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INTERACTION OF FLANGE/EDGE - STIFFENED COLD FORMED STEEL C - SECTIONS

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SUMMARY

A revision to the Canadian Standard (S136-94)[1] and the American Specification (AISI-89)[2], in which the procedure to calculate the effective width of an edge-stiffened compressive flange is modified, has been proposed by Dinovitzer et al.[3]. The proposal involves a change of the equations for the flange plate buckling coefficients of Case II compressive elements, which eliminates a discontinuity in the effective width formulation. The modified local buckling procedure was compared with the current Canadian Cold Formed Steel Standard using a program of beam tests at the University of Waterloo[4] and data available in the literature[8,9,10,11,12]. Statistical results of the comparison indicate that the revised method is more accurate than current design standards and use of this procedure simplifies the current plate buckling equations. It is recommended that the Dinovitzer approach be adopted by the North American Design Standards.

1 INTRODUCTION

Dinovitzer et al.[3] completed an investigation of compressive elements where a discontinuity in the effective width equation for sections with partially stiffened flanges and simple edge stiffeners (lips) was discovered (see Figure 1). A partially stiffened flange is an element that is supported by a web on one side and an edge stiffener of inadequate rigidity ($I_r < 1$) on the other. The

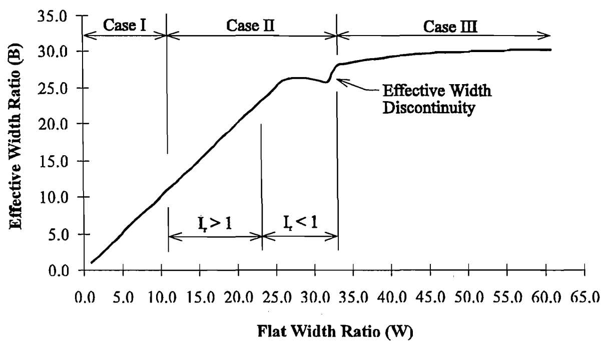

Figure 1 - Flat Width Ratio vs. S136[1] Effective Width Ratio

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S136-M89 Design Standard[5] was examined to find the source of this discontinuity in the flange effective width formulation. Dinovitzer observed that the plate buckling coefficient equations were identical for Case II and Case III flanges except for an exponent change from 1/2 to 1/3. The objective of the investigation was to then develop an equation which would allow the exponent to vary from 1/2 to 1/3 gradually. Dinovitzer concluded that *the stepwise transition from design Case II to Case III should be replaced with the linear formulation of the plate buckling exponent transition*[3]. For Case II and Case III sections with an edge stiffener of inadequate rigidity ($I_r < 1$), the following plate buckling coefficient equations and linear formulation of the exponent, n, were recommended:

$$d_i/w \le 0.25 \qquad k = 3.57\,(I_r)^n + 0.43, \tag{1}$$

$$0.25 < d_i/w \le 0.8 \qquad k = [4.82 - 5(d_i/w)]\,(I_r)^n + 0.43, \tag{2}$$

$$n = \frac{25}{43} - \frac{37W}{192}\sqrt{\frac{f}{E}} \qquad (1/3 \le n \le 1/2). \tag{3}$$

Where $W = w/t$.

This new formulation will only affect the plate buckling coefficient of sections with Case II flanges, since $n = 1/3$ for $w/t > W_{lim2}$. Dinovitzer's flange method also simplifies the procedure required for the analysis of compressive flanges, by eliminating the need to differentiate between Case II and Case III elements.

2 Current Effective Width Procedure of an Edge-Stiffened Flange Element

The flat width of the flange, w, is calculated as the overall width minus the thickness, t, and inside bend radius, r_i, for each corner. The flat width ratio, w/t, has a limit of 60 as given in Clause 5.4 of S136-94[1].

The "Case" of the flange is determined according to the following flat width ratio limits,

$$W_{lim1} = 0.644\sqrt{kE/f} \quad \text{with } k = 0.43, \tag{4}$$

$$W_{lim2} = 0.644\sqrt{kE/f} \quad \text{with } k = 4, \tag{5}$$

where $f = F_y$ or F_y' when cold work of forming is used. The "Case" of the flange is determined as follows,

Case I flange	$w/t \le W_{lim1}$,	(6)
Case II flange	$W_{lim1} < w/t \le W_{lim2}$,	(7)
Case III flange	$w/t > W_{lim2}$.	(8)

The influence of the edge stiffener (lip) is determined by means of the adequate moment of inertia, I_a, equations, developed by Desmond[6],

Case I flange	$I_a = 0$ (no edge stiffener required),	(9)
Case II flange	$I_a = 399t^4(W / W_{lim2} - 0.327)^3$,	(10)
Case III flange	$I_a = t^4[115\,(W / W_{lim2}) + 5]$,	(11)

where $W = w/t$.

