EXPERIMENTAL STUDY OF LONGITUDINALLY STIFFENED WEB CHANNELS SUBJECTED PREDOMINANTLY TO SHEAR

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ABSTRACT

The buckling and strength capacities of channel members depend on the geometry of the whole section. For channel sections, the shear buckling modes occur mainly in the web. The structural efficiency of the sections in shear can be improved by adding intermediate stiffeners cold-formed longitudinally in the web. Recently, the Direct Strength Method (DSM) of design of cold-formed sections has been extended in the North American Specification for Cold-Formed Steel Structural Members-NAS S100:2012 to include shear. The two new features of the DSM rules for shear researched are the effect of full-section shear buckling as opposed to web-only shear buckling and Tension Field Action (TFA). The prequalified sections in the rules include sections with flat webs and webs with small intermediate longitudinal stiffeners. In order to extend the range to larger intermediate stiffeners as occurs in practice, a series of fourteen shear tests have been performed at the University of Sydney for C-sections with rectangular stiffeners of varying sizes. Six different types of stiffeners were tested with an additional preferred plain section. Each type of sections was tested twice to ensure accuracy. As the web stiffener sizes increase, the shear buckling and strength of the sections are expected to improve accordingly. However, the tests show that the shear ultimate strengths only increase slightly in association with the respective increase of stiffener sizes. The test results are compared with the DSM design rules for shear and found to be lower than those predicted by the DSM curve for shear with TFA. The test failures were observed mainly due to the combined bending and shear modes. The effect of the bending is therefore significant and starts to govern when the shear capacity is significantly strengthened by adding the large longitudinal web stiffener. The test results are subsequently plotted against the DSM interaction curves between bending and shear where the interaction is found to be significant. Modifications and recommendations for prequalified sections with longitudinally stiffened web channels in shear are proposed in the report.

KEYWORDS

Cold-formed sections; High strength steel; Longitudinal web stiffener; Shear strength; Complex channel sections; Direct strength method.

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INTRODUCTION

Cold-formed steel structural members have been effectively and widely used around the world in such applications as wall studs, girts, steel housing frames, roof systems, etc. Among these types of structures, cold-formed purlins as intermediate members to transfer loads from the roof decks to main structural frames are manufactured by bending flat sheet to certain shapes at ambient temperature. Most commonly utilised purlin shapes are C and Z- sections with attractive attributes such as high strength to self-weight ratio, ease of prefabrication and installation, versatility and high structural efficiency. With continued advance of technology, cold-formed members are now being fabricated with higher yield stress materials up to 550 MPa. Also, the resulting reduction of thicknesses of high strength steel leads to the development of highly stiffened sections with more folds and stiffeners. As a result, the range of available purlin shapes and sizes is experiencing significant expansion.

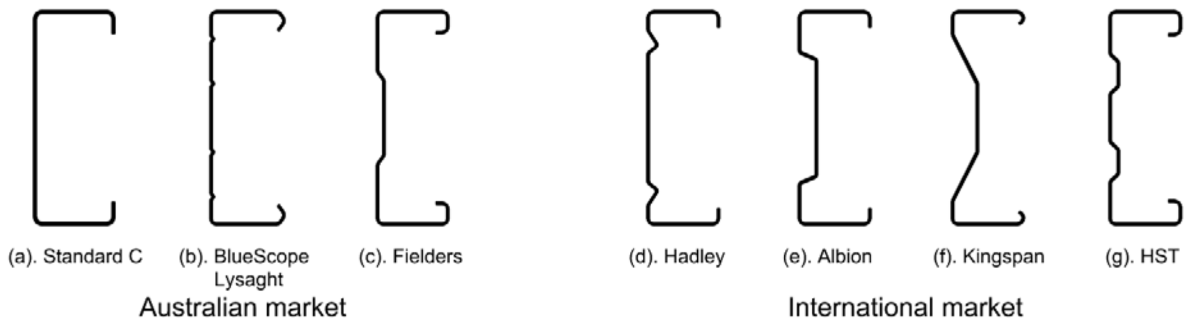


Figure 1. Profile shapes of manufactured purlin profiles

In today's market, for channel sections in particular, there is a wide variety of commercially available purlin shapes as shown in Fig. 1. In Australia, besides the standard plain C- section (see Fig. 1a), BlueScope Lysaght (BlueScope Steel Ltd., Melbourne, Australia) and the University of Sydney have developed the new SupaCee purlin profile shown in Fig. 2b which gives higher capacity and a more economical solution. Four small longitudinal web stiffeners and return lips of this section significantly improve the performance in bending and shear (Pham and Hancock 2012a, 2013). Another Australian provider, Fielders (Fielders Steel Roofing Pty Ltd., Adelaide, Australia), introduced a new DHS (Dimond Hi-Span) structural purlin (see Fig.1c) which has a single web stiffener created by offsetting the inner portion of the web and return lips. In international markets, there is a more extensive range of purlin profiles in comparison with those manufactured in Australia. Particularly in the United Kingdom, Hadley Group (Hadley Industries PLC, West Midlands, UK) manufactures the complex channel section called UltraBEAM (see Fig. 1d) with two uniquely shaped intermediate web stiffeners. British company Albion (Albion Sections Ltd., West Midlands, UK) developed the Albion Sigma beam purlin as shown in Fig. 1e. The design of the section is similar to the DHS except the lips are simple (with no return) and the web swage is much more pronounced up to 16 mm offset as compared with 2-5 mm offset of the DHS. The pitch of the segments connecting inner and outer web portions is also significantly steeper. The other roofing product is the Multibeam roof purlin (see Fig. 1f) introduced by Kingspan (Kingspan Structural Products, North Yorkshire, UK). This section possesses a lip inwardly curved rather than perpendicularly folded. The length of the edge stiffener is also relatively small. Further, the length of the inner portion of the web is possibly the largest available in the market, making up to approximately 75% of the total profile depth. Another considerably complex product is the HST section (see Fig. 1g) made by a New Zealand company Steel & Tube (Steel & Tube Holdings Ltd., Wellington, New Zealand). The distinguishing feature of the HST is the configuration of the web stiffener. Unlike other sections which are created with a single web swage, the HST has two smaller swages. For American market, it seems that the standard C- purlins are the most widely available channel sections in the US. Flexospan (Flexospan Steel Buidlings, Inc., Sandy Lake, PA, USA), Metroll USA (Metroll USA, Fontana, CA, USA) and Canam Group (Canam Group Inc., Quebec, Canada) are a few of the numerous North-American construction groups producing and marketing the standard lipped C- and even-profile purlins and girts.

