Effective Width of a Simple Edge-stiffener Subjected to a Stress Gradient

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SUMMARY

The most recent editions of the North American Design Standards present a unified effective width approach for the design of compressive elements. This paper outlines a comparison of various modifications to the existing procedure used to calculate the effective width of a simple edge-stiffener subjected to a stress gradient. The comparison involves three methods where the magnitude of the compressive stress is altered, and two stress gradient methods where the plate bucking coefficient is based on the ratio of compressive stresses at the top and bottom of the flat width of the simple edge-stiffener. Analysis of these methods was carried out using specimens tested at the University of Waterloo and data available in the literature. Results of the comparison indicate that the variation in statistical values between the five effective width methods is marginal. Therefore, it is recommended that the current procedures used to calculate the effective width of simple edge-stiffeners subjected to a stress gradient remain unchanged in the North American Design Standards.

1 INTRODUCTION

The latest editions of the North American Design Standards[1,2] present a unified effective width approach where all compressive elements are analysed using the basic effective width expression, with plate buckling coefficients that reflect the actual boundary conditions. Although a simple edge-stiffener of a section in bending is under a stress gradient, current Standards specify that this type of element be designed assuming a uniform compressive stress. The present method used to determine the effective width of a simple edge-stiffener is given by Pekӧz[3], as well as, the S136[4] and AISI[5] Commentaries. The objective of this work was to refine the procedure used to calculate the effective width of a simple edge-stiffener subjected to a stress gradient. This objective was accomplished by using the results of C-section tests carried out at the University of Waterloo[6], and applicable available data found in the literature[7,8,9,10]. The existing procedure which is used to calculate the effective width of an edge-stiffener subjected to a stress gradient was refined by comparing various plate buckling coefficient methods and magnitudes of the compressive stress. The most accurate method was determined by statistically comparing the test-to-predicted bending moment ratios of the applicable test specimens.

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2 Simple Edge-Stiffeners Subjected to a Stress Gradient

In cross-sections subjected to bending, where the edge-stiffener (lip) is of a simple shape, i.e., without stiffeners of its own, the buckling coefficient is given as 0.43 in the North American Design Standards[1,2]. The actual stress is assumed to be uniform at the maximum compressed position of the lip, i.e., at the top of the flat width (see f_3 in Figure 1). Peköz[3] recommends that this simplified conservative approximation be used since there is a lack of experimental data regarding edge-stiffener behaviour under a stress gradient.

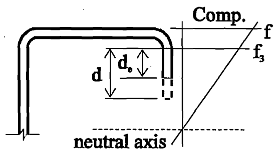

Figure 1 - Unstiffened Element Subjected to a Stress Gradient

Equations for the buckling coefficient of an unstiffened element subjected to a stress gradient have been formulated by Kollbrunner and Meister[11], Thomasson[12] and Cohen[13]. These researchers define the plate buckling coefficient, k, based on a ratio of compressive stresses at the top and bottom of the flat width of a simple edge-stiffener.

3 S136 Effective Width of Compressed Simple Edge-Stiffeners

The flat width of a simple edge-stiffener, d, is calculated as the out-to-out width of the lip, d_i, minus the thickness, and minus the inside bend radius. The flat width ratio, d/t, has a limit of 14 as given in Clause 5.6.2.3 of the S136 Standard[1]. The plate buckling coefficient, k, equals 0.43 and the lip is assumed to be subjected to a uniform compressive stress, f_3, which is located at the top of the flat width (see Figure 1). The limiting flat width ratio, W_{lim}, is calculated and compared with the flat width ratio of the lip, d/t.

$$W_{lim} = 0.644\sqrt{kE/f} \quad \text{with } f = f_3 \text{ and } k = 0.43 \tag{1}$$

If the limiting flat width ratio is exceeded, i.e., $d/t > W_{lim}$, then the lip must be reduced in width according to the basic effective width equation.

$$d_e = 0.95t\sqrt{\frac{kE}{f}}\left[1 - 0.208\frac{t}{d}\sqrt{\frac{kE}{f}}\right] \tag{2}$$

Where d_e is the effective width of the lip, which may be further reduced if the lip does not have an adequate moment of inertia to support the flange. Inadequately stiffened elements typically fail in the distortional mode with both the flange element and the edge-stiffener buckling out-of-plane at about the same time. If the flange element is inadequately stiffened, i.e., $I_r < 1$, then the effective width of the lip is represented by d_r where $d_r = d_e \cdot I_r$.

