (Lysaght, 2003) 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.

The development of the DSM for columns and beams, including the reliability of the method is well researched. In the review of the DSM of cold-formed steel member design, Schafer (2006) noted that no formal provisions for shear, and combined bending and shear currently exist for the DSM. However, as recommended in the AISI Direct Strength Design Guide (AISI 2006), the existing provisions in the North American Design Specification and AS/NZS 4600:2005 (Standards Australia 2005) could be suitably modified into the DSM format.

To investigate this proposition, vacuum rig tests on continuous lapped cold-formed purlins at the University of Sydney over a 10 year period, have been used to calibrate DSM design proposals for shear and combined bending and shear (Pham and Hancock, 2009a). The conclusions from this calibration are that the existing bending and shear equations in AS/NZS 4600:2005 in DSM format will provide reliable designs irrespective of whether the limiting design moment in the interaction equation is based on the lesser of the local buckling and distortional buckling moments (called Proposal 1) or the local buckling moment alone (called Proposal 2). To further investigate these proposals, additional tests on C-sections in combined bending and shear, and bending alone have been performed at the University of Sydney (Pham and Hancock, 2009b, 2009c).

The main purpose of this paper is to provide test data on simply supported channel sections, and to further refine the proposals based on tests which concentrated on combined bending and shear. The paper also summarises proposals for extension of the Direct Strength Method to combined bending and shear. The proposals are made both with and without Tension Field Action (TFA) and are compared with the test results on the lipped C-sections.

2. EXPERIMENTS ON PLAIN C- LIPPED AND SUPACEE® CHANNEL SECTIONS IN SHEAR, AND COMBINED BENDING AND SHEAR

2.1 Experimental Rig and Tests Specimens

Two testing programs on both high strength cold formed steel plain C- lipped sections and SupaCee® sections for the extension to the Direct Strength Method for shear, combined bending and shear, and bending only were performed. The first experimental program comprised a total of thirty six tests which included two test series 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 plain C- lipped channel sections of 150 mm and 200 mm depths as shown in Fig. 1 were chosen with three different thicknesses of 1.5 mm, 1.9 mm and 2.4 mm. The first series *(V)* is predominantly shear and is described in a separate paper at this conference. The second series *(MV)* is combined bending and shear. This series consisted of twenty four tests and used the test rig configuration as shown in Fig. 2. The third series is bending only *(M)* which used the common four point loading configuration as shown in Fig 3. A total of twelve tests of this series were conducted. Although the tests described in LaBoube and Yu (1978) contained straps at the loading points as described later, tests both with and without straps are included in the test program as shown in Fig. 4.

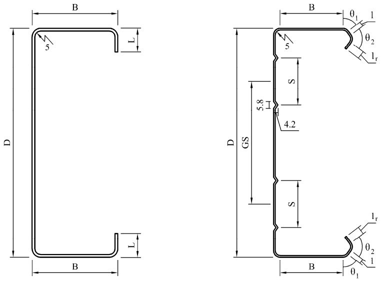


Figure 1. Dimensions of Plain and SupaCee® Channel Sections

The second testing program was also performed at the University of Sydney including a total of twenty four tests of commercially available SupaCee® sections as also shown in Fig. 1. Two different depths of 150 mm and 200 mm were chosen with three different thicknesses of 1.2 mm, 1.5 mm and 2.4 mm. Three test series, which were conducted identically to the first testing program, also consisted of predominantly shear *(V)* (as also described in separate paper at this conference), combined bending and shear *(MV)*, and bending only *(M)* tests. These test series each included twelve tests each and used the same test rig configurations with the first test program.

The average measured dimensions and properties for the *MV* and *M* series of both plain C- lipped and SupaCee$^{®}$ sections are given in Pham and Hancock (2009b, 2009c) respectively. The basic design of the test rig was developed by LaBoube and Yu (1978). A diagram of the test set-up is shown in Fig. 2 for *MV* series. The detailed test configuration of the bending only series is shown in Fig. 3. The four point bending arrangement provided a central region of uniform bending moment and zero shear force. At the two supports, the rig assembly is exactly the same as that of the predominantly shear test set-up. The difference is at the loading points which have a similar configuration to the support points. The channel section members were loaded symmetrically at two points via a centrally loaded spreader I beam with stiffeners. The distance between the two half rounds bolted to the I beam at the loading points was 1000 mm. These two half rounds bore upon two 20 mm thick load transfer plates. The half round ensured that the applied loads were vertical. The distance between the support and the adjacent loading point was 800 mm.