Currently, two basic design methods for cold-formed steel members are formally available in the Australian/New Zealand Standard for Cold-Formed Steel Structures (AS/NZS 4600:2005) (Standards Australia, 2005) or the North American Specification for Cold-Formed Steel Structural Members (NAS, S100-2012). They are the traditional Effective Width Method (EWM) and the newly developed Direct Strength Method of design (DSM) (Chapter 7 of AS/NZS 4600:2005, Appendix 1 NAS S100-2012). As sections become more complex with additional longitudinal web stiffeners and return lips as designed in Fig. 1, 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 sections. There is no need to calculate cumbersome effective sections especially with intermediate stiffeners. The development of the DSM for compression and bending including the reliability of the method is well researched.

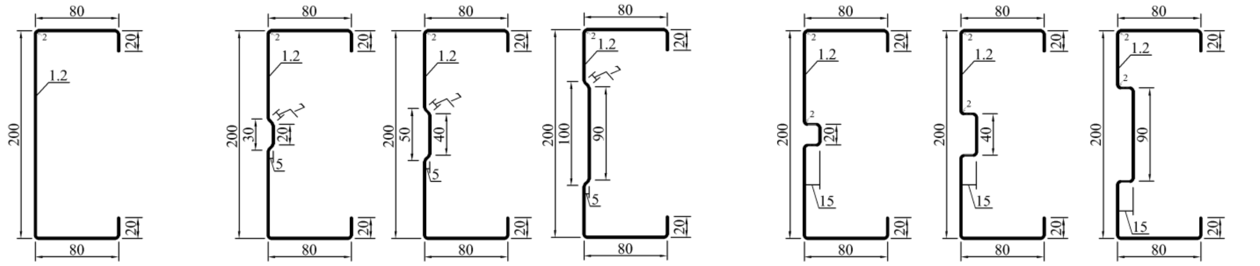
The recent development of the Direct Strength Method (DSM) of design of cold-formed sections in pure shear (Pham and Hancock, 2012a) has been extended in the North American Specification for Cold-Formed Steel Structural Members (NAS S100-2012). Proposed DSM design rules for sections with and without Tension Field Action (TFA) were calibrated against a series of predominantly shear tests of both plain C- and SupaCee sections (Pham and Hancock, 2010, 2012a) performed at the University of Sydney. In the proposals, the elastic buckling load in shear is required to be computed. Hancock and Pham (2011, 2012) have employed the complex Semi-Analytical Finite Strip Method (SAFSM) of Plank and Wittrick (1974) to compute the signature curves for channel sections in pure shear. The method assumes the ends of the half-wavelength under consideration are free to distort and the buckle is part of a very long length without restraint from end conditions. Further extended studies of this theory on complex sections with rectangular and triangular intermediate stiffeners in the web have been performed by Pham, Pham and Hancock (2012a, b). In practice, sections may be restrained at their ends by transverse stiffeners leading to the change in shear buckling modes and the increase of the buckling loads by the end effects. To provide solutions, Pham and Hancock (2009, 2012b) have used the Spline Finite Strip Method (SFSM) developed for shear elastic buckling by Lau and Hancock (1986). Another more efficient alternative in computation is the new theory of the Semi-Analytical Finite Strip Method (SAFSM) using multiple series terms (Hancock and Pham, 2013) recently developed to study the elastic buckling of channel sections with simply supported ends in shear.

In order to extend the range of complex sections to larger intermediate stiffeners as occurs in practice (see Fig. 1), an experimental program was performed at the University of Sydney. The main aim of this report is to provide test data on stiffened web channels (SWC) with various stiffener sizes subjected to predominantly shear. The test results were compared with the DSM design rules for shear. Also, as the shear strength is significantly improved by the large web stiffeners, the effect of bending becomes important. Significant failures in combined bending and shear modes were observed. The test results were also plotted against the DSM interaction equations between bending and shear. The recommendations on the extended range of the prequalified sections are given in the report for the stiffened web channels predominantly subjected to shear.

EXPERIMENTS ON STIFFENED WEB CHANNEL (SWC) IN SHEAR

Specimen Nomenclature, Dimensions of Stiffened Web Channel (SWC)

The stiffened web channel sections tested in this report are fabricated by bending the steel metal sheet to form predetermined complex channels using a press brake machine. Based on a standard plain C- channel with a web depth of 200 mm, a flange width of 80 mm and a lip size of 20 mm as a preferred section, six different stiffened web channel sections are designed by adding one single longitudinal web stiffener with various sizes. The nominal geometries of the seven stiffened web channels including plain C- section are shown in Fig. 2. Two web indents of 5 mm and 15 mm and three web stiffener depths of 20 mm, 40 mm and 90 mm were chosen for the longitudinal web stiffener dimensions. The two segments between the inner and outer web portions for 5 mm indent are inclined 45^0 due to the minimum required gap between two bends (see Fig. 2b) whereas those for 15 mm indent are folded perpendicularly to form a rectangular web stiffener (see Fig.2c). All sections have the same thickness of t = 1.2 mm.