The flat width ratio of the lip, d/t, is currently limited to 14, as recommended by Willis & Wallace[7] and the ratio of the out-to-out depth of the lip to the flat width of the flange, d_i/w, is limited to 0.8, given in Clause 5.6.2.3 of S136-94[1]. The moment of inertia of the simple edge stiffener is calculated about its own centroid, as defined below.

$$I_s = t\,d^3 \sin^2(\alpha) / 12 \tag{12}$$

The ratio of actual to adequate moment of inertia ($I_r = I_s / I_a$) is calculated and used with the equations from Table 1 to determine the plate buckling coefficient for the compressed flange element.

Table 1 - Buckling Coefficients for Edge-Stiffened Flange Elements

		$d_i/w \le 0.25$	$0.25 < d_i/w \le 0.8$
Case II	$I_r \ge 1$	$k = 4$	$k = 5.25 - 5(d_i/w)$
	$I_r < 1$	$k = 3.57\,(I_r)^{1/2} + 0.43$	$k = [4.82 - 5(d_i/w)]\,(I_r)^{1/2} + 0.43$
Case III	$I_r \ge 1$	$k = 4$	$k = 5.25 - 5(d_i/w)$
	$I_r < 1$	$k = 3.57\,(I_r)^{1/3} + 0.43$	$k = [4.82 - 5(d_i/w)]\,(I_r)^{1/3} + 0.43$
Note: $d/t \le 14$			

The flat width ratio limit, W_{lim}, is calculated and compared to the flat width ratio of the flange, w/t.

$$W_{lim} = 0.644\sqrt{kE/f} \quad \text{with } f = F_y \text{ or } f = F_y' \tag{13}$$

If $w/t > W_{lim}$ then the flange must be reduced in width according to the following equation,

$$B = 0.95\sqrt{\frac{kE}{f}}\left[1 - \frac{0.208}{W}\sqrt{\frac{kE}{f}}\right], \tag{14}$$

where $W = w/t$, and $b = Bt$ is the effective width of the flange, which is separated into components using the following equations:

$$b_1 = I_r\,Bt/2 \le Bt/2, \tag{15}$$
$$b_2 = Bt - b_1. \tag{16}$$

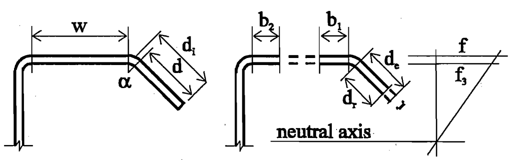

Figure 2 - Edge-Stiffened Flange Element Subjected to Uniform Compressive Stress[1]

Figure 2 shows the gross dimensions, effective widths and stress distribution of a typical edge-stiffened flange element subjected to a uniform compressive stress.

The compressive stress in the flange, f, is not dependent on the position of the neutral axis unless yielding of the tensile flange initially occurs. If the cross-section of the member is such that the tensile flange reaches the maximum allowable stress, F_y or F_y', prior to failure of the compressive flange, then the stress values used in the effective width formulation will depend on the position of the neutral axis.

The lambda format presented in the 1989 AISI Cold-Formed Steel Specification[2] is an inverse format of the S136[1] approach which yields identical results for uniformly compressed flange elements.

3 COMPARISON WITH WATERLOO TEST DATA

Five of the series tested as part of the Waterloo study[4] contained test specimens with inadequately stiffened ($I_r < 1$) Case II flanges. In total, seven test specimens from these series were applicable to the Dinovitzer[3] flange method investigation. Tables A.1 and Figure A.1 of the Appendix contain test specimen dimensions and material properties as well as a test beam cross-section. The specimen identification numbers and the resulting Dinovitzer exponents, n, and plate buckling coefficients as well as the S136[1] plate buckling coefficients are summarised in Table 2. Test-to-predicted bending moment ratios for the current S136 Design procedure and for the proposed Dinovitzer method are listed in Table 3. Regarding the test specimens listed in Table 2, the Dinovitzer method resulted in more accurate predictions of the bending moment resistance. A mean of 1.04, a standard deviation of 0.090 and a coefficient of variation of 0.106 were calculated for the Dinovitzer method as compared to a mean of 1.06, a standard deviation of 0.097 and a coefficient of variation of 0.111 for the current S136 Design procedure (see Table 6).