4 Plate Buckling Coefficient - Stress Gradient Approaches

Five methods were used to determine the nominal moment resistance of the applicable test sections. The first three methods alter the magnitude of the compressive stress (see Figure 2) and keep the plate buckling coefficient constant (k=0.43). The f_3 position refers to the maximum compressive stress in the element, which is specified in the current S136 Standard[1]. The f_5 position refers to the third point compressive stress and the f_6 position refers to the mid-point compressive stress. The final two methods involve the calculation of a plate buckling coefficient, k, which is dependent on the ratio of stresses f_3 and f_4. For these two procedures the compressive stress, f_3, is kept constant in the characteristic stress function.

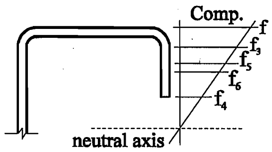

Figure 2 - Edge-Stiffener Stress Position Comparison

The initial stress gradient method, recommended by Cohen[13], is formulated as follows,

$$\psi = \frac{f_3}{f_4}, \tag{3}$$

$$k = \frac{1.70}{1 + 3/\psi}, \tag{4}$$

where $0.43 \leq k \leq 1.70$.

Another version of the previous stress gradient approach is contained in the Eurocode 3 Standard[14], under Clause A3.3 - Singly Supported Elements Case IIa., where the plate buckling coefficient is calculated as given in Eqs. 5 and 6.

$$\psi = \frac{f_4}{f_3} \tag{5}$$

$$k = \frac{0.578}{\psi + 0.34} \tag{6}$$

The Eurocode[14] stress gradient method uses the inverse ratio of the compressive stresses but otherwise yields the same results as Cohen's[13] formulation, hence, it can be considered equivalent for this paper. These plate buckling equations are valid only when the edge-stiffener remains in compression over its entire length, i.e., $0 \leq \psi \leq 1$, and $0.43 \leq k \leq 1.70$.

The ISO Standard[15] presents the stress gradient approach for simple edge-stiffeners under Clause 3.2.2 case IIa., where the plate bucking coefficient is determined as follows,

$$Q = \frac{f_4}{f_3}, \tag{7}$$

$$k = \frac{1.967}{1 + 3Q}, \tag{8}$$

where both f_3 and f_4 are compressive stresses ($f_4 \leq f_3$) and the plate buckling coefficient is in the following range; $0.43 \leq k \leq 1.70$.

All other components of the analysis are based on the effective moment resistance method specified in the S136 Standard[1]. A comparison of the effective width modifications was completed by analysing the resulting test-to-predicted bending moment ratios of the applicable test sections. An attempt to isolate the contribution of the simple edge-stiffener to the bending moment resistance was made by using test beams which have locally stable webs, i.e., fully effective, according to the S136 Standard[1]. Cold formed sections tested by other researchers were used only when the web element was found to be fully effective. However, C-sections tested at the University of Waterloo[6] were considered applicable when the web element was greater than 90% effective.

5 COMPARISON WITH WATERLOO TEST DATA

The Waterloo[6] Case I flange specimens, C1-1, are fully effective at their yield stress, hence, cold work of forming was applied for the moment resistance calculations. The existing unified effective width formulation accurately predicts the moment resistance of the C-sections, as do all other stress gradient methods (see Table 1 and Table A.2 of the Appendix). The plate buckling coefficients range from 0.430 to 0.570 using the ISO[15] and Cohen/Eurocode [13,14] stress gradient expressions (see Table 2).