(a). Plain C- Section (b). Stiffened Web Channel with an Inclined Stiffener (c). Stiffened Web Channel with a Rectangular Stiffener

Figure 2. Stiffened web channel types

The test specimens were labelled to express the predominantly shear test series, channel sections, types of web stiffeners. The label for plain C- section "C20012" (see Fig. 2a) is defined as:

(i) "C200" expresses plain C- section with the depth of 200 mm,
(ii) The final "12" is the actual thickness times 10 in mm.

For stiffened web channels (SWC), typical test labels "SWC-I20x5" and "SWC-R20x5" are defined as follows:

(i) "SWC" indicates stiffened web channels,
(ii) "I" indicates specimens with inclined stiffener (see Fig. 2b),
(alternatively "R" indicates specimens with rectangular stiffener (see Fig. 2c),
"20x5" indicates the various sizes of the depth (20 mm) and width of the stiffener (5 mm).

The testing series comprised a total of fourteen tests on seven types of cross sections as shown in Fig. 2. Each typical type of section had two identical tests to ensure the accuracy of the results. The average measured dimensions are given in Table 1 and Fig. 3. In this table, t is the thickness of the section. D is the overall depth. B and L are the average overall flange widths and lip sizes respectively. b_{s1} and d_{s1} are the stiffener width and inner depth. d_{s2} is outer depth of the inclined stiffener.

Section	t mm	D mm	B mm	L mm	b_{s1} mm	d_{s1} mm	d_{s2} mm
C20012-1	1.2	202.5	81.45	20.40	-	-	-
C20012-2	1.2	201.6	81.36	20.75	-	-	-
SWC-I20X5-1	1.2	202.7	81.25	20.58	5.35	20.15	30.25
SWC-I20X5-2	1.2	202.6	81.38	20.80	5.25	20.15	30.20
SWC-I40X5-1	1.2	202.6	81.18	20.90	5.25	40.15	50.25
SWC-I40X5-2	1.2	201.9	81.23	20.78	5.25	40.20	50.30
SWC-I90X5-1	1.2	202.6	81.15	20.65	5.25	90.25	100.20
SWC-I90X5-2	1.2	202.6	81.13	20.65	5.30	90.40	100.25
SWC-R20x15-1	1.2	202.4	81.18	20.80	15.25	20.20	20.20
SWC-R20x15-2	1.2	202.0	81.13	20.80	15.30	20.20	20.20
SWC-R40x15-1	1.2	201.5	81.18	20.93	15.35	40.25	40.25
SWC-R40x15-2	1.2	202.0	81.23	20.68	15.27	40.25	40.25
SWC-R90x15-1	1.2	201.7	81.33	20.90	15.30	90.25	90.25
SWC-R90x15-2	1.2	202.0	81.18	20.70	15.25	90.25	90.25

Table 1. Measured specimen dimensions

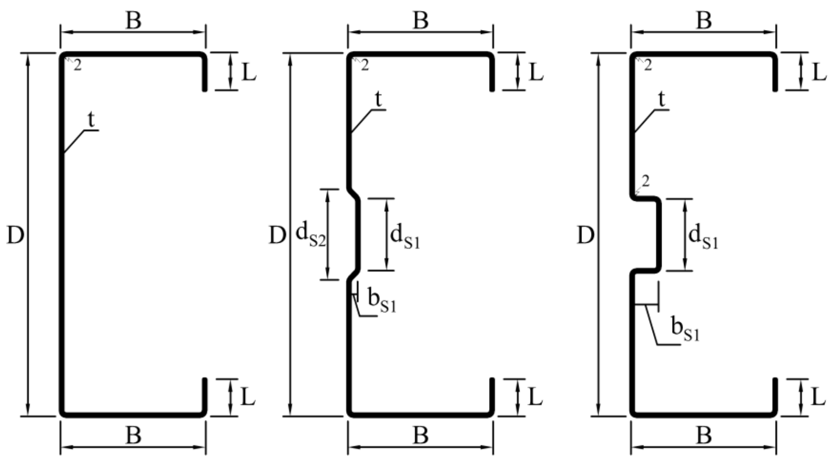


Figure 3. Cross section geometries

Tensile Coupon Tests

To determine the mechanical properties of high strength steel material, four coupon specimens were tested in the J.W. Roderick laboratory for Materials and Structures at the University of Sydney. Two coupons out of four were taken longitudinally from the web flat of channel section member. Similarly, one coupon each was taken from the compression and tension flanges respectively. The tensile coupon dimensions conformed to the Australian Standard AS 1391 (Standards Australia 1991) for the tensile testing of metals using 12.5 mm wide coupons with gauge length 40 mm. The test specimens were galvanized by two layers of corrosion protection coating during the manufacturing process. Since the thickness of the steel sheet is very thin, these coatings may allow the steel to carry more load, hence the base metal thickness of the virgin material had to be determined. The coatings were removed to expose the virgin (base) material by acid etching. The total thickness of the two coatings is approximately 0.05 mm. Fig. 4 shows the detail of a coupon test configuration. All coupon tests were performed using the 300 kN capacity Sintech/MTS 65/G testing machine operated in a displacement control mode. A constant displacement rate of 0.5 mm/min was maintained. The coupons were secured in a pair of vice grips and an extensometer was used to record the elongation. The extensometer has a range of 25 mm

The coupons were identified as follows: “C20012” means the first coupon was cut longitudinally from the “compression” flange of channel of a 200 mm depth and 1.2 mm thickness, alternatively, “W20012” from the “web” and “T20012” from the “tension” flange of the channel. The mean yield stress f_y of 583.82 MPa was obtained by using the 0.2 % nominal proof stress. The average Young’s modulus of elasticity was calculated according to the tensile coupon stress-strain curves to be 204,862 MPa. Table 2 lists the details of every individual coupon test.