Table 2 - Exponent, n, and Plate Buckling, k, Values

Specimen	n	k-Din	k-S136	Specimen	n	k-Din	k-S136
C2-DW20-1-A	0.338	1.43	0.972	C2-DW20-1-B	0.342	1.29	0.877
C2-DW45-1-A	0.349	2.92	2.90	C2-DW45-1-B	0.345	2.85	2.76
C2-DW25-2-A	0.446	1.83	1.69	C2-DW25-2-B	0.447	1.76	1.63
C2-DW20-3-A	0.388	1.90	1.57	C2-DW20-3-B	0.388	1.92	1.60
C2-DW35-3-A	0.383	3.11	3.11	C2-DW35-3-B*	0.500	3.11	3.11
C2-DW25-4-A	0.438	1.07	0.934	C2-DW25-4-B	0.437	1.24	1.09
C2R-DW20-1-A	0.384	1.15	0.874	C2R-DW20-1-B	0.384	1.15	0.874

Note: * $I_r > 1$ for test specimen C2-DW35-3-B.

Table 3 - M_T/M_P Ratios - Local Buckling Methods

Specimen	M_T kN·m	S136 M_P kN·m	S136 M_T/M_P	AISI M_P kN·m	AISI M_T/M_P	Din S136 M_P kN·m	Din S136 M_T/M_P
C2-DW20-1-A,B	4.19	3.73	1.12	3.88	1.08	3.98	1.05
C2-DW45-1-A,B	5.16	4.84	1.07	4.86	1.06	4.85	1.06
C2-DW25-2-A,B	9.21	7.75	1.19	7.75	1.19	7.75	1.19
C2-DW20-3-A,B	11.3	10.8	1.04	11.4	0.99	11.1	1.01
C2-DW35-3-A,B	12.2	12.9	0.94	13.7	0.89	12.9	0.94
C2-DW25-4-A,B	31.9	33.9	0.94	36.6	0.87	34.4	0.93
C2R-DW20-1-A,B	4.16	3.64	1.14	3.71	1.12	3.80	1.09

4 Comparison with Available Test Data

Twenty available test specimens consisting of sections with inadequately supported ($I_r < 1$) Case II flanges were included in this study. Table 4 lists the applicable sections tested by Cohen[8], Moreyra[9], Schuster[10], Shan[11] and Winter[12]. Also listed are the corresponding Dinovitzer[3] exponents, n, plate buckling coefficients as well as the S136[1] plate buckling coefficients. Test-to-predicted bending moment ratios for both the Dinovitzer exponent method and the current S136 procedure are found in 5. Similar to the Waterloo[4] test result comparison, the Dinovitzer method more accurately predicted the bending moment resistance of the available test data. Dinovitzer's flange method resulted in a mean of 1.00, a standard deviation of 0.147 and a coefficient of variation of 0.090 for the available test data. In comparison, the current S136 procedure yielded a mean of 1.01, a standard deviation of 0.158 and a coefficient of variation of 0.166 (see Table 6).

However, it must be noted that eleven of the applicable test specimens were subject to the distortional buckling mode of failure. The test-to-predicted bending moment ratios of these sections were significantly unconservative (< 1). Specimens tested by Moreyra[9], Schuster [10] and Shan[11] (12B,16,...) were removed from the comparison so that local buckling concerns could be isolated. The Dinovitzer[3] method remained more accurate for the available test data with a mean of 1.13, a standard deviation of 0.087 and a coefficient of variation of 0.090, as compared to a mean of 1.15, a standard deviation of 0.100 and a coefficient of variation of 0.101 for the S136[1] method (see Table 6).