The C2-1 specimens are subject to local buckling of the flange and/or edge-stiffener, hence, cold work of forming was not applied. The ISO[15] and Cohen/Eurocode[13,14] stress gradient methods closely predict the moment resistance of the sections as does the existing S136[1] method (see Table 1 and Table A.2 of the Appendix). The plate buckling coefficients range from 0.430 to 0.699 (see Table 2).

The results of test series C2R are summarised in Table 1 and Table A.2 of the Appendix. Again, the five stress gradient methods result in similar test-to-predicted bending moment ratios, and the plate buckling coefficients range from 0.430 to 0.693 (see Table 2).

Test series C2-2 also contains sections which are fully effective. Specimen DW25 does not utilise cold work of forming properties since the edge-stiffener and/or flange is partially effective at the yield stress. The five gradient methods yield the same test-to-predicted ratios for all of the specimens in this series (see Table 1 and Table A.2 of the Appendix). The plate buckling coefficients range from 0.430 to 0.711 (see Table 2).

Test series four, C3, can be accurately predicted by the five gradient methods (see Table 1 and Table A.2 of the Appendix). The existing S136[1] method, as well as, the Cohen/Eurocode[13,14] and the ISO[15] methods result in near similar test-to-predicted bending moment ratios. The plate buckling coefficients range from 0.430 to 0.738 (see Table 2).

Overall, the Waterloo test specimens are accurately predicted by all five of the stress gradient methods. Mean, standard deviation and coefficient of variation values show no indication of an advantage to revising the current S136 Standard[1] procedure used to calculate the effective width of a simple edge-stiffener subject to a stress gradient (see Table 1 and Table A.2 of the Appendix).

Table 1 - Statistical Comparison of M_T/M_P Ratios

Method	Mean	S. D.	C.o.V.	Method	Mean	S. D.	C.o.V.
$S136_1$	1.12	0.094	0.087	$S136_1$*	1.07	0.065	0.063
$S136_2$	1.12	0.095	0.089	$S136_2$*	1.07	0.065	0.064
$S136_3$	1.12	0.095	0.088	$S136_3$*	1.07	0.065	0.063
$S136_4$	1.12	0.096	0.090	$S136_4$*	1.07	0.065	0.064
$S136_5$	1.12	0.097	0.090	$S136_5$*	1.07	0.066	0.064

Table 2 - Plate Buckling Coefficient Values, k

Specimen	$k_{1,2,3}$	k_4	k_5	Specimen	$k_{1,2,3}$	k_4	k_5
C1-DW30-1-A	0.430	0.430	0.494	C2R-DW55-1-A	0.430	0.552	0.638
C1-DW30-1-B	0.430	0.430	0.494	C2R-DW55-1-B	0.430	0.555	0.643
C1-DW40-1-A	0.430	0.441	0.510	C2R-DW65-1-A	0.430	0.597	0.691
C1-DW40-1-B	0.430	0.441	0.510	C2R-DW65-1-B	0.430	0.598	0.693
C1-DW60-1-A	0.430	0.465	0.539				
C1-DW60-1-B	0.430	0.465	0.538	C2-DW25-2-A	0.430	0.451	0.522
C1-DW80-1-A	0.430	0.492	0.570	C2-DW25-2-B	0.430	0.449	0.520
C1-DW80-1-B	0.430	0.492	0.570	C2-DW40-2-A	0.430	0.481	0.557
				C2-DW40-2-B	0.430	0.481	0.556
C2-DW20-1-A	0.430	0.447	0.517	C2-DW50-2-A	0.430	0.505	0.584
C2-DW20-1-B	0.430	0.444	0.513	C2-DW50-2-B	0.430	0.502	0.581
C2-DW35-1-A	0.430	0.495	0.573	C2-DW60-2-A	0.430	0.534	0.617
C2-DW35-1-B	0.430	0.495	0.573	C2-DW60-2-B	0.430	0.533	0.617
C2-DW45-1-A	0.430	0.521	0.602	C2-DW70-2-A	0.430	0.567	0.656
C2-DW45-1-B	0.430	0.515	0.596	C2-DW70-2-B	0.430	0.568	0.657
C2-DW55-1-A	0.430	0.551	0.638	C2-DW80-2-A	0.430	0.606	0.701
C2-DW55-1-B	0.430	0.551	0.638	C2-DW80-2-B	0.430	0.614	0.711
C2-DW65-1-A	0.430	0.602	0.698				
C2-DW65-1-B	0.430	0.604	0.699	C3-DW20-1-A	0.430	0.495	0.573
				C3-DW20-1-B	0.430	0.495	0.572
C2R-DW20-1-A	0.430	0.440	0.509	C3-DW30-1-A	0.430	0.536	0.620
C2R-DW20-1-B	0.430	0.439	0.508	C3-DW30-1-B	0.430	0.539	0.623
C2R-DW35-1-A	0.430	0.497	0.575	C3-DW35-1-A	0.430	0.595	0.689
C2R-DW35-1-B	0.430	0.499	0.578	C3-DW35-1-B	0.430	0.596	0.690
C2R-DW45-1-A	0.430	0.506	0.585	C3-DW45-1-A	0.430	0.639	0.740
C2R-DW45-1-B	0.430	0.511	0.591	C3-DW45-1-B	0.430	0.637	0.738