Figure 4. Coupon test configuration

Specimen	Thickness (mm)	b (mm)	A (mm^2)	$f_{y0.2\%}$ (MPa)	E (MPa)
C20012-1	1.24	12.56	15.62	569.64	207,513
W20012-2	1.21	12.45	15.07	590.79	203,194
W20012-3	1.22	12.47	15.21	591.58	202,086
T20012-4	1.20	12.43	18.62	583.27	206,655
			Mean	583.82	204,862

Table 2. Coupon Test Results

Test Rig Design

The experimental program was performed in the J. W. Roderick Laboratory for Materials and Structures at the University of Sydney. All tests were conducted in the 2000 kN capacity DARTEC testing machine, using a servo-controlled hydraulic ram. A diagram of the test set-up configuration is shown in Fig. 5. This is the same rig as used by Pham and Hancock (2010, 2012a).

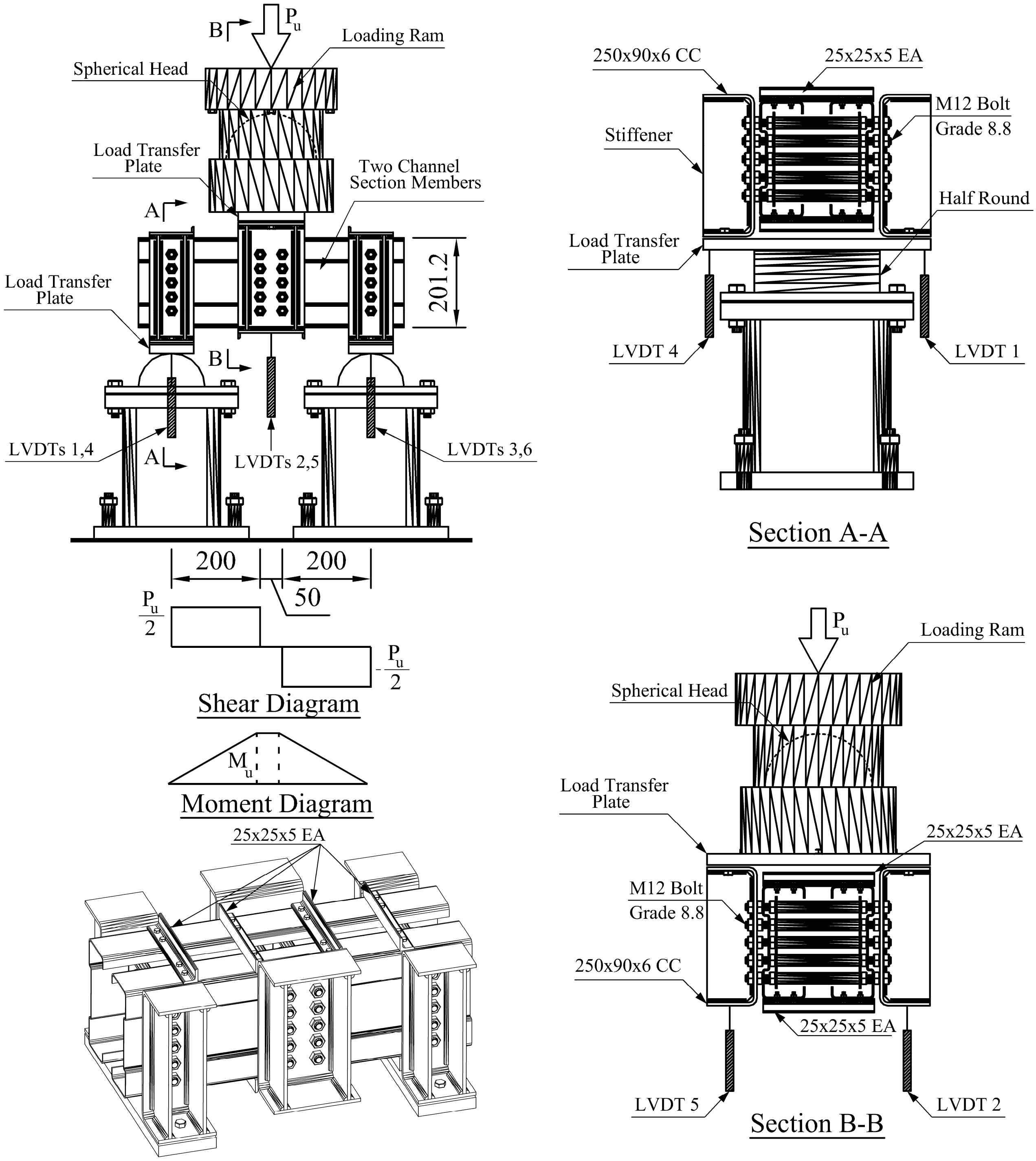


Figure 5: Predominantly shear test configuration

Fourteen tests of the seven types of stiffened web channels (SWC) including plain-C section as shown in Fig. 2 were conducted. Each type of section was tested twice to ensure accuracy. In each test, two identical specimens were tested in pairs with top flanges facing inwards and with a gap between them to ensure that the inside assembly was possible.

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 steel bearing plate of 20 mm thickness, and moved downwards at a constant stroke rate of 2 mm/min during testing. The load was transferred to two stiffened channel sections 250x90x6CC (Cold-formed Channel) 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.

At the supports, the two test specimens were bolted through the webs by vertical rows of M12 high tensile bolts. These rows of bolts were connected through the webs of two stiffened channel sections 250x90x6CC. The load was subsequently transferred to steel load transfer plates of 20 mm thickness bolted through the flanges of the stiffened channel sections 250x90x6CC. These load bearing plates eventually 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 test beam specimen and CC (Cold-formed Channel) section so that the specimen did not attach directly on the CC thus minimizing restraint to the web.

Five bolts were used at each support and ten bolts at the loading point. Six LVDTs (Linear Variable Displacement Transducers) were utilized as also shown in Fig. 5. All LVDTs were mounted directly to the base of the DARTEC testing machine. This set-up allowed for the vertical displacement of the specimen to be determined without being affected by bending of the test specimen.

