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Cold Formed Steel Flat Width Ratio Limits, d/t and d_i/w

Colin A. Rogers

R. M. Schuster

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COLD FORMED STEEL FLAT WIDTH RATIO LIMITS, d/t AND d_i/w

C.A. Rogers[1] and R.M. Schuster[2]

SUMMARY

This paper reports the findings of an investigation of the flat width ratio limit for simple edge-stiffeners of channels in bending. Willis & Wallace concluded that the lip flat width ratio limit, d/t, should have a value of 14 based on a comparison of the 1980 and 1986 editions of the American Iron and Steel Institute (AISI) Cold Formed Steel Specification. This conclusion was made using the results of only three channel beam tests with various lip sizes, Case III flanges and locally unstable webs. The CAN/CSA-S136 Technical Committee adopted the recommendations of Willis & Wallace and included the lip flat width ratio limit in the 1989 and 1994 S136 Standards.

A test program was initiated at the University of Waterloo to investigate the findings of Willis & Wallace. The investigation consisted of the testing and analysis of 44 C-section beams with Case I, II and III flanges, locally stable and unstable webs, and systematically varied lip depths. The d/t and d_i/w ratios of these C-sections were compared with the applied test moments and flange "Cases". The objectives of this study were to determine when the use of the existing d/t limit is required, if its current value is accurate, and whether it should remain in the next edition of the S136 Standard. Analysis of the Waterloo, as well as, the Willis & Wallace test data revealed that a d/t or d_i/w limit is not required in the S136 Standard.

1 INTRODUCTION

The most recent edition of the Canadian Cold Formed Steel Design Standard (S136-94)[1] contains a limiting flat width ratio for simple edge-stiffeners of d/t = 14. The maximum value of 14 recommended by Willis & Wallace[2] is based on the results of only three C-section purlins, placed into a conventional single span test apparatus and subjected to a uniformly distributed gravity load. Purlins with an edge-stiffener flat width ratio exceeding 14 experienced a decrease in their load carrying capacity. Similar behaviour of lipped C-sections in flexure was reported by Moreyra & Peköz[3]. All of the Willis & Wallace test C-sections have locally unstable webs, Case III flanges and constant section dimensions, except for the systematically varied compressive lip depths (see Table A1 and Figure A1 of the Appendix). The CAN/CSA-S136 Technical Committee included the d/t limit of 14 in Clause 5.6.2.3 (Table 6) of the S136 Standard, with the understanding that further testing would be completed to substantiate the findings of Willis & Wallace.

The existing d/t limit is based on a restricted number of beam tests which do not represent the entire range of possible web, flange and lip size combinations. The edge-stiffener flat width ratio

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[1] Ph.D. Research Student, School of Civil and Mining Engineering, University of Sydney, Australia
Former M.A.Sc. Research Student, Department of Civil Engineering, University of Waterloo, Canada
[2] Professor, Department of Civil Engineering, University of Waterloo, Canada

limit investigation presented in this paper consists of the analysis of 44 C-section beams with Case I, II and III flanges, locally stable and unstable webs, and systematically varied lip depths[4]. The *d/t* and d_l/w ratios of the experimental C-sections were compared with the applied test moments for nine test series. The recommendations and data presented by Willis & Wallace[2] were also reviewed and compared with the findings of this research.

2 PROBLEMS WITH CURRENT FLAT WIDTH RATIO, *d/t*, LIMIT

Willis & Wallace[2] define the parameters of their edge-stiffener limit as D_c, the out-to-out depth, and *t*, the thickness of the lip. A reduction in bending moment occurs at approximately D_c/t equal to 14, as seen in Figure 2. The S136 Standard[1] defines the limit as $d/t = 14$, where *d* is the flat width of the lip and *t* is the thickness. An adjustment must be made to the S136 Standard since the Willis & Wallace and S136 Standard limits are based on different definitions of the lip size (see Figure 1). Had Willis & Wallace used *d/t* values instead of D_c/t, the result would probably have been a limit of 12, as seen in Figure 3.

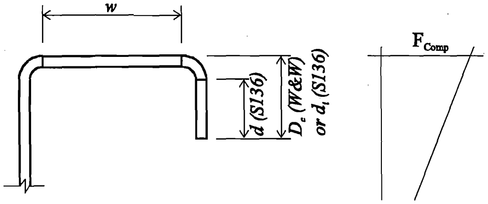

Figure 1 Lip Depth Dimension Comparison

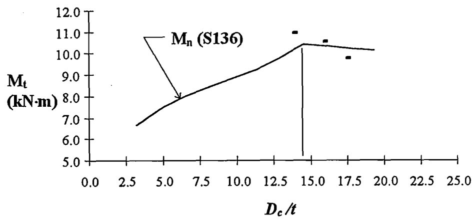

Figure 2 Willis & Wallace[2]
M_t vs. D_c/t Ratios

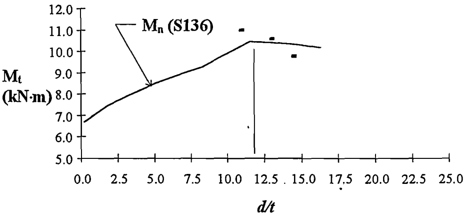

Figure 3 Willis & Wallace[2]
M_t vs. *d/t* Ratios

3 ALTERNATE FLAT WIDTH RATIO, d_l/w, LIMIT

It is also possible to define a limit based on the ratio of d_l/w (out-to-out lip depth / flange flat width). Willis & Wallace[2] suggest that a limiting value for D_c/w of 0.4 or 0.45 be used in place of the edge-stiffener flat width ratio limit. Desmond et al. state that *for D_s/w ratios larger than about .4, critical buckling is initiated solely by local plate buckling ... local instability of the edge stiffener interacts with the to-be-stiffened flange and initiates a premature local buckling of that element*[5] (where D_s is the out-to-out depth of the simple edge-stiffener). If the conclusions of both Desmond and Willis & Wallace are considered, a lip depth limit of $d_l/w = 0.4$ would apply (see Figure 4).