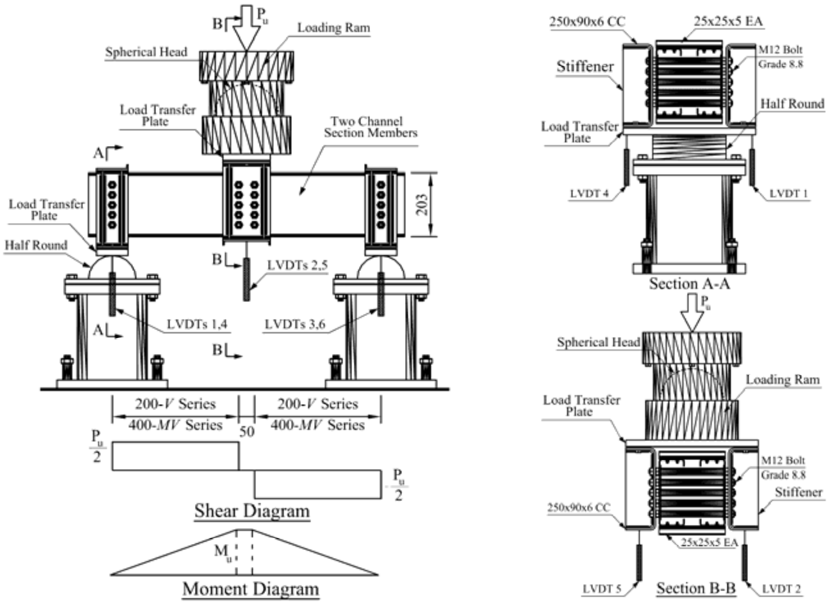


Figure 2. *MV* Test Series Configuration (Dimensions for 200 mm Deep Section)

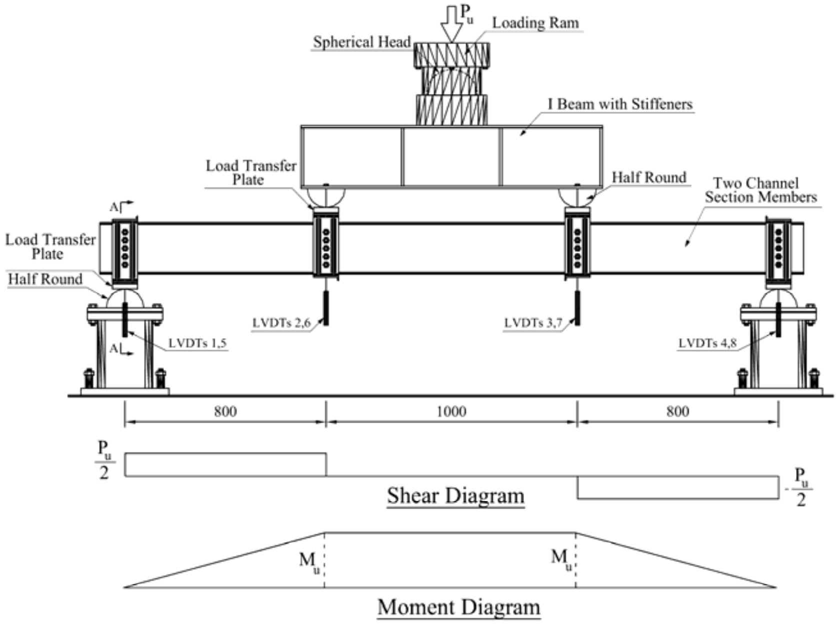
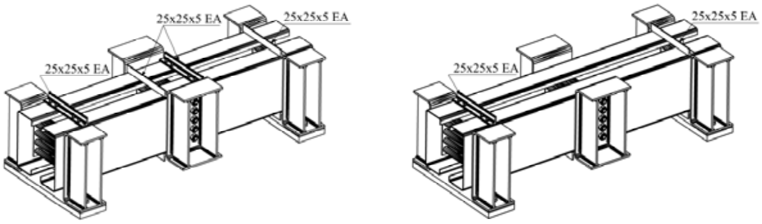