Further, the test beam specimens were also connected by four 25x25x5EA (Equal Angle) steel straps on each top and bottom flange adjacent to the loading point and supports as shown in Fig. 5. Self-tapping screws were used to attach these straps to the test beam specimens. The object of these straps was to prevent section distortion at the loading point and supports. The use of stiffened channel sections 250x90x6CC was introduced to prevent a bearing failure at the loading point and supports which could be caused by using conventional bearing plates.

EXPERIMENTAL RESULTS AND OBSERVATIONS

Table 3 summaries the results of the fourteen predominantly shear tests for stiffened web channel sections. Included in Table 3 are shear span (s), the ultimate peak loads (P_T) of each test, the test shear loads (V_T) and the test bending moments (M_T).

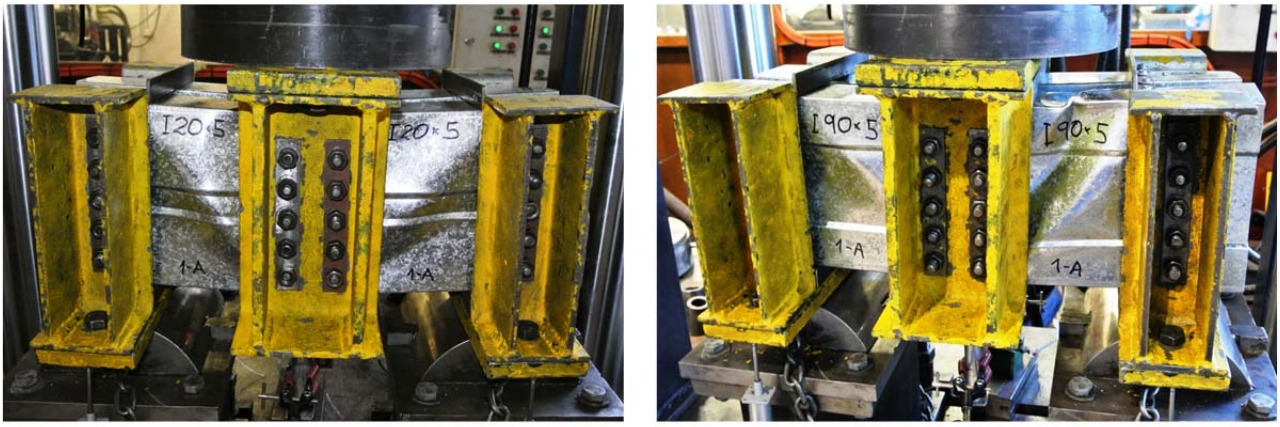
Section	s mm	P_T kN	$V_T = \frac{P_T}{4}$ kN	$M_T = \frac{P_T * s}{4}$ kNm
C20012-1	200	150.53	37.63	7.53
C20012-2	200	163.23	40.81	8.16
SWC-I20X5-1	200	180.02	45.00	9.00
SWC-I20X5-2	200	183.62	45.90	9.18
SWC-I40X5-1	200	179.22	44.81	8.96
SWC-I40X5-2	200	188.56	47.14	9.43
SWC-I90X5-1	200	178.55	44.64	8.93
SWC-I90X5-2	200	138.93	Premature	Failure
SWC-R20x15-1	200	199.24	49.81	9.96
SWC-R20x15-2	200	196.25	49.06	9.81
SWC-R40x15-1	200	204.25	51.06	10.21
SWC-R40x15-2	200	203.15	50.79	10.16
SWC-R90x15-1	200	192.47	48.12	9.62
SWC-R90x15-2	200	182.46	45.61	9.12

Table 3. Predominantly shear test results

Typical failure modes for predominantly shear tests of the stiffened web channel (SWC) sections are shown in Figs. 6 and 7. For channel sections with relatively small web stiffener width such as SWC-I20x5-1 (b_{s1}=5 mm, d_{s1}=20 mm) (see Fig. 6a), the failure pattern shows definite shear buckle across the whole web. As the stiffener depth (d_{s1}) is increased, for example: SWC-I90x5-1 (b_{s1}=5 mm, d_{s1}=90 mm) (see Fig. 6b), the shear failure mode appears to be influenced by the bending moment. It can be seen in Fig. 6b that the failure channel members occurs adjacent to the middle of shear span in combined bending and shear buckling mode.

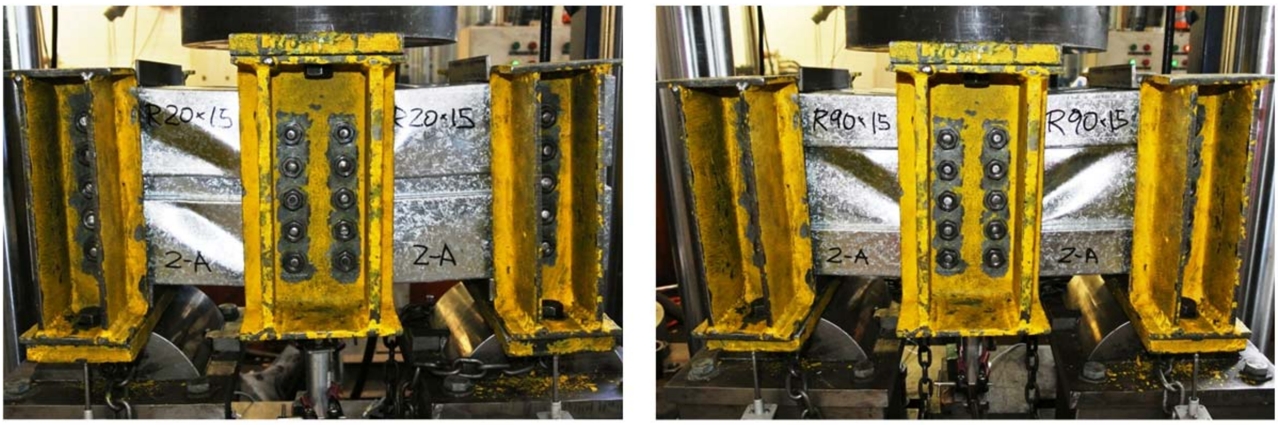
For the SWC-I90x5-2 test, premature failure was observed as a result of localized failure at the positions of the screws which were used to attach top straps to top flanges of the SWC sections. The result of this test is therefore discarded in the latter design calculation sections.