Note: ** Cold work of forming used.*
1) S136 uniform compressive stress at the top of the flat width (Current).
2) S136 uniform compressive stress at the mid-point of the flat width.
3) S136 uniform compressive stress at the third point of the flat width.
4) Cohen/Eurocode stress gradient.
5) ISO stress gradient.

6 COMPARISON WITH AVAILABLE TEST DATA

A limited number of available test specimens have web elements that are fully effective and are included in this paper. These consist of all four C-sections from Desmond et al.[7], test B-10-1 from LaBoube & Yu[8], tests 2G,16,1&2(N) and 2G,16,3&4(N) from Shan et al.[9], and specimens B2 and B4 to B10 from Winter[10]. The resulting test-to-predicted bending moment ratios and plate buckling coefficients are summarised in Tables 3 and 4, as well as, Table A.3 of the Appendix.

The test-to-predicted bending moment ratios for test section E-45.6B-4 from Desmond et al.[7] range from 1.10 for the existing S136[1] method to 1.07 for the ISO[15] method (see Table A.3 of the Appendix). All other sections exhibit a smaller range in test-to-predicted bending moment ratios between the various stress gradient methods. Plate buckling coefficients range from 0.489 to 0.726 for the Cohen/Eurocode[13,14] method and from 0.566 to 0.842 for the ISO method (see Table 4).

The single applicable section from LaBoube & Yu[8] has a consistent test-to-predicted bending moment ratio of 1.06 for all five simple edge-stiffener effective width methods (see Table

A.3 of the Appendix). The plate buckling coefficients are approximately 0.518 for the Cohen/Eurocode[13,14] method and 0.600 for the ISO[15] method (see Table 4).

The two test sections from Shan et al.[9] also show constant test-to-predicted bending moment ratios for each of the stress gradient methods (see Table A.3 of the Appendix). The plate buckling coefficients range from 0.529 to 0.561 for the Cohen/Eurocode[13,14] method and from 0.612 to 0.649 for the ISO[15] method (see Table 4).

The eight applicable C-sections from Winter[10] produce test-to-predicted bending moment ratios which range from 1.00 to 1.14 (see Table A.3 of the Appendix). This range of values remains constant for each of the stress gradient methods. The plate buckling coefficients range from 0.466 to 0.564 for the Cohen/Eurocode[13,14] method and from 0.540 to 0.652 for the ISO[15] method (see Table 4).

As found with the Waterloo[6] test data, all of the stress gradient methods can be used to accurately predict the bending moment resistance of the applicable available test specimens[7,8,9,10]. Mean, standard deviation, and coefficient of variation values show no indication of an advantage to revising the current S136[1] procedure used to calculate the effective width of a simple edge-stiffener subject to a stress gradient (see Table 3).