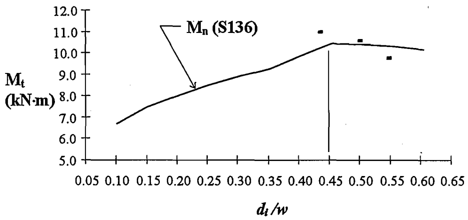

Figure 4 Willis & Wallace[2] M_t vs. d_l/w Ratios

4 WILLIS & WALLACE BENDING MOMENT RESISTANCE PREDICTABILITY

Willis & Wallace[2] also conclude that the then governing 1986 AISI Specification[6] over-predicts the flexural capacity of purlins with large simple edge-stiffeners. Comparison of the Willis & Wallace test data using the current North American Design Standards shows that the S136 Standard[1] adequately predicts the bending moment resistance of the three purlin sections. The test-to-predicted bending moment ratios range from 0.95 to 1.12, with a mean of 1.04, a standard deviation of 0.073, and a coefficient of variation of 0.121. Analysis using the current AISI Specification[7] results in an unconservative prediction of the bending moment resistance, with test-to-predicted ratios ranging from 0.86 to 1.01, a mean of 0.942, a standard deviation of 0.065, and a coefficient of variation of 0.120 (see Table A2 of the Appendix for individual test results). The existing *d/t* limit is not necessary since the decreasing bending moment resistance of the Willis & Wallace[2] test purlins can adequately be predicted using the S136 Standard[1].

5 BENDING MOMENT VS. LIP DIMENSION RATIO, WITH WATERLOO TEST DATA

A comparison study, similar to that completed by Willis & Wallace[2], was initiated at the University of Waterloo to determine the relationship between the tested bending moment resistance, M_t, (see Table A5 of the Appendix) and two lip dimension ratios, *d/t* and d_l/w (see Table A4 of the Appendix)[4]. The Waterloo test specimens were proportioned to cover the entire range of possible lip, flange, and web dimensions, since Willis & Wallace tested only C-purlin sections with locally unstable webs and Case III flanges. Specimens with Case I, II and III flanges, locally stable and unstable webs, and systematically varied compressive lip depths were tested. Nine series were separately examined by charting the M_t vs. *d/t* and M_t vs. d_l/w parameters. A direct comparison between these variables can be made because all section dimensions were held near constant within each test series, except for the compressive lip depth (see Table A3 of the Appendix).

WATERLOO TEST PROGRAM

The main objective of the experimental testing phase was to complete series of tests consisting of sections with locally stable webs, i.e., fully effective according to the S136 Standard[1], constant flange widths and systematically varied edge-stiffener depths[4]. These series were then repeated with sections that had increased web depths, resulting in locally unstable or partially effective webs according to the S136 Standard, and all other dimensions as per the previous series. Effective width analysis based on the North American Design Standards[1,7] requires that a "Case" (I, II or III) be determined from the flat width ratio of the compressive flange. The S136

Standard[1] and AISI Specification[7] differ in the procedure used to calculate the distribution of effective width for a web element subjected to a stress gradient. Various equations used to calculate the adequate moment of inertia of the supporting edge-stiffener and the flange plate buckling coefficient are dependent on this "Case" classification. Sections with Case I, II and III flanges are included, all of which have flat width ratios, *w/t*, within the specified limit of 60. Test specimens were also proportioned to cover the full range of dimensions allowed by the North American Design Standards, e.g., $h/t \leq 200$. A summary of the out-to-out dimensions and flat width ratios for all test specimens can be found in Tables A3 and A4 of the Appendix, with the corresponding cross-section given in Figure 5.

FABRICATION OF TEST SPECIMENS

All test specimens were constructed of two equally sized C-sections 1525mm in length with solid webs and edge-stiffeners at right angles to the flanges, except for sections in the C1-3 series which were 2134mm in length. Sections were brake formed by various cold formed steel fabricators and were placed facing each other in a box-beam arrangement, with a 75mm space separating the edge-stiffener components (see Figure 5). This configuration was used to create a symmetric section to avoid the shear centre eccentricity problem associated with C-sections. In construction, cold formed sections are typically braced on one or both flanges by sheathing, e.g., plywood, as well as, blocking or strapping between members to minimise the effect of shear eccentricity. Aluminum bracing angles (42 x 42 x 4mm) were secured to the flanges of the specimens with #12 self-drilling screws. Two bracing angles were located on the tensile and compressive flanges in the shear span of each test specimen. The compressive flange angles were spaced at 350mm and the tensile flange angles at 300mm to provide clearance of the support reaction beam as the specimen deflected under load. Bracing angles were not placed in the constant moment region to allow for the unrestrained movement of the C-sections under loading.

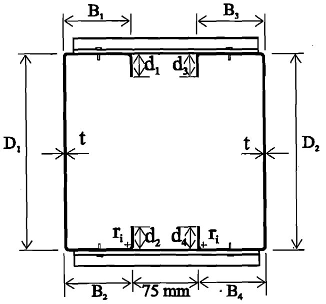

Figure 5 Typical Test Specimen Cross-Section[4]

MECHANICAL PROPERTIES OF TEST SPECIMENS

Tensile coupon tests were carried out in the Mechanical Engineering Materials Laboratory at the University of Waterloo. Coupons were cut from the web of each specimen and machined to size according to ASTM A370-92[8]. Galvanised coatings were removed prior to testing using an hydrochloric acid bath. Thickness, yield stress, ultimate tensile strength, and percent elongation, based on a 50mm gauge length, were determined from an average of four coupons per test series.

All steels were sharp yielding with yield strengths ranging from 302 MPa to 418 MPa. A summary of the material properties is given in Table A3 of the Appendix.

SET-UP OF TEST FRAME

The test specimens were simply supported (roller and pin) and subjected to a two point load as shown in Figures 6 and 7. A point load was applied to the spreader beam and then transferred by a roller and pin support system to the box-beam specimen. All loads and reactions were transferred by 75×14mm plates bolted to the webs of each specimen through pre-drilled holes. The plates were installed to avoid localised crippling of the webs at points of concentrated load. The shear spans of each test specimen were set at 500mm and the constant moment region at 420mm, except for the C3-1 series which had shear spans 800mm in length and a constant moment region 445mm in length. An increased beam length was used for the C3-1 series to allow for unrestricted displacement of the elements in each C-section.