For the tests with a larger stiffener width (b_{s1}=15 mm), the failures in the local buckling modes were firstly observed in the top flanges adjacent to the loading points. The shear buckles subsequently occurred in two larger web portions as shown in SWC-R20x15-2 test (b_{s1}=15 mm, d_{s1}=20 mm) (see Fig. 7a). Similarly for SWC-R90x15-2 test (b_{s1}=15 mm, d_{s1}=90 mm), the local buckling in the top flanges adjacent to the loading points occurred prior to the shear bucking in the middle web portion (or web stiffener depth, d_{s1}) as can be seen in Fig. 7b.



(a). SWC-I20x5 **(b). SWC-I90x5**

Figure 6: Typical failure patterns for channels with b_{s1} = 5 mm



(a). SWC-R20x15 **(b). SWC-R90x15**

Figure 7: Typical failure patterns for channels with b_{s1} = 15 mm

DIRECT STRENGTH METHOD (DSM) OF DESIGN FOR COLD-FORMED SECTIONS

DSM DESIGN RULES FOR PURE SHEAR

DSM design rules in shear without Tension Field Action

The nominal shear strength (V_n) of beams without holes in the web and without web stiffeners is determined from Appendix 1, Section 1.2.2.2.1 of NAS-2012 (AISI, 2012) as follows:

$$\text{For } \lambda_v \le 0.815 \ : V_n = V_y \quad (1)$$

$$\text{For } 0.815 < \lambda_v \le 1.227 \ : V_n = 0.815\sqrt{V_{cr}V_y} \quad (2)$$

$$\text{For } \lambda_v > 1.227 : V_n = V_{cr} \quad (3)$$

$$V_y = 0.6 A_w F_y \quad (4)$$

$$V_{cr} = \frac{k_v \pi^2 E A_w}{12(1-\nu^2)(d_1/t_w)^2} \quad (5)$$

where V_y is the yield load of web based on an average shear yield stress of $0.6F_y$;

V_{cr} is the elastic shear buckling force of the whole section derived by integration of the shear stress distribution at buckling over the whole section; $\lambda_v = \sqrt{V_y / V_{cr}}$;

k_v is the shear buckling coefficient of the whole section based on the Spline Finite Strip Method (SFSM) (Pham and Hancock, 2009, 2012b) or the Semi-Analytical Finite Strip Method (SAFSM) (Hancock and Pham, 2011, 2012) and Pham, Pham and Hancock, 2012a, b).

DSM design rules in shear with Tension Field Action

The nominal shear strength (V_n) of beams without holes in the web including tension field action is determined from Appendix 1, Section 1.2.2.2.1 of NAS-2012 (AISI, 2012) as follows:

$$V_n = \left[1 - 0.15\left(\frac{V_{cr}}{V_y}\right)^{0.4}\right]\left(\frac{V_{cr}}{V_y}\right)^{0.4} V_y \quad (6)$$

DSM DESIGN RULES FOR FLEXURE

Local Buckling Strength

The nominal flexural strength at local buckling (M_{nl}) of beams without holes is determined from Appendix 1, Section 1.2.2.1.2 of NAS-2012 (AISI, 2012) as follows:

$$\text{For } \lambda_l \le 0.776 \ : M_{nl} = M_{ne} \quad (7)$$

$$\text{For } \lambda_l > 0.776 \ : M_{nl} = \left[1 - 0.15\left(\frac{M_{crl}}{M_{ne}}\right)^{0.4}\right]\left(\frac{M_{crl}}{M_{ne}}\right)^{0.4} M_{ne} \quad (8)$$

where λ_l is the non-dimensional slenderness used to determine M_{nl} ($\lambda_l = \sqrt{M_{ne}/M_{crl}}$);

M_{ne} is the critical elastic lateral-torsional buckling moment

M_{crl} is the elastic local buckling moment of the section ($M_{crl} = S_f f_{crl}$);

f_{crl} is the elastic local buckling stress of the section in bending;

S_f is the section modulus about a horizontal axis of the full section.

Distortional Buckling Strength

The nominal flexural strength at distortional buckling (M_{nd}) of beams without holes is determined from Appendix 1, Section 1.2.2.1.3 of NAS-2012 (AISI, 2012) as follows:

$$\text{For } \lambda_d \leq 0.673 \ : \ M_{nd} = M_y \tag{9}$$

$$\text{For } \lambda_d > 0.673 \ : \ M_{nd} = \left[1 - 0.22\left(\frac{M_{crd}}{M_y}\right)^{0.5}\right]\left(\frac{M_{crd}}{M_y}\right)^{0.5} M_y \tag{10}$$

where λ_d is the non-dimensional slenderness used to determine M_{nd} ($\lambda_l = \sqrt{M_y / M_{crd}}$);

M_y is the yield moment of the full section ($M_y = S_f F_y$);

M_{crd} is the elastic distortional buckling moment of the section ($M_{crd} = S_f f_{crd}$);

f_{crd} is the elastic distortional buckling stress of the section in bending;

S_f is the section modulus about a horizontal axis of the full section.