Figure 3. *M* Test Series Configuration (Dimensions for 200 mm Deep Section)

2.2 Test With and Without Straps Configurations

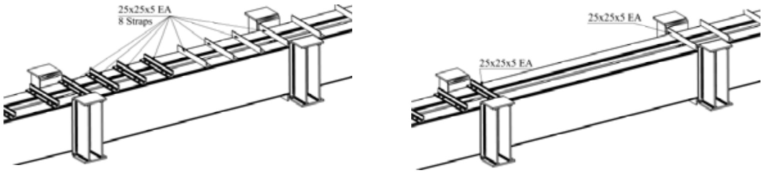
For the combined bending and shear *(MV)* test series, twenty four tests (18 of plain lipped C- sections and 6 of SupaCee® sections) of total thirty six tests had four 25x25x5EA straps connected by self-tapping screws on each of the top and bottom flanges adjacent to the loading point and reactions as shown in Fig. 4(a). Twelve remaining tests were tested without the two 25x25x5EA straps adjacent to the loading points on the top flange as shown in Fig. 4(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.

For the bending only *(M)* test series, twelve tests (6 of each plain lipped C- and SupaCee® sections) of total twenty four tests were tested with eight 25x25x5EA straps which were uniformly distributed in the pure bending moment region between the two loading points as shown in Fig. 5(a). The purpose of the straps is to force the channel members to buckle locally rather than by distortional buckling. The twelve remaining tests in this series were tested without the six middle 25x25x5EA straps as shown in Fig. 5(b). Only two straps adjacent to the loading points were attached to the channel members to prevent distortion at the loading points.



(a) With Straps (b) Without Straps

Figure 4. *MV* Test Series Configuration With and Without Straps



(a) With Straps (b) Without Straps

Figure 5. *MV* Test Series Configuration With and Without Straps

2.3 Plain Lipped C- Section Test Results

The full set of test results for the plain lipped C-Sections is given in the research report by Pham and Hancock (2009b). The tests results are compared with existing design methods in AS/NZS 4600:2005 and with the tension field action included using the rules of AS 4100:1998 (Standards Australia 1998). All slender section specimens in the *V* and *MV* Series were found to develop tension field action as the connection bolts at the loading and support points extended over the full depth of the section whether 150 mm (4 bolts) or 200 mm (5 bolts). The inclusion of straps attached to the flanges to prevent distortion at the loading and support points further enhanced the tension field action. They are compared with DSM design proposals in Section 3 following.

2.4 SupaCee® Section Test Results

The full set of test results for the SupaCee® sections is given in the research report by Pham and Hancock (2009c). The tests results are compared with existing design methods in AS/NZS 4600:2005 and with the tension field action included using the rules of AS 4100:1998 (Standards Australia 1998). As for the plain lipped C-Sections, all slender section specimens in the *V* and *MV* Series were found to develop tension field action. The inclusion of straps attached to the flanges to prevent distortion at the loading and support points further enhanced the tension field action.

3. DIRECT STRENGTH METHOD (DSM) OF DESIGN OF COLD-FORMED C- SECTIONS IN COMBINED BENDING AND SHEAR

3.1 DSM Design Rules for Flexure

The nominal section moment capacity at local buckling (M_{sl}) is determined from Section 7.2.2.3 of AS/NZS 4600:2005 [Appendix 1, Section 1.2.2.2 of NAS (AISI 2007)] as follows:

$$\text{For } \lambda_l \leq 0.776 \;:\; M_{sl} = M_y \tag{1}$$

$$\text{For } \lambda_l > 0.776 \;:\; M_{sl} = \left[1 - 0.15\left(\frac{M_{ol}}{M_y}\right)^{0.4}\right]\left(\frac{M_{ol}}{M_y}\right)^{0.4} M_y \tag{2}$$

where λ_l is non-dimensional slenderness used to determine M_{sl} ;

$\lambda_l = \sqrt{M_y / M_{ol}}$; $M_y = Z_f f_y$,

M_{ol} is elastic local buckling moment of the section; $M_{ol} = Z_f f_{ol}$,

Z_f is section modulus about a horizontal axis of the full section,

f_{ol} is elastic local buckling stress of the section in bending.