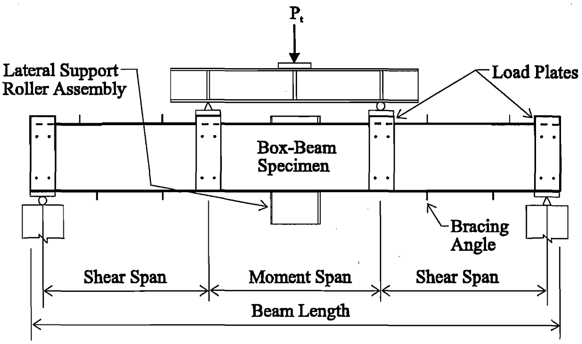

Figure 6 Test Frame Elevation[4]

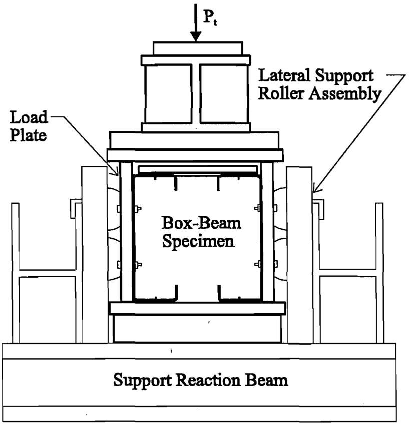

Figure 7 Test Frame Section[4]

Lateral support was provided at the midpoint of the specimens with a roller assembly placed on either side of the box-beam. Light-duty 152mm diameter gravity conveyor rollers were secured to a 500mm long C180 channel with corresponding attachment holes. Each assembly was supported by a WF hot rolled beam which was attached to the support reaction beams at either end of the test frame (see Figure 7).

TEST PROCEDURE

The box-beam specimens were placed in the test frame and carefully positioned and aligned. The reaction and test beams were shimmed level to allow for an even distribution of load through each C-section. A displacement transducer was placed at the centre position of the box-beam to record the maximum deflection, and the lateral support roller assemblies were secured to the supporting WF beams. Loading was applied at a constant rate under stroke control until failure occurred. The test loads were applied with an MTS 446 Electro-Hydraulic Servo Control System, having a 156kN capacity load cell. A load-deflection history was recorded for each test using a Hewlett-Packard 7046A X-Y plotter connected to a DC displacement transducer located at the centre of the moment span. Loads were displayed in volts with the maximum failure reading recorded with a voltmeter.

6 BENDING MOMENT VS. LIP DIMENSION RATIO COMPARISON

Graphs showing the bending moment to lip depth ratio relationship for the nine series are found in Figures 8 to 25. Included with each graph is a curve which represents the nominal bending moment resistance, M_n, as predicted for a typical section using the current S136 Standard[1]. A typical section is determined from the average dimensions of the C-sections within each series. The graphs give only an approximate value for the predicted bending moment resistance of the test beams, due to variations between the typical and actual C-sections. Accurate test-to-predicted bending moment ratios for each individual beam can be found in Table A5 of the Appendix.

CASE I FLANGE SERIES

Test series C1-1 gives no indication of a loss in bending moment resistance as the lip depth is increased up to 14mm (see Figures 8 and 9). The revised d/t limit of 12 is not exceeded, however all of the sections have d_i/w values near or above the alternate 0.4 limit. The bending moment resistance is adequately predicted for the sections in this series using cold work of forming. Without this allowable increase in yield strength, the nominal moment resistance is overly conservative (see Table A5 of the Appendix). Test series C1-2, consists of sections with locally unstable webs and also gives no indication of a loss in bending moment resistance as the lip depth is increased up to 14mm (see Figures 10 and 11). As in the C1-1 series, the revised d/t limit is not exceeded and all of the sections have d_i/w values near or above the alternate 0.4 limit. The bending moment resistance is unconservatively predicted by the S136 Standard[1] due to the distortional buckling mode of failure. Similarly, the final series, C1-3, with Case I flanges, does not exhibit a decrease in the bending moment resistance as the lip depth is increased up to approximately 19.5mm (see Figures 12 and 13). The revised d/t limit is not exceeded and all of the sections have d_i/w values above the alternate 0.4 limit. Local web buckling caused the predicted nominal moment values to be above the actual test results except for specimen C1-DW60-3. This section was restricted from buckling in the local web pattern by placing additional wooden blocks within the box-beam and as lateral support. All of the C-sections with Case I flanges exhibit an increase in bending moment resistance as the compressive lip depth is increased. The test sections do not violate the revised *d/t* limit of 12, although the alternate d_l/w limit of 0.4 is exceeded by nine of the specimens in these three series.

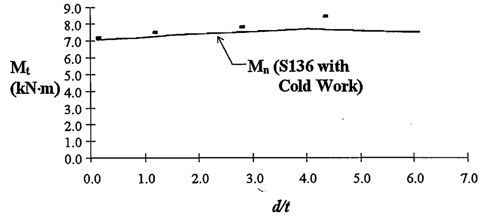

Figure 8 Series C1-1 M_t vs. *d/t* Ratios

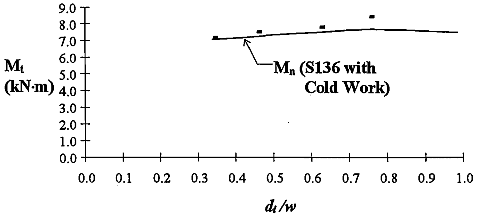

Figure 9 Series C1-1 M_t vs. d_l/w Ratios

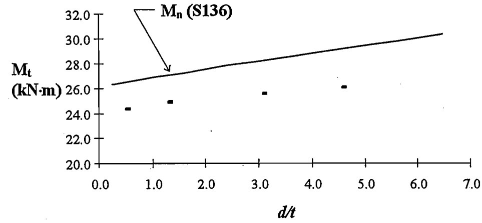

Figure 10 Series C1-2 M_t vs. *d/t* Ratios

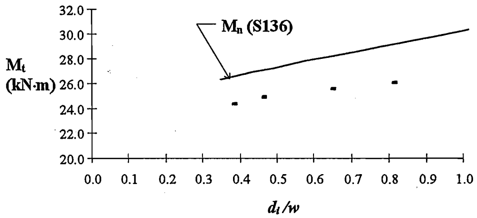

Figure 11 Series C1-2 M_t vs. d_l/w Ratios

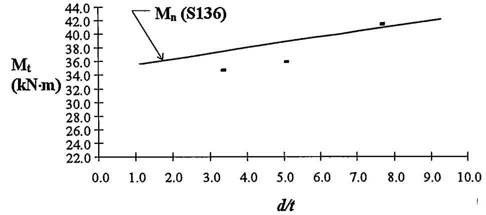

Figure 12 Series C1-3 M_t vs. *d/t* Ratios

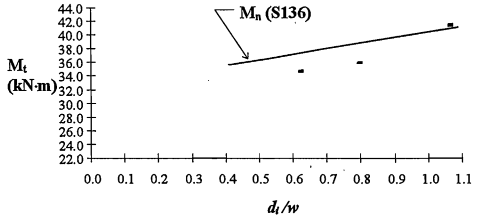

Figure 13 Series C1-3 M_t vs. d_l/w Ratios

CASE II FLANGE SERIES

The C-sections contained in the C2-2 and C2-4 series have flange flat width ratios slightly above the W_{lim1} limit. Hence, the bending moment resistance relative to lip depth ratio was predicted to be similar to the Case I flange sections. Series C2-2 consists of C-sections with locally stable webs and lip depths up to 24mm. The bending moment resistance does not decrease as the lip depth is gradually increased (see Figures 14 and 15). All of the sections have *d/t* ratios below the revised limit of 12 and five of the six sections have d_l/w values above the alternate 0.4 limit. The predicted nominal bending moment resistance is below the actual test results for all of the sections in the series. Cold work of forming can be used to more accurately calculate the bending moment resistance for four of the C-sections (see Table A5 of the Appendix). Series C2-