Table 3 - Statistical Comparison of M_T/M_P Ratios

Method	Mean	S. D.	C.o.V.
$S136_1$	1.10	0.059	0.058
$S136_2$	1.09	0.059	0.058
$S136_3$	1.09	0.059	0.058
$S136_4$	1.09	0.059	0.059
$S136_5$	1.09	0.060	0.059

Table 4 - Plate Buckling Coefficient Values, k

Specimen	$k_{1,2,3}$	k_4	k_5	Specimen	$k_{1,2,3}$	k_4	k_5
Desmond et al.[7]				LaBoube & Yu[8]			
E-45.6B-1	0.430	0.489	0.566	B-10-1a	0.430	0.517	0.599
E-45.6B-2	0.430	0.515	0.595	B-10-1b	0.430	0.518	0.600
E-45.6B-3	0.430	0.623	0.722				
E-45.6B-4	0.430	0.726	0.842	Winter[10]			
				B2	0.430	0.509	0.589
Shan et al.[9]				B4	0.430	0.466	0.540
2G,16,1&2(N)_A	0.430	0.529	0.612	B5	0.430	0.516	0.597
2G,16,1&2(N)_B	0.430	0.529	0.612	B6	0.430	0.475	0.550
2G,16,3&4(N)_A	0.430	0.561	0.649	B7	0.430	0.564	0.652
2G,16,3&4(N)_B	0.430	0.534	0.618	B8	0.430	0.504	0.584
				B9	0.430	0.480	0.556
				B10	0.430	0.549	0.635

Note: *1) S136 uniform compressive stress at the top of the flat width (Current).*
2) S136 uniform compressive stress at the mid-point of the flat width.
3) S136 uniform compressive stress at the third point of the flat width.
4) Cohen/Eurocode stress gradient.
5) ISO stress gradient.

7 CONCLUSIONS

The S136 Standard[1] and AISI Specification[2] require that a simple edge-stiffener subjected to a stress gradient be treated as a uniformly compressed element subjected to a maximum stress, with the plate buckling coefficient, k, set at 0.43. Modifications to the current effective width procedure involving three methods where the magnitude of the compressive stress is altered were compared. Two stress gradient approaches (Cohen/Eurocode[13,14] and ISO[15]) where the plate bucking coefficient is based on the ratio of compressive stresses at the top and bottom of the flat width were also included. Analysis of test-to-predicted bending moment results indicate that the variation in statistical values between the five effective width methods is marginal. Therefore, it is recommended that the current effective width procedures for simple edge-stiffeners subjected to a stress gradient remain unchanged in the North American Design Standards.

ACKNOWLEDGEMENTS

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REFERENCES

1) S136-94, "Cold Formed Steel Structural Members", Canadian Standards Association, Rexdale (Toronto), Ontario, Canada, 1994.
2) American Iron and Steel Institute, "Specification for the Design of Cold-Formed Steel Structural Members", August 19, 1986 Edition with December 11, 1989 Addendum, Washington D.C., USA, 1989.
3) Peköz, T., "Development of a Unified Approach to the Design of Cold-Formed Steel Members", Report to the Advisory Group on the Specification for the Design of Cold-Formed Steel Structural Members, AISI, Report CF 87-1, March 1987.
4) S136.1-95, "Commentary on CSA Standard S136-94, Cold Formed Steel Structural Members", Canadian Standards Association, Rexdale (Toronto), Ontario, Canada, 1995.
5) American Iron and Steel Institute, "Commentary on the Specification for the Design of Cold-Formed Steel Structural Members", August 19, 1986 Edition with December 11, 1989 Addendum, Washington D.C., USA, 1989.
6) Rogers, C.A., "Local and Distortional Buckling of Cold Formed Steel Channel and Zed Sections in Bending", M.A.Sc. Thesis presented to the Department of Civil Engineering, University of Waterloo, Waterloo Ontario, May, 1995.
7) Desmond, T.P., Peköz, T., Winter, G., "Edge Stiffeners for Thin Walled Members", Journal of the Structural Division, ASCE, Vol. 107, No. ST2, February 1981, pp 329-353.
8) LaBoube, R.A., Yu, W.W., "Webs for Cold-Formed Steel Flexural Members - Structural Behaviour of Beam Webs Subjected to Bending Stress", Final Report, Civil Engineering Study 78-1, Structural Series, University of Missouri-Rolla, Rolla, Missouri, June 1978.
9) Shan, M.Y., LaBoube, R.A., Yu, W.W., "Behaviour of Web Elements with Openings Subjected to Bending, Shear and the Combination of Bending and Shear", Final Report, Civil Engineering Study 94-2 Structural Series, University of Missouri-Rolla, Rolla, Missouri, May 1994.
10) Winter, G., "Strength of Thin Steel Compression Flanges", Transactions, ASCE, Vol. 112, 1947, pp. 527-6576.
11) Kollbrunner, C.F., Meister, M., "Ausbeulen - Theorie und Berechnung von Blechen", Springer-Verlag, Berlin, West Germany, 1958.
12) Thomasson, P.O., "Thin-walled C-shaped panels in axial compression", Document D1;1978, Swedish Council for Building Research, Stockholm, Sweden, 1978.
13) Cohen, J.M., "Local Buckling Behaviour of Plate Elements", A thesis presented to the Faculty of the Graduate School of Cornell University in partial fulfilment for the Degree of Doctor of Philosophy, Department of Structural Engineering., Cornell University, Ithaca N.Y., August 1987.