The nominal section moment capacity at distortional buckling (M_{sd}) is determined from Section 7.2.2.4 of AS/NZS 4600:2005 [Appendix 1, Section 1.2.2.3 of AISI (2007)] as follows:

$$\text{For } \lambda_d \le 0.673 \;:\; M_{sd} = M_y \tag{3}$$

$$\text{For } \lambda_d > 0.673 \;\mathbf{:}\; M_{sd} = \left[1 - 0.22\left(\frac{M_{od}}{M_y}\right)^{0.5}\right]\left(\frac{M_{od}}{M_y}\right)^{0.5} M_y \tag{4}$$

where λ_d is non-dimensional slenderness used to determine M_{sd} ;

$\lambda_l = \sqrt{M_y / M_{od}}$; $M_y = Z_f\, f_y$,

M_{od} is elastic distortional buckling moment of the section;

$M_{od} = Z_f\, f_{od}$,

Z_f is section modulus about a horizontal axis of the full section,

f_{od} is elastic distortional buckling stress of the section in bending.

3.2 Proposed DSM Design Rules for Shear

3.2.1 Nominal Shear Capacity Based on AISI in DSM Format in Shear Without Tension Field Action

The equations in Section 3.2.1 of the North American Specification (AISI 2007) 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:

$$\text{For } \lambda_v \le 0.815 \;:\; V_v = V_y \tag{5}$$

$$\text{For } 0.815 < \lambda_v \le 1.231 \;:\; V_v = 0.815\sqrt{V_{cr} V_y} \tag{6}$$

$$\text{For } \lambda_v > 1.231 \;:\; V_v = V_{cr} \tag{7}$$

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 web plane,

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

k_v = shear buckling coefficient for the whole channel 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 (2009d) by using the Spline Finite Strip Method. In this way, the DSM philosophy of section rather than element buckling can now be incorporated in the nominal shear capacity.

The computed values of the shear buckling coefficients (k_v) for the plain channels increase from the theoretical value of a simply supported rectangular plate in shear of 9.34 for a Span:Panel Depth of 1:1 (*V* Series) to 9.926 and 10.006 for the 150mm and 200 mm depth sections respectively. For the SupaCee® sections, the corresponding values are 12.204 and 11.709 as a result of the longitudinal intermediate stiffeners in the web. For a Span:Panel Depth of 2:1 (*MV* Series), the shear buckling coefficients k_v for the plain channels increase from the theoretical value of a simply supported rectangular plate in shear of 6.34 to 7.122 and 7.237 for the 150mm and 200 mm depth sections respectively. For the SupaCee® sections, the corresponding values are 8.007 and 7.813.

3.2.2 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 plain lipped C- and SupaCee® sections are summarized in a separate paper at this conference and in Pham and Hancock (2009b, 2009c). 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:

$$V_v = \left[1 - 0.15\left(\frac{V_{cr}}{V_y}\right)^{0.4}\right]\left(\frac{V_{cr}}{V_y}\right)^{0.4} V_y \tag{8}$$

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 (as shown in Section 3.2.1).

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.

3.3 Proposed DSM Design Rules for Combined Bending and Shear

In limit states design standards, the interaction is expressed in terms of bending moment and shear force so that the interaction formula for combined bending and shear of a section with an unstiffened web is given in Clause 3.3.5 of AS/NZS 4600:2005 [Section C 3.3.2 of AISI (2007)]:

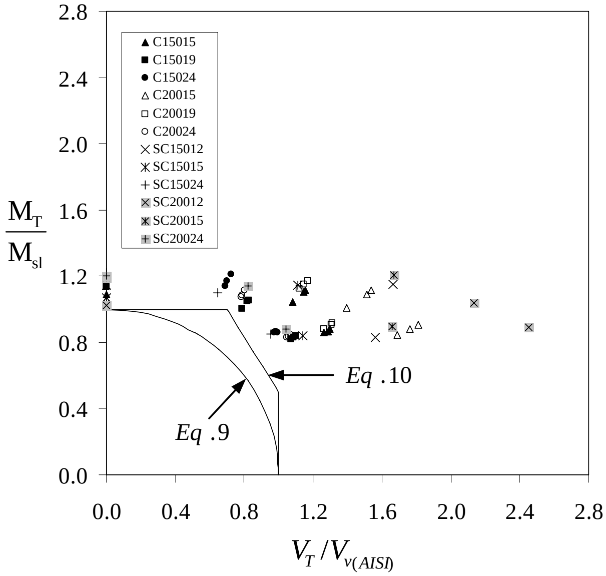
$$\left(\frac{M^*}{M_s}\right)^2 + \left(\frac{V^*}{V_v}\right)^2 = 1 \tag{9}$$

where M^* is bending action,
M_s is the bending section capacity in pure bending,
V^* is the shear action, and
V_v is the shear capacity in pure shear.

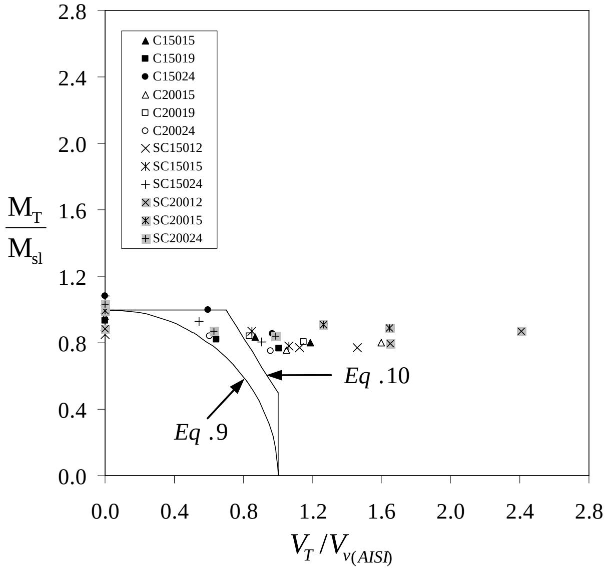
The equation for combined bending and shear with stiffened webs is also given in Clause 3.3.5 of AS/NZS 4600:2005 [Section C 3.3.2 of AISI (2007)]:

$$0.6\left(\frac{M^*}{M_s}\right) + \frac{V^*}{V_v} = 1.3 \tag{10}$$

The interactions between (M_T/M_s) and (V_T/V_v) with and without the straps based on either AISI without TFA (Eqs. 5-7) or DSM proposed shear curve with TFA (Eq. 8) are graphically reproduced in Figs. 6-10 for both plain C- and SupaCee® section purlins. While the choice of the nominal section moment capacities, M_s, is based on the DSM, the nominal shear capacities, V_v, is based on AISI (without Tension Field Action) in DSM format (Figs. 6-7) and DSM proposed shear curve (with Tension Field Action) (Figs. 8-9) respectively.