4 consists of beams with locally unstable webs and lip depths up to 24mm. The test results show an increasing trend in bending moment resistance as the lip depth is increased (see Figures 18 and 19). The specimen with a test moment greater than the predicted nominal value (C2-DW60-4) seems to reveal a decrease in the bending moment resistance. However, the general trend of this series is an increasing bending moment and the extreme moment value of this specimen can be attributed to scatter of test results. As in the previous Case II series, all of the sections have *d/t* ratios below the revised limit of 12 and five of the six sections have d_i */w* values above the alternate 0.4 limit. Bending moment resistance is adequately predicted using the S136 Standard[1] without cold work of forming. Whereas, for five of the sections where cold work of forming is applicable, the test-to-predicted bending moment ratios are unconservative (see Table A5 of the Appendix).

Series C2-3 and C2R-1 have flange flat width ratios near the W_{lim2} limit. Hence, the results of this analysis were predicted to be similar to that found for the Case III sections tested by Willis & Wallace[2]. Yet series C2R-1, which consists of sections with locally stable webs and lip depths up to 22.5mm, does not show the characteristic drop in bending moment resistance (see Figures 20 and 21). The revised *d/t* limit of 12 is surpassed by two of five sections and the d_i */w* limit of 0.4 is exceeded by four of five sections. The nominal bending moment curve accurately traces the behaviour of the test sections as the lip depth is increased. Series C2-3, which is made up of sections with locally unstable webs and lip depths up to approximately 27mm, exhibits an increasing trend in bending moment resistance except for the final beam in the series (C2-DW80-3) (see Figures 16 and 17). The maximum bending moment resistance occurs at approximately *d/t* =15 or d_i */w* = 0.7, with two of six sections above the revised *d/t* limit of 12 and five of six sections above the alternate d_i */w* limit of 0.4. The test bending moment resistance is adequately predicted using the S136 Standard[1].

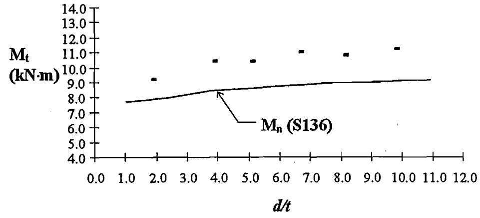

Figure 14 Series C2-2 M_t vs. *d/t* Ratios

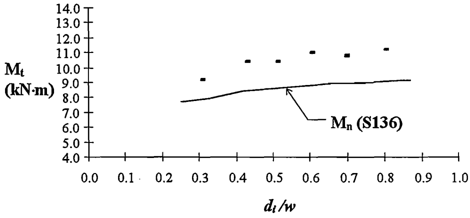

Figure 15 Series C2-2 M_t vs. d_l */w* Ratios

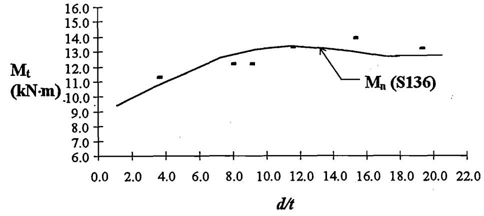

Figure 16 Series C2-3 M_t vs. *d/t* Ratios

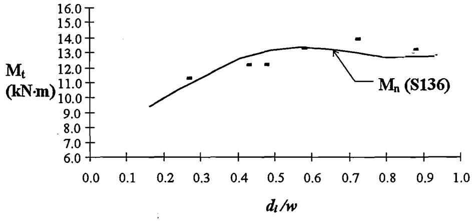

Figure 17 Series C2-3 M_t vs. d_l */w* Ratios

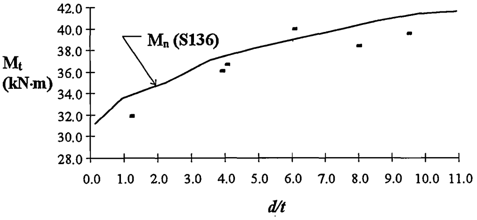

Figure 18 Series C2-4 M_t vs. *d/t* Ratios

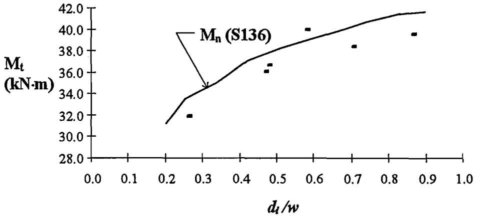

Figure 19 Series C2-4 M_t vs. d_i/w Ratios

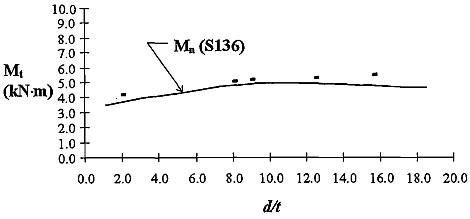

Figure 20 Series C2R-1 M_t vs. *d/t* Ratios

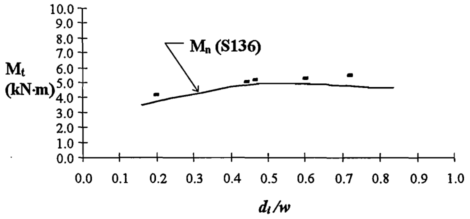

Figure 21 Series C2R-1 M_t vs. d_i/w Ratios

All of the C-sections with Case II flanges, except for specimen C2-DW80-3 exhibit an increase in bending moment resistance as the compressive lip depth is increased. Four of the test sections have *d/t* values greater than the revised limit of 12 and nineteen of the sections have d_i/w values greater than the alternate 0.4 limit.