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 upper limit interaction formula for combined bending and shear of a section with a vertically unstiffened web is given Section C 3.3.2 of NAS-2012 (AISI, 2012):

$$\sqrt{\left(\frac{M^*}{M_{nxo}}\right)^2 + \left(\frac{V^*}{V_n}\right)^2} = 1 \tag{11}$$

where M* is bending action (required strength), M_{nxo} is the bending section capacity (strength) in pure bending based on Eqs. 7-8, V* is the shear action (required strength), and V_n is the shear capacity (strength) in pure shear. The upper limit equation for combined bending and shear of vertically stiffened webs is also given in Section C 3.3.2 of NAS-2012 (AISI, 2012):

$$0.6\left(\frac{M^*}{M_{nxo}}\right) + \frac{V^*}{V_n} = 1.3 \tag{12}$$

where M_{nxo} is the bending section capacity (strength) in pure bending based on the lesser of Eqs. 7-8 or Eqs 9-10.

COMPARISON OF DIRECT STRENGTH METHOD (DSM) DESIGN LOADS FOR SHEAR WITH PREDOMINANTLY SHEAR TESTS OF STIFFENED WEB CHANNELS

COMPARISON WITH THE EXISTING DSM DESIGN SPECIFICATION FOR SHEAR

The results of predominantly shear tests for the stiffened web channel (SWC) sections are summarised in Table 4. Also included in the table are the shear yield loads (V_y – Eq. 4), the elastic shear buckling loads for the whole sections (V_{cr} – Eq. 5), the shear non-dimensional slenderness ($\lambda_v = \sqrt{V_y / V_{cr}}$) and the ratios of V_T/V_y.

Section	V_T (kN)	V_y (kN)	V_{cr} (kN)	$\sqrt{V_y / V_{cr}}$	V_T / V_y
C20012-1	37.63	82.43	15.94	2.274	0.457
C20012-2	40.81	82.05	16.01	2.264	0.497
SWC-I20X5-1	45.00	82.51	48.69	1.302	0.545
SWC-I20X5-2	45.90	82.47	48.71	1.301	0.557
SWC-I40X5-1	44.81	82.47	64.07	1.135	0.543
SWC-I40X5-2	47.14	82.18	64.30	1.130	0.574
SWC-I90X5-1	44.64	82.47	41.11	1.416	0.541
SWC-R20x15-1	49.81	82.39	57.41	1.198	0.605
SWC-R20x15-2	49.06	82.22	57.41	1.197	0.597
SWC-R40x15-1	51.06	82.01	76.82	1.033	0.623
SWC-R40x15-2	50.79	82.22	76.63	1.036	0.618
SWC-R90x15-1	48.12	82.09	55.36	1.218	0.586
SWC-R90x15-2	45.61	82.22	55.28	1.220	0.555

Table 4. Test results and DSM design loads for stiffened web channel sections

The test result points are subsequently plotted in Fig. 8 against both DSM design curves for shear with Tension Field Action (TFA) (Eqs. 1-3) and without TFA (Eq. 6) except that the SWC20012-I90x5-2 test due to premature failure has been eliminated. The TFA curve (Basler, 1961) and the elastic buckling curve (Vcr) are also graphically reproduced in Fig. 8. For plain C-section (C20012), the predominantly shear tests lie close to the DSM shear curve with TFA.

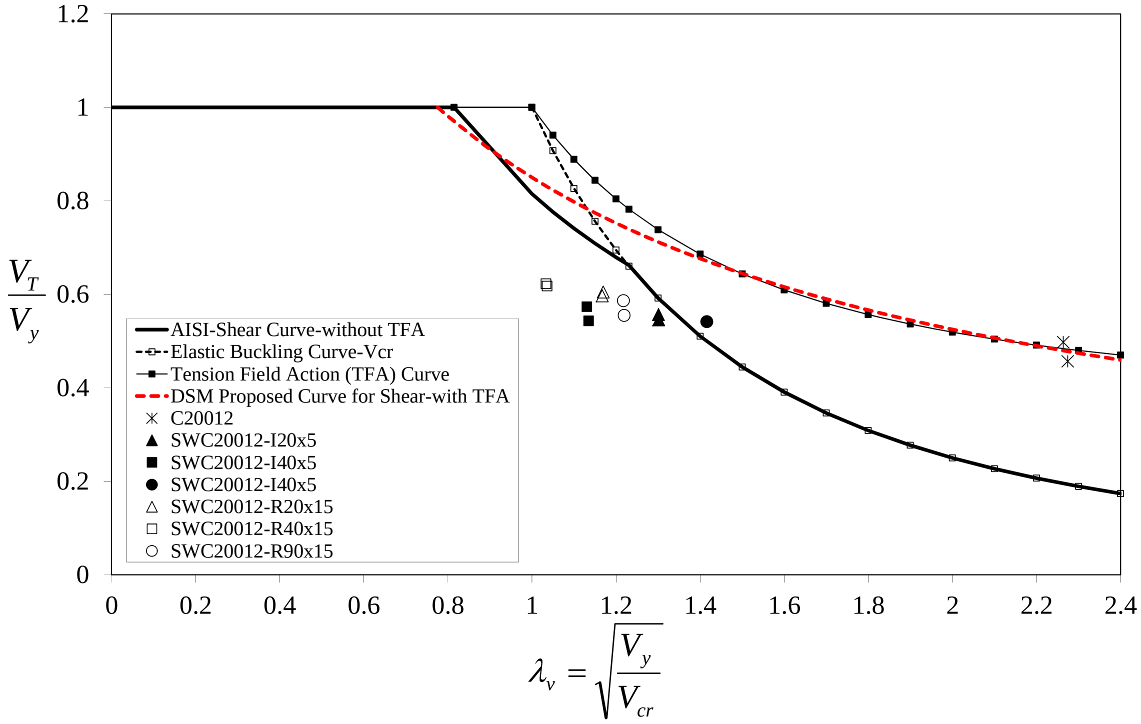


Figure 8: Test data vs DSM shear curves

For channel sections with stiffeners, depending on the sizes of the stiffeners, the elastic shear buckling loads (V_{cr}) based on the Spline Finite Strip Method (SFSM) (Pham and Hancock, 2009, 2012) increase significantly as the stiffeners become larger. The test points are therefore shifted horizontally to the left as shown in Fig. 8. However, it is interesting to note that the shear strengths (V_T) of the stiffened web channel sections only increase slightly on the vertical axis of Fig. 8 in association with the increase of stiffener sizes. As a result, the test points of the SWC lie below the DSM shear curve with TFA. The reason for this may be explained by a significant increase in the shear capacity (V_n) relative to the bending capacity (M_{nl}) so that combined bending and shear now becomes important.