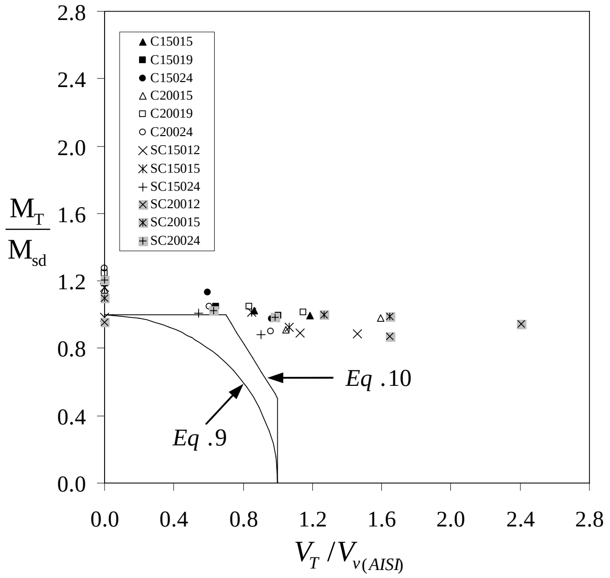


(a) With Straps



(b) Without Straps

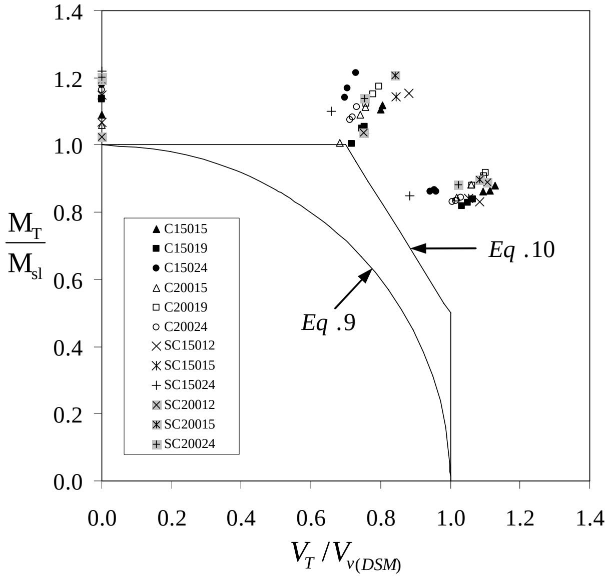
Figure 6. Interaction between (M_T/M_s) and (V_T/V_v) with M_{sl} based on DSM, V_v based on AISI without TFA – Plain C- and SupaCee® Sections



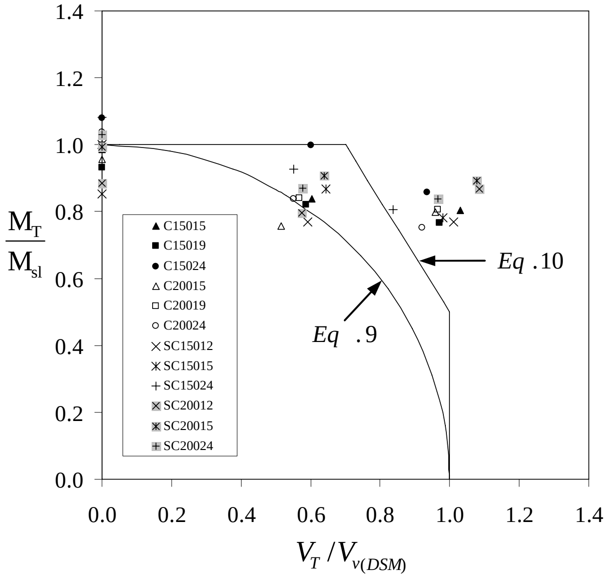
Without Straps

Figure 7. Interaction between (M_T/M_s) and (V_T/V_v) with M_{sd} based on DSM, V_v based on AISI without TFA – Plain C- and SupaCee® Sections

All results shown in Fig. 6(a) lie well above Eq. 10 trilinear so that the interaction between bending and shear is therefore not significant. The explanation for this fact is that the V_v, based on AISI, is calculated by using the elastic buckling stress of the whole sections which provides very conservative predictions, whereas the test results are based on the ultimate strength of the full section including tension field action. It is interesting to note that the slender sections (e.g. C20015 and SC20012) 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. Conversely, the stockier sections (e.g C15019, C15024, C20024, SC15024 and SC20024) of *(MV)* tests are more accurately predicted. In Fig. 6(b) for the tests without straps, the results are lower than those in Fig. 6(a) and mainly conservative except the stockier sections (e.g C15019, C15024, C20024, SC15024 and SC20024) of *(MV)* tests which lie just outside the circular domain limit (Eq. 9) and below Eq. 10 trilinear. In Fig. 7, the interaction between (M_T/M_s) and (V_T/V_v) without straps is similar to that in Fig. 6(b). The only difference is that the $M_s=M_{sd}$ is utilized instead of the $M_s=M_{sl}$ as it has a lower value. The results are shifted higher than those in Fig. 6(b) and lie above Eq. 10 trilinear. The interaction is therefore not as significant and very conservative.