CASE III FLANGE SERIES

Two series were tested with Case III flanges in order to obtain additional specimens similar to those used by Willis & Wallace[2]. Series C3-1 consists of C-sections with locally stable webs and lip depths up to 26mm. Series C3-2 consists of C-sections with locally unstable webs and lip depths up to approximately 36.8mm. The bending moment resistance of both series flattens as the depth of the compression lip is increased, rather than decreasing sharply as occurs with the Willis & Wallace data (see Figures 22 to 25). For the C3-1 series, the bending moment resistance levels at approximately *d/t* = 16 or d_i/w = 0.4, and for the C3-2 series levelling occurs at approximately

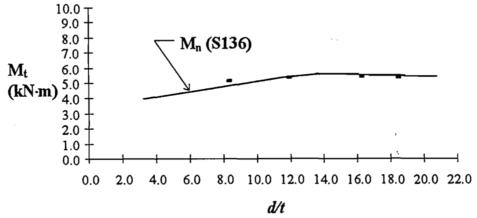

Figure 22 Series C3-1 M_t vs. *d/t* Ratios

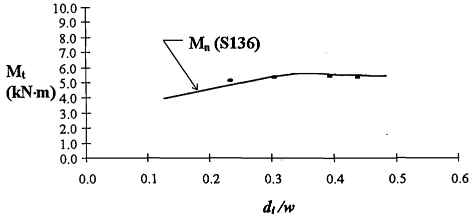

Figure 23 Series C3-1 M_t vs. d_i/w Ratios

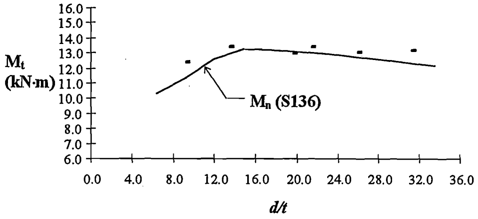

Figure 24 Series C3-2 M_t vs. d/t Ratios

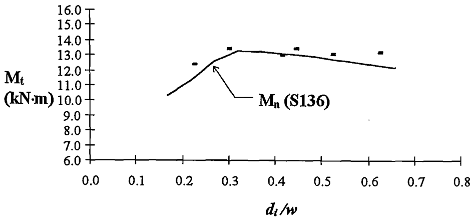

Figure 25 Series C3-2 M_t vs. d_i/w Ratios

$d/t = 20$ or $d_i/w = 0.4$. The S136 Standard[1] can be used to adequately predict the bending moment resistance for all sections in the Case III flange range.

The Case III sections included in this paper indicate that a levelling of the bending moment resistance appears at approximately $d_i/w = 0.4$. This result is in agreement with the previous conclusions given by Willis & Wallace[2], where the bending moment resistance decreases at approximately the same point. However, a conclusion can not be reached regarding a value for a flat width limit, d/t, of the simple edge-stiffener.

9 CONCLUSIONS

A comparison of the d/t and d_i/w ratios for a range of cold formed steel flexural test specimens with Case I, II and III flanges has been presented. Waterloo[4] test specimens in the Case I and II ranges do not exhibit a decrease in test bending moment as the lip depth is increased. Waterloo test specimens in the Case III range show a levelling trend in test bending moment as the lip depth is increased. Willis & Wallace[2] test specimens exhibit a drop in test bending moment as the lip depth is increased. However, test bending moments are accurately predicted using the current S136 Standard[1] for sections with lip depths greater than the $d/t = 14$ limiting flat width ratio. The use of a d/t or d_i/w limiting ratio for the edge-stiffener of sections in bending is not required based on the results of the Willis & Wallace and Waterloo studies.

ACKNOWLEDGEMENTS

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APPENDIX

Table A1 Willis & Wallace[2] Dimensions, Material Properties and Dimension Ratios

Specimen	d_1 mm	B_1 mm	D_1 mm	B_2 mm	d_2 mm	t mm	r_i mm	F_y MPa	h mm	h/t	w mm	w/t	d mm	d/t	d_i/w
1C2	27.0	58.8	203	58.8	27.0	1.55	3.10	372	194	125	49.5	31.9	22.4	14.4	0.546
1C3	24.6	58.8	203	58.8	27.8	1.55	3.10	372	194	125	49.5	31.9	20.0	12.9	0.498
1C4	21.4	58.8	203	58.8	27.8	1.55	3.10	372	194	125	49.5	31.9	16.8	10.8	0.433

Table A2 Willis & Wallace[2] M_T/M_P Ratios

		S136		AISI	
Specimen	M_T kN·m	M_P kN·m	M_T/M_P	M_P kN·m	M_T/M_P
1C2	9.78	10.3	0.95	11.4	0.86
1C3	10.6	10.4	1.02	11.5	0.92
1C4	11.0	10.2	1.08	11.3	0.97

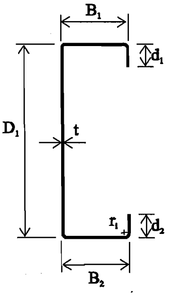

Figure A1 Willis & Wallace[2] Test Specimen Cross-Section

Table A3 Test Specimen Dimensions and Material Properties[4]