14) Appendix 'A' Eurocode 3, "Cold Formed Steel Sheeting and Members", Revised version according to the Karlsruhe meeting, March 1989.
15) ISO TC167 WG2, "Steel Structures Part Two : Design of Cold Formed Steel Members and Sheeting", Working Draft #3, 1991

APPENDIX

Table A.1 - Waterloo Test Specimen Dimensions and Material Properties[6]

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
C2-DW20-1	7.00	41.0	102	41.0	13.0	6.50	40.5	103	40.0	13.0	1.14	2.29	362	439	28.3
C2-DW35-1	13.0	42.5	102	42.5	13.0	13.0	42.5	102	42.5	13.0	1.14	2.29	362	439	28.3
C2-DW45-1	15.0	39.5	100	39.5	15.0	14.5	40.0	99.0	40.0	15.0	1.14	2.29	362	439	28.3
C2-DW55-1	18.0	38.5	101	38.5	18.0	18.0	38.5	101	38.5	18.0	1.14	2.29	362	439	28.3
C2-DW65-1	23.0	44.0	101	44.0	23.5	23.0	44.0	101	43.0	23.5	1.14	2.29	362	439	28.3
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-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
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

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

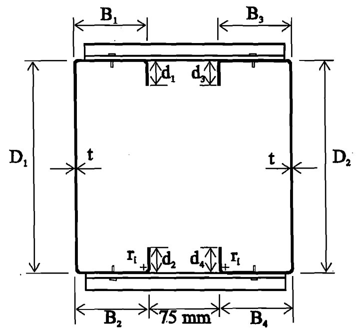

Figure A.1 - Waterloo Test Specimen Cross-Section[6]

Table A.2 - M_T/M_P Ratios - Waterloo Test Data[6]