COMPARISON WITH THE EXISTING DSM DESIGN SPECIFICATION FOR COMBINED BENDING AND SHEAR

Table 5 shows the test results, the DSM shear capacity (V_n) with TFA based on Eq. 6 and the bending section capacity (strength) (M_{nl}) at local buckling based on Eqs. 7-8. The ratios of $V_T/V_{n(DSM)}$ and M_T/M_{nl} are also included in Table 5. The bending section capacity (strength) M_{nd} based on Eqs. 9 and 10 has not been included in the calculations because the test specimens had straps at the loading point which eliminated this mode.

Section	V_T (kN)	$V_{n(DSM)}$ (kN)	M_T (kNm)	M_{nl} (kNm)	$V_T/V_{n(DSM)}$	M_T/M_{nl}
C20012-1	37.63	39.40	7.53	10.07	0.955	0.747
C20012-2	40.81	39.35	8.16	10.04	1.037	0.813
SWC-I20X5-1	45.00	58.70	9.00	10.57	0.767	0.851
SWC-I20X5-2	45.90	58.69	9.18	10.58	0.782	0.868
SWC-I40X5-1	44.81	64.44	8.96	10.64	0.695	0.842
SWC-I40X5-2	47.14	64.37	9.43	10.59	0.732	0.891
SWC-I90X5-1	44.64	55.34	8.93	10.76	0.807	0.830
SWC-R20x15-1	49.81	63.06	9.96	10.55	0.790	0.944
SWC-R20x15-2	49.06	63.02	9.81	10.51	0.779	0.933
SWC-R40x15-1	51.06	68.22	10.21	10.59	0.748	0.964
SWC-R40x15-2	50.79	68.28	10.16	10.61	0.744	0.957
SWC-R90x15-1	48.12	61.14	9.62	10.90	0.787	0.882
SWC-R90x15-2	45.61	61.17	9.12	10.92	0.746	0.836

Table 5. Test results, $V_{n(DSM)}$ based on DSM design equation for shear with TFA and M_{nl} based on DSM at local buckling for stiffened web channel sections

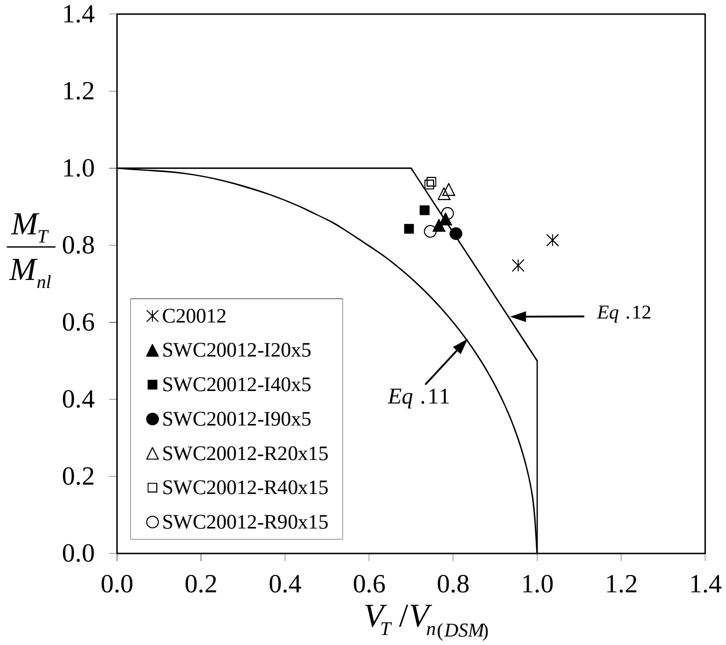


Figure 9: Interaction between (M_T/M_{nl}) and ($V_T/V_{n(DSM)}$)

Fig. 9 shows the interaction between (M_T/M_{nl}) and (V_T/V_n). It can be seen in Fig. 9 that the tests for SWC sections are no longer pure shear as for the plain sections. They lie around the bending and shear limits given by Eq. 12 but above Eq. 11 unit circular. The interaction between bending and shear for the SWC sections is therefore significant and Eq. 11 unit circle may be applicable to check in these cases although Eq. 12 may provide a mean fit. The failure mode of the SWC20012-I90x5 test under combined bending and shear can be observed in Fig. 6b with a local buckle in the flange as well as shear buckle in the web.

CONCLUSIONS

A predominantly shear test program on stiffened web channels was carried out to extend the newly developed DSM of design in shear. The test results were utilised to plot against the new DSM shear curves. For the stiffened web channel sections, by adding stiffeners, the shear strengths improve significantly with larger stiffener sizes. However, the test results (see Fig. 8) lie below the DSM shear curve with TFA. This fact may be explained by a significant increase in the shear capacity relative to the bending capacity so that combined bending and shear now becomes important. The interaction between bending and shear (see Fig. 9) is therefore significant for the SWC sections and the unit circle may be applicable to check in these cases although Eq. 12 may provide a mean fit. Although the DSM pure shear curve could not be validated directly due to combined bending and shear failures, the results validate the shear, and combined bending and shear methodology in the NAS S100:2012 Specification for the range of web stiffeners tested.

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