Specimen	d_1 mm	B_1 mm	D_1 mm	B_2 mm	d_2 mm	d_3 mm	B_3 mm	D_2 mm	B_4 mm	d_4 mm	t mm	r_i mm	F_y MPa	F_u MPa	% Elg.
C1-DW30-1	6.00	29.0	102	29.0	13.0	6.00	29.0	101	29.0	13.0	1.92	3.84	359	457	31.5
C1-DW40-1	8.00	29.0	102	29.0	13.0	8.00	29.0	102	29.0	13.0	1.92	3.84	359	457	31.5
C1-DW60-1	11.0	29.0	101	29.0	13.0	11.0	29.0	102	29.0	13.0	1.92	3.84	359	457	31.5
C1-DW80-1	14.0	30.0	102	30.0	14.0	14.0	30.0	102	30.0	14.0	1.92	3.84	359	457	31.5
C1-DW30-2	6.60	28.2	305	28.3	14.3	6.40	28.2	305	28.1	14.3	1.85	3.70	396	470	29.2
C1-DW40-2	7.90	28.3	298	28.4	14.2	8.00	28.4	305	28.4	14.3	1.85	3.70	396	470	29.2
C1-DW60-2	11.3	28.4	306	28.3	14.2	11.1	28.4	305	28.4	15.0	1.85	3.70	396	470	29.2
C1-DW80-2	14.0	28.4	305	28.3	14.3	14.0	28.4	305	28.2	14.3	1.85	3.70	396	470	29.2
C1-DW30-3	11.7	29.5	401	29.0	14.4	11.4	29.8	401	29.6	14.6	1.83	3.66	379	444	32.8
C1-DW40-3	14.5	29.4	401	29.8	14.5	14.9	29.6	401	29.7	14.0	1.83	3.66	379	444	32.8
C1-DW60-3	19.4	29.3	402	30.0	14.1	19.5	29.4	401	29.3	14.7	1.83	3.66	379	444	32.8
C2-DW25-2	9.20	41.2	99.0	40.9	26.4	9.00	41.0	99.0	41.3	26.6	1.87	3.73	386	492	30.6
C2-DW40-2	12.8	41.2	100	41.3	26.4	12.8	41.1	100	41.2	26.7	1.87	3.73	386	492	30.6
C2-DW50-2	15.2	40.8	99.3	41.1	26.3	15.0	41.0	99.8	41.1	26.5	1.87	3.73	386	492	30.6
C2-DW60-2	18.0	41.0	100	41.2	26.5	18.0	41.1	101	41.2	26.6	1.87	3.73	386	492	30.6
C2-DW70-2	20.7	40.9	100	41.0	26.7	20.7	41.0	99.9	41.0	26.8	1.87	3.73	386	492	30.6
C2-DW80-2	23.7	41.2	102	41.4	26.4	24.0	40.8	100	41.0	26.5	1.87	3.73	386	492	30.6
C2R-DW20-1	6.00	38.0	101	38.3	25.8	6.00	38.0	102	38.2	26.1	1.21	2.42	329	381	34.4
C2R-DW35-1	13.2	37.7	102	38.3	26.3	13.4	37.7	102	38.6	26.0	1.21	2.42	329	381	34.4
C2R-DW45-1	14.2	38.4	103	38.7	25.8	14.7	38.8	103	38.5	25.4	1.21	2.42	329	381	34.4
C2R-DW55-1	18.5	38.3	102	38.5	25.5	18.8	38.8	102	38.6	25.3	1.21	2.42	329	381	34.4
C2R-DW65-1	22.6	38.7	103	38.8	26.7	22.5	38.8	102	38.5	26.5	1.21	2.42	329	381	34.4
C2-DW20-3	8.00	37.6	241	38.0	27.1	8.10	37.7	242	37.9	25.7	1.21	2.43	326	369	38.8
C2-DW35-3	13.2	38.4	240	38.6	25.9	13.3	38.3	240	38.5	25.8	1.21	2.43	326	369	38.8
C2-DW45-3	14.8	38.0	241	37.9	25.7	14.4	38.0	241	38.1	26.1	1.21	2.43	326	369	38.8
C2-DW55-3	17.6	37.9	241	38.0	26.0	17.6	37.9	241	38.4	25.7	1.21	2.43	326	369	38.8
C2-DW65-3	22.1	37.8	242	37.8	25.8	22.0	37.8	241	37.8	25.8	1.21	2.43	326	369	38.8
C2-DW80-3	26.8	38.2	239	38.1	26.0	27.2	38.0	239	38.0	25.8	1.21	2.43	326	369	38.8
C2-DW25-4	7.90	42.7	301	42.3	26.2	8.40	42.9	300	42.2	25.6	1.90	3.81	418	457	31.5
C2-DW40-4	13.4	40.0	307	38.8	25.3	13.1	39.6	307	40.0	26.0	1.90	3.81	418	457	31.5
C2-DW50-4	13.6	39.9	305	40.0	25.8	13.7	40.8	305	40.0	26.0	1.90	3.81	418	515	27.2
C2-DW60-4	17.3	41.4	303	42.0	26.0	17.5	42.0	303	41.4	25.8	1.90	3.81	418	515	27.2
C2-DW70-4	21.1	41.5	305	41.3	25.0	21.1	41.7	305	41.5	24.5	1.90	3.81	418	515	27.2
C2-DW80-4	24.1	38.7	308	40.0	25.0	23.8	40.0	308	40.2	24.6	1.90	3.81	418	515	27.2
C3-DW20-1	13.5	65.6	98.0	66.4	25.8	13.5	65.7	99.0	66.0	25.9	1.20	2.40	302	372	39.6
C3-DW30-1	17.6	65.9	99.8	66.1	25.8	17.9	65.9	100	66.0	25.9	1.20	2.40	302	372	39.6
C3-DW35-1	23.0	66.0	102	66.2	25.8	23.1	66.2	102	66.1	25.7	1.20	2.40	302	372	39.6
C3-DW45-1	25.7	66.2	99.0	66.0	26.0	25.6	66.2	99.0	66.0	25.8	1.20	2.40	302	372	39.6
C3-DW20-2	13.1	65.6	244	65.4	26.0	13.2	65.4	244	65.4	25.8	1.07	2.13	341	381	37.1
C3-DW30-2	17.5	65.5	243	65.5	26.6	17.8	65.4	243	65.5	25.5	1.07	2.13	341	381	37.1
C3-DW35-2	24.5	65.4	240	64.2	25.8	24.3	65.6	240	64.2	25.4	1.08	2.16	332	372	36.8
C3-DW45-2	26.2	65.7	242	65.6	26.2	26.1	65.5	242	65.8	26.2	1.07	2.13	341	381	37.1
C3-DW50-2	31.0	65.7	240	65.5	25.7	30.8	65.7	240	65.5	25.9	1.07	2.13	341	381	37.1
C3-DW60-2	36.6	65.4	240	65.2	25.3	36.8	65.3	240	65.1	25.1	1.07	2.13	341	381	37.1

Note: Material properties are based on an average of four coupon tests per series.
Percent elongation is based on a 50mm gauge length.