Specimen	M_T	S136₁		S136₁*		S136₂		S136₂*		S136₃		S136₃*		S136₄		S136₄*		S136₅		S136₅*	
	kN·m	M_P kN·m	M_T/M	M_P kN·m	M_T/M	M_P kN·m	M_T/M	M_P kN·m	M_T/M	M_P kN·m	M_T/M	M_P kN·m	M_T/M	M_P kN·m	M_T/M	M_P kN·m	M_T/M	M_P kN·m	M_T/M	M_P kN·m	M_T/M
C1-DW30-1	7.17	6.03	1.19	7.00	1.03	6.03	1.19	7.00	1.03	6.03	1.19	7.00	1.03	6.03	1.19	7.00	1.03	6.03	1.19	7.00	1.03
C1-DW40-1	7.48	6.25	1.20	7.25	1.03	6.25	1.20	7.25	1.03	6.25	1.20	7.25	1.03	6.25	1.20	7.25	1.03	6.25	1.20	7.25	1.03
C1-DW60-1	7.83	6.44	1.22	7.47	1.05	6.44	1.22	7.47	1.05	6.44	1.22	7.47	1.05	6.44	1.22	7.47	1.05	6.44	1.22	7.47	1.05
C1-DW80-1	8.43	6.84	1.23	7.90	1.07	6.84	1.23	7.90	1.07	6.84	1.23	7.90	1.07	6.84	1.23	7.90	1.07	6.84	1.23	7.90	1.07
C2-DW20-1	4.19	3.73	1.12	3.73	1.12	3.73	1.12	3.73	1.12	3.73	1.12	3.73	1.12	3.73	1.12	3.73	1.12	3.73	1.12	3.73	1.12
C2-DW35-1	4.43	4.71	0.94	4.71	0.94	4.71	0.94	4.71	0.94	4.71	0.94	4.71	0.94	4.71	0.94	4.71	0.94	4.71	0.94	4.71	0.94
C2-DW45-1	5.16	4.84	1.07	4.84	1.07	4.84	1.07	4.84	1.07	4.84	1.07	4.84	1.07	4.84	1.07	4.84	1.07	4.84	1.07	4.84	1.07
C2-DW55-1	5.09	4.87	1.04	4.87	1.04	4.90	1.04	4.90	1.04	4.89	1.04	4.89	1.04	4.91	1.04	4.91	1.04	4.93	1.03	4.93	1.03
C2-DW65-1	5.57	5.01	1.11	5.01	1.11	5.06	1.10	5.06	1.10	5.04	1.11	5.04	1.11	5.08	1.10	5.08	1.10	5.11	1.09	5.11	1.09
C2R-DW20-1	4.16	3.64	1.14	3.64	1.14	3.64	1.14	3.64	1.14	3.64	1.14	3.64	1.14	3.64	1.14	3.64	1.14	3.64	1.14	3.64	1.14
C2R-DW35-1	5.05	4.77	1.06	4.93	1.02	4.77	1.06	4.93	1.02	4.77	1.06	4.93	1.02	4.77	1.06	4.93	1.02	4.77	1.06	4.93	1.02
C2R-DW45-1	5.22	4.97	1.05	5.18	1.01	4.97	1.05	5.18	1.01	4.97	1.05	5.18	1.01	4.97	1.05	5.18	1.01	4.97	1.05	5.18	1.01
C2R-DW55-1	5.26	4.93	1.07	4.93	1.07	4.95	1.06	4.95	1.06	4.94	1.06	4.94	1.06	4.96	1.06	4.96	1.06	4.96	1.06	4.96	1.06
C2R-DW65-1	5.49	4.81	1.14	4.81	1.14	4.85	1.13	4.85	1.13	4.83	1.14	4.83	1.14	4.87	1.13	4.87	1.13	4.89	1.12	4.89	1.12
C2-DW25-2	9.21	7.75	1.19	7.75	1.19	7.75	1.19	7.75	1.19	7.75	1.19	7.75	1.19	7.75	1.19	7.75	1.19	7.75	1.19	7.75	1.19
C2-DW40-2	10.4	8.45	1.23	8.85	1.18	8.45	1.23	8.85	1.18	8.45	1.23	8.85	1.18	8.45	1.23	8.85	1.18	8.45	1.23	8.85	1.18
C2-DW50-2	10.4	8.51	1.22	9.50	1.10	8.51	1.22	9.50	1.10	8.51	1.22	9.50	1.10	8.51	1.22	9.50	1.10	8.51	1.22	9.50	1.10
C2-DW60-2	11.0	8.81	1.24	9.83	1.12	8.81	1.24	9.83	1.12	8.81	1.24	9.83	1.12	8.81	1.24	9.83	1.12	8.81	1.24	9.83	1.12
C2-DW70-2	10.8	8.89	1.22	9.91	1.09	8.89	1.22	9.91	1.09	8.89	1.22	9.91	1.09	8.89	1.22	9.91	1.09	8.89	1.22	9.91	1.09
C2-DW80-2	11.2	9.16	1.23	9.96	1.13	9.16	1.23	9.96	1.13	9.16	1.23	9.96	1.13	9.16	1.23	9.96	1.13	9.16	1.23	9.96	1.13
C3-DW20-1	5.14	4.67	1.10	4.67	1.10	4.67	1.10	4.67	1.10	4.67	1.10	4.67	1.10	4.67	1.10	4.67	1.10	4.67	1.10	4.67	1.10
C3-DW30-1	5.37	5.38	1.00	5.38	1.00	5.39	1.00	5.39	1.00	5.38	1.00	5.38	1.00	5.39	1.00	5.39	1.00	5.39	1.00	5.39	1.00
C3-DW35-1	5.43	5.60	0.97	5.60	0.97	5.64	0.96	5.64	0.96	5.63	0.96	5.63	0.96	5.66	0.96	5.66	0.96	5.68	0.95	5.68	0.95
C3-DW45-1	5.37	5.36	1.00	5.36	1.00	5.40	0.99	5.40	0.99	5.39	1.00	5.39	1.00	5.42	0.99	5.42	0.99	5.45	0.98	5.45	0.98