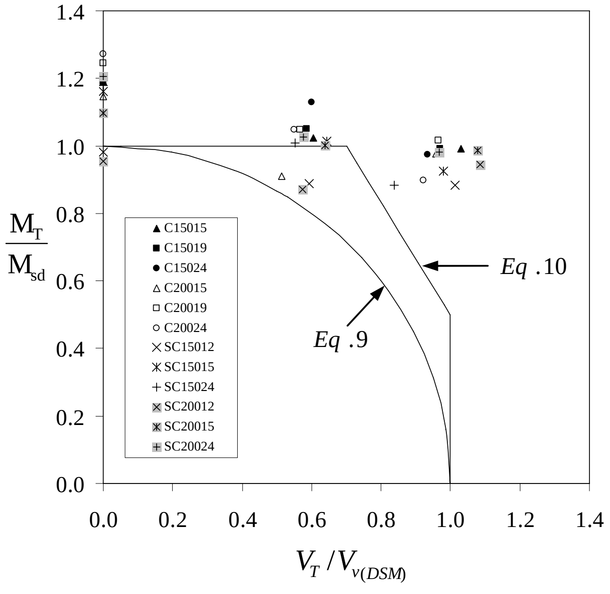


(a) With Straps



(b) Without Straps

Figure 8. Interaction between (M_T/M_s) and (V_T/V_v) with M_{sl} based on DSM, V_v based on DSM Proposal with TFA – Plain C- and SupaCee® Sections



Without Straps

Figure 9. Interaction between (M_T/M_s) and (V_T/V_v) with M_{sd} based on DSM, V_v based on DSM Proposal with TFA – Plain C- and SupaCee® Sections

In Fig. 8(a), the mean of the ratios V_T/V_v for the *V* test series is almost equal to 1.0. This fact shows that the V_v based on DSM proposed shear curve with TFA gives the best prediction for the tested sections for nominal shear capacity of the whole section compared with that based on the AISI without TFA [see Fig. 6(a)]. The DSM proposed shear equation with tension field action gives a good mean fit to the *V* tests. The tests for the *(V)* and the *(MV)* also group very closely. This fact can be explained by the use of the shear buckling coefficient (k_v) for the whole channel sections instead of the web panel only. This method, therefore, gives more accurate prediction on the post-buckling strengths of the whole channel sections for bending and shear. Fig. 8(b) shows the interaction between (M_T/M_s) and (V_T/V_v) without straps where M_s is based on M_{sl} and V_v is based on the DSM proposed shear curve with TFA. It can be seen in this figure that the interaction between bending and shear is very significant. All tests for *(MV)* test series lie below Eq. 10 trilinear and are closer to Eq. 9 unit circle. The very slender sections (C20015, SC15012 and SC20012) even lie below the circular domain limit. This fact shows that it is unconservative to use Eq. 10 trilinear for design with M_{sl} and tension field action included. Therefore, Eq. 9 unit circle may be applicable in this case.

In Fig. 9, the M_s=M_{sd} is utilized instead of M_{sl} as it is lower. The results are higher than those in Fig. 8(b) and generally lie above Eq. 10 trilinear. However, the tests with very slender sections (C20015, SC15012 and SC20012) of *MV* test series lie below Eq. 10 trilinear. The interaction is therefore less significant and conservative. The explanation is due to the fact that M_{sd} is normally lower than M_{sl} and it is conservative to use M_{sd} to predict M_s in the case of the tests without straps.

3. CONCLUSION

Two experimental programs were carried out at the University of Sydney to determine the ultimate strength of high strength cold-formed channel purlins subjected to combined bending and shear, and bending only. The high strength cold-formed channel purlins included plain C- sections and SupaCee® sections in each program respectively.

For combined bending and shear, all test results were plotted in this paper as interaction diagrams where V_v and M_s are determined by different methods. The nominal shear capacities, V_v, were based on AISI without tension field action in DSM format or DSM proposed shear curve with tension field action. The nominal section moment capacity, M_s, is based on either M_{sl} or M_{sd} of the DSM. The tests show that the DSM proposal with and without tension field action requires M_s=M_{sl} to satisfy Eq. 10 trilinear interaction in cases of tests with straps. Also if tension field action is included in the DSM proposal, then Eq. 9 circular interaction must be used with both M_s=M_{sl} and M_s=M_{sd} in cases of tests without straps. Tension field action cannot be used with the DSM in case of tests without straps to satisfy Eq. 10 trilinear interaction.

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