Table A4 Test Specimen Dimension Ratios[4]

Specimen	h mm	h/t	w mm	w/t	d mm	d/t	d_i/w	Specimen	h mm	h/t	w mm	w/t	d mm	d/t	d_i/w
C1-DW30-1-A	90.5	47.1	17.5	9.10	0.24	0.12	0.343	C2-DW20-3-A	233	192	30.2	24.9	4.26	3.52	0.265
C1-DW30-1-B	89.5	46.6	17.5	9.10	0.24	0.12	0.343	C2-DW20-3-B	234	193	30.4	25.0	4.40	3.62	0.267
C1-DW40-1-A	90.5	47.1	17.5	9.10	2.24	1.16	0.458	C2-DW35-3-A	233	192	31.1	25.7	9.56	7.88	0.424
C1-DW40-1-B	90.5	47.1	17.5	9.10	2.24	1.16	0.458	C2-DW35-3-B	233	192	31.1	25.6	9.72	8.02	0.428
C1-DW60-1-A	89.5	46.6	17.5	9.12	5.29	2.75	0.628	C2-DW45-3-A	233	192	30.8	25.4	11.2	9.23	0.481
C1-DW60-1-B	90.5	47.1	17.6	9.17	5.39	2.80	0.624	C2-DW45-3-B	234	193	30.8	25.4	10.8	8.92	0.468
C1-DW80-1-A	90.5	47.1	18.5	9.64	8.29	4.31	0.756	C2-DW55-3-A	234	193	30.6	25.2	14.0	11.5	0.575
C1-DW80-1-B	90.5	47.1	18.6	9.67	8.34	4.34	0.754	C2-DW55-3-B	234	193	30.6	25.2	14.0	11.5	0.575
								C2-DW65-3-A	234	193	30.6	25.2	18.5	15.3	0.723
C1-DW30-2-A	294	159	17.1	9.26	1.06	0.57	0.386	C2-DW65-3-B	234	193	30.6	25.2	18.4	15.2	0.719
C1-DW30-2-B	294	159	17.1	9.26	0.86	0.46	0.374	C2-DW80-3-A	231	191	31.0	25.5	23.2	19.1	0.865
C1-DW40-2-A	287	155	17.2	9.31	2.36	1.27	0.459	C2-DW80-3-B	231	191	30.8	25.4	23.6	19.4	0.884
C1-DW40-2-B	294	159	17.3	9.37	2.46	1.33	0.462								
C1-DW60-2-A	294	159	17.4	9.39	5.80	3.14	0.651	C2-DW25-4-A	290	152	31.1	16.3	1.99	1.04	0.254
C1-DW60-2-B	293	159	17.3	9.37	5.56	3.01	0.641	C2-DW25-4-B	289	152	31.4	16.5	2.59	1.36	0.268
C1-DW80-2-A	294	159	17.3	9.37	8.46	4.58	0.809	C2-DW40-4-A	296	155	28.3	14.9	7.38	3.88	0.474
C1-DW80-2-B	294	159	17.3	9.34	8.41	4.55	0.811	C2-DW40-4-B	296	155	28.2	14.8	7.39	3.88	0.465
								C2-DW50-4-A	294	154	28.4	14.9	7.79	4.09	0.479
C1-DW30-3-A	390	213	18.5	10.1	6.21	3.39	0.632	C2-DW50-4-B	294	154	29.0	15.2	7.58	3.98	0.473
C1-DW30-3-B	390	213	18.8	10.3	5.91	3.23	0.606	C2-DW60-4-A	292	153	29.8	15.7	11.4	6.01	0.580
C1-DW40-3-A	390	213	18.4	10.1	9.01	4.92	0.787	C2-DW60-4-B	292	153	30.3	15.9	11.5	6.06	0.577
C1-DW40-3-B	390	213	18.6	10.2	9.41	5.14	0.800	C2-DW70-4-A	294	154	30.0	15.8	15.3	8.03	0.704
C1-DW60-3-A	391	214	18.3	10.0	13.9	7.60	1.059	C2-DW70-4-B	294	154	30.0	15.8	15.1	7.93	0.704
C1-DW60-3-B	390	213	18.4	10.1	14.0	7.66	1.059	C2-DW80-4-A	296	156	27.3	14.3	18.4	9.66	0.883
								C2-DW80-4-B	296	156	28.2	14.8	17.7	9.29	0.845
C2-DW25-2-A	87.8	47.1	30.0	16.1	3.60	1.93	0.307								
C2-DW25-2-B	87.8	47.1	29.8	16.0	3.40	1.83	0.302	C3-DW20-1-A	90.8	75.7	58.4	48.7	9.90	8.25	0.231
C2-DW40-2-A	88.8	47.6	30.0	16.1	7.20	3.86	0.427	C3-DW20-1-B	91.8	76.5	58.5	48.7	9.90	8.25	0.231
C2-DW40-2-B	89.0	47.7	29.9	16.0	7.20	3.86	0.428	C3-DW30-1-A	92.6	77.2	58.7	48.9	14.0	11.7	0.300
C2-DW50-2-A	88.1	47.2	29.6	15.9	9.60	5.15	0.513	C3-DW30-1-B	93.1	77.6	58.7	48.9	14.3	11.9	0.305
C2-DW50-2-B	88.6	47.5	29.8	16.0	9.40	5.04	0.503	C3-DW35-1-A	94.6	78.8	58.8	49.0	19.4	16.2	0.391
C2-DW60-2-A	89.1	47.8	29.8	16.0	12.4	6.65	0.604	C3-DW35-1-B	94.6	78.8	59.0	49.2	19.5	16.2	0.392
C2-DW60-2-B	89.3	47.9	29.9	16.0	12.4	6.65	0.602	C3-DW45-1-A	91.8	76.5	59.0	49.2	22.1	18.4	0.436
C2-DW70-2-A	88.8	47.6	29.7	15.9	15.1	8.10	0.697	C3-DW45-1-B	91.8	76.5	59.0	49.2	22.0	18.3	0.434
C2-DW70-2-B	88.7	47.6	29.8	16.0	15.1	8.10	0.694								
C2-DW80-2-A	90.3	48.4	30.0	16.1	18.1	9.71	0.790	C3-DW20-2-A	238	223	59.0	55.4	9.73	9.13	0.222
C2-DW80-2-B	89.0	47.7	29.6	15.9	18.4	9.87	0.811	C3-DW20-2-B	238	223	59.0	55.4	10.0	9.38	0.224
								C3-DW30-2-A	237	222	59.0	55.4	14.2	13.4	0.296
C2R-DW20-1-A	93.9	77.7	30.8	25.5	2.38	1.97	0.195	C3-DW30-2-B	237	222	58.9	55.2	14.5	13.6	0.302
C2R-DW20-1-B	94.3	78.0	30.8	25.5	2.38	1.97	0.195	C3-DW35-2-A	234	216	58.9	54.5	21.2	19.7	0.416
C2R-DW35-1-A	94.6	78.3	30.5	25.2	9.58	7.93	0.433	C3-DW35-2-B	234	216	59.1	54.8	21.1	19.5	0.411
C2R-DW35-1-B	94.3	78.0	30.5	25.2	9.78	8.09	0.440	C3-DW45-2-A	236	221	59.3	55.6	23.0	21.6	0.442
C2R-DW45-1-A	95.8	79.3	31.2	25.8	10.6	8.75	0.456	C3-DW45-2-B	235	221	59.0	55.3	22.8	21.4	0.442
C2R-DW45-1-B	95.8	79.3	31.6	26.1	11.1	9.17	0.466	C3-DW50-2-A	234	219	59.2	55.5	27.7	26.0	0.524
C2R-DW55-1-A	94.7	78.4	31.1	25.7	14.9	12.3	0.596	C3-DW50-2-B	234	219	59.3	55.6	27.6	25.9	0.520
C2R-DW55-1-B	94.6	78.3	31.6	26.1	15.2	12.6	0.596	C3-DW60-2-A	233	219	58.9	55.2	33.3	31.2	0.621
C2R-DW65-1-A	95.4	78.9	31.5	26.0	19.0	15.7	0.719	C3-DW60-2-B	234	219	58.7	55.1	33.4	31.3	0.627
C2R-DW65-1-B	94.6	78.3	31.6	26.1	18.9	15.6	0.713								