Note: * *Cold work of forming used.*

1) S136 uniform compressive stress at the top of the flat width (Current).
2) S136 uniform compressive stress at the mid-point of the flat width.
3) S136 uniform compressive stress at the third point of the flat width.
4) Cohen/Eurocode stress gradient.
5) ISO stress gradient.

Table A.3 - M_T/M_P Ratios - Available Test Data

Specimen	M_T kN·m	$S136_1$ M_P kN·m	$S136_1$ M_T/M_P	$S136_2$ M_P kN·m	$S136_2$ M_T/M_P	$S136_3$ M_P kN·m	$S136_3$ M_T/M_P	$S136_4$ M_P kN·m	$S136_4$ M_T/M_P	$S136_5$ M_P kN·m	$S136_5$ M_T/M_P
Desmond et al.[7]											
E-45.6B-1	21.5	17.2	1.25	17.2	1.25	17.2	1.25	17.2	1.25	17.2	1.25
E-45.6B-2	21.5	18.3	1.17	18.3	1.17	18.3	1.17	18.3	1.17	18.3	1.17
E-45.6B-3	21.6	20.3	1.07	20.4	1.06	20.3	1.06	20.5	1.05	20.6	1.05
E-45.6B-4	21.2	19.3	1.10	19.5	1.09	19.5	1.09	19.7	1.08	19.8	1.07
LaBoube & Yu[8]											
B-10-1	6.26	5.89	1.06	5.89	1.06	5.89	1.06	5.89	1.06	5.89	1.06
Shan et al.[9]											
2B,16,1&2(N)	3.82	3.50	1.09	3.50	1.09	3.50	1.09	3.50	1.09	3.50	1.09
2B,16,3&4(N)	3.90	3.61	1.08	3.61	1.08	3.61	1.08	3.61	1.08	3.61	1.08
Winter[10]											
B2	10.8	10.4	1.04	10.4	1.04	10.4	1.04	10.4	1.04	10.4	1.04
B4	49.4	44.4	1.11	44.4	1.11	44.4	1.11	44.4	1.11	44.4	1.11
B5	4.84	4.54	1.06	4.54	1.06	4.54	1.06	4.54	1.06	4.54	1.06
B6	38.3	34.7	1.10	34.7	1.10	34.7	1.10	34.7	1.10	34.7	1.10
B7	5.59	5.58	1.00	5.58	1.00	5.58	1.00	5.58	1.00	5.58	1.00
B8	22.7	21.1	1.08	21.1	1.08	21.1	1.08	21.1	1.08	21.1	1.08
B9	34.5	32.2	1.07	32.2	1.07	32.2	1.07	32.2	1.07	32.2	1.07
B10	12.1	10.6	1.14	10.6	1.14	10.6	1.14	10.6	1.14	10.6	1.14

Note: *1) S136 uniform compressive stress at the top of the flat width (Current).*
2) S136 uniform compressive stress at the mid-point of the flat width.
3) S136 uniform compressive stress at the third point of the flat width.
4) Cohen/Eurocode stress gradient.
5) ISO stress gradient.