Table A5 Test Specimen M_T/M_P Ratios[4]

		S136		S136*		AISI		AISI*	
Specimen	M_T kN·m	M_P kN·m	M_T/M_P	M_P kN·m	M_T/M_P	M_P kN·m	M_T/M_P	M_P kN·m	M_T/M_P
C1-DW30-1	7.17	6.03	1.19	7.00	1.03	6.03	1.19	7.14	1.00
C1-DW40-1	7.48	6.25	1.20	7.25	1.03	6.25	1.20	7.40	1.01
C1-DW60-1	7.83	6.44	1.22	7.47	1.05	6.44	1.22	7.62	1.03
C1-DW80-1	8.43	6.84	1.23	7.90	1.07	6.84	1.23	8.06	1.05
C1-DW30-2	24.3	26.6	0.91	28.9	0.84	29.4	0.83	32.0	0.76
C1-DW40-2	24.9	26.8	0.93	29.2	0.85	29.8	0.84	32.4	0.77
C1-DW60-2	25.6	28.4	0.90	30.9	0.83	31.5	0.81	34.3	0.75
C1-DW80-2	26.1	29.3	0.89	31.9	0.82	32.7	0.80	35.6	0.73
C1-DW30-3	34.7	37.5	0.93	40.3	0.86	39.6	0.88	42.8	0.81
C1-DW40-3	35.9	38.8	0.93	41.8	0.86	41.0	0.88	44.5	0.81
C1-DW60-3	41.4	40.8	1.01	44.0	0.94	43.3	0.96	47.0	0.88
C2R-DW20-1	4.16	3.64	1.14	3.64	1.14	3.71	1.12	3.71	1.12
C2R-DW35-1	5.05	4.77	1.06	4.93	1.02	4.78	1.06	5.03	1.00
C2R-DW45-1	5.22	4.97	1.05	5.18	1.01	4.97	1.05	5.25	0.99
C2R-DW55-1	5.26	4.93	1.07	4.93	1.07	4.92	1.07	4.92	1.07
C2R-DW65-1	5.49	4.81	1.14	4.81	1.14	4.82	1.14	4.82	1.14
C2-DW25-2	9.21	7.75	1.19	7.75	1.19	7.75	1.19	8.75	1.05
C2-DW40-2	10.4	8.45	1.23	8.85	1.18	8.45	1.23	9.41	1.11
C2-DW50-2	10.4	8.51	1.22	9.50	1.10	8.51	1.22	9.64	1.08
C2-DW60-2	11.0	8.81	1.24	9.83	1.12	8.81	1.24	9.97	1.10
C2-DW70-2	10.8	8.89	1.22	9.91	1.09	8.89	1.22	10.1	1.08
C2-DW80-2	11.2	9.16	1.23	9.96	1.13	9.16	1.23	9.85	1.14
C2-DW20-3	11.3	10.8	1.04	10.8	1.04	11.4	0.99	11.4	0.99
C2-DW35-3	12.2	12.9	0.94	13.0	0.94	13.7	0.89	14.1	0.87
C2-DW45-3	12.2	13.1	0.93	13.6	0.90	13.9	0.88	14.4	0.85
C2-DW55-3	13.3	13.4	0.99	13.4	0.99	14.2	0.94	14.2	0.94
C2-DW65-3	13.9	13.1	1.06	13.1	1.06	13.8	1.00	13.8	1.00
C2-DW80-3	13.2	12.6	1.05	12.6	1.05	13.4	0.99	13.4	0.99
C2-DW25-4	31.9	33.9	0.94	33.9	0.94	36.6	0.87	36.6	0.87
C2-DW40-4	36.1	37.3	0.97	40.6	0.89	40.6	0.89	44.1	0.82
C2-DW50-4	36.7	37.5	0.98	40.7	0.90	40.8	0.90	44.3	0.83
C2-DW60-4	40.0	39.2	1.02	42.5	0.94	42.8	0.94	46.4	0.86
C2-DW70-4	38.4	40.8	0.94	44.2	0.87	44.5	0.86	48.3	0.80
C2-DW80-4	39.6	41.0	0.97	41.0	0.97	44.9	0.88	44.9	0.88
C3-DW20-1	5.14	4.67	1.10	4.67	1.10	4.69	1.10	4.69	1.10
C3-DW30-1	5.37	5.38	1.00	5.38	1.00	5.37	1.00	5.37	1.00
C3-DW35-1	5.43	5.60	0.97	5.60	0.97	5.61	0.97	5.61	0.97
C3-DW45-1	5.37	5.36	1.00	5.36	1.00	5.36	1.00	5.36	1.00
C3-DW20-2	12.4	11.5	1.08	11.5	1.08	11.8	1.05	11.8	1.05
C3-DW30-2	13.4	13.4	1.00	13.4	1.00	13.8	0.97	13.8	0.97
C3-DW35-2	13.0	13.1	0.99	13.1	0.99	13.5	0.96	13.5	0.96
C3-DW45-2	13.4	13.1	1.02	13.1	1.02	13.4	1.00	13.4	1.00
C3-DW50-2	13.1	12.7	1.03	12.7	1.03	13.0	1.00	13.0	1.00
C3-DW60-2	13.2	12.3	1.07	12.3	1.07	12.6	1.05	12.6	1.05

Note: * Cold work of forming used.