Table 4 - Exponent, n, and Plate Buckling, k, Values

Specimen	n	k-Din	k-S136
Cohen[8]			
It2-rmin-d90-1L1	0.333	2.44	2.03
It2-rmin-d90-2L1	0.333	2.44	2.03
IIt2-rmin-d90-1L1	0.333	2.44	2.03
Moreyra[9]			
B-W*	0.347	2.69	2.67
B-TB*	0.337	2.54	2.41
C-W*	0.337	2.51	2.31
C-TB*	0.337	2.45	2.22
Winter[12]			
B4	0.433	2.55	2.39
B6	0.365	2.32	1.92
B7	0.345	3.57	3.54
C5	0.350	3.08	2.84

Specimen	n	k-Din	k-S136
Schuster[10]			
BS1-A*	0.385	3.08	2.97
BS1-B*	0.385	3.08	2.97
BS2-A*	0.385	3.08	2.97
BS2-B*	0.385	3.08	2.97
CS1-A*	0.373	2.91	2.80
CS1-B*	0.373	2.91	2.80
CS2-A*	0.373	2.91	2.80
CS2-B*	0.373	2.91	2.80
CS3-A*	0.367	2.83	2.67
CS3-B*	0.373	2.91	2.80
Shan[11]			
2B,16,1&2(N)_A	0.384	2.37	2.11
2B,16,1&2(N)_B	0.382	2.36	2.09
2B,16,3&4(N)_A	0.385	2.67	2.51
2B,16,3&4(N)_B	0.382	2.41	2.15
12B,16,1&2(N)_A*	0.394	2.63	2.47
12B,16,1&2(N)_B*	0.394	2.79	2.70
12B,16,3&4(N)_A*	0.393	2.37	2.13
12B,16,3&4(N)_B*	0.394	2.79	2.70

Note: * Subject to distortional buckling mode of failure.

Table 5 - M_T/M_P Ratios - Local Buckling Methods

Specimen	M_T kN·m	S136 M_P kN·m	S136 M_T/M_P	AISI M_P kN·m	AISI M_T/M_P	Din S136 M_P kN·m	Din S136 M_T/M_P
Cohen[8]							
It2-rmin-d90-1L1	70.5	55.7	1.27	59.9	1.18	57.5	1.23
It2-rmin-d90-2L1	73.3	55.7	1.32	59.9	1.22	57.5	1.28
IIt2-rmin-d90-1L1	66.2	55.7	1.19	59.9	1.10	57.5	1.15
Moreyra[9]							
B-W*	13.2	15.1	0.87	16.3	0.81	15.2	0.87
B-TB*	14.0	15.5	0.91	17.0	0.82	15.6	0.90
C-W*	15.6	13.9	1.12	15.4	1.02	14.1	1.11
C-TB*	15.0	14.9	1.00	16.6	0.90	15.2	0.99
Schuster[10]							
BS1*	8.46	9.07	0.93	10.3	0.82	9.07	0.93
BS2*	8.61	9.07	0.95	10.3	0.84	9.07	0.95
CS1*	9.05	10.8	0.83	11.9	0.76	10.9	0.83
CS2*	9.05	10.9	0.83	11.9	0.76	10.9	0.83
CS3*	9.29	10.8	0.86	11.9	0.78	10.9	0.86
Shan[11]							
2B,16,1&2(N)	3.82	3.50	1.09	3.49	1.10	3.56	1.07
2B,16,3&4(N)	3.90	3.61	1.08	3.60	1.08	3.64	1.07
12B,16,1&2(N)*	22.5	28.9	0.78	30.5	0.74	28.9	0.78
12B,16,3&4(N)*	23.4	28.5	0.82	30.1	0.78	28.7	0.82
Winter[12]							
B4	49.4	44.4	1.11	44.3	1.11	44.4	1.11
B6	38.3	34.7	1.10	34.7	1.11	35.8	1.07
B7	5.59	5.58	1.00	5.57	1.00	5.59	1.00
C5	16.5	14.2	1.16	15.3	1.08	14.4	1.15

Note: * Subject to distortional buckling mode of failure.

5 Comparison with Waterloo and Available Test Data

The Dinovitzer[3] method was again more accurate in comparison with the current S136[1] procedure when the applicable Waterloo[4] and available test data[8,9,10,11,12] were analysed together. Analysis of the test-to-predicted bending moment ratios for the twenty-seven test specimens resulted in a mean of 1.01, a standard deviation of 0.134 and a coefficient of variation of 0.138 for Dinovitzer's method and a mean of 1.02, a standard deviation of 0.145 and a coefficient of variation of 0.147 for the current S136 procedure (see Table 6).

The Dinovitzer[3] method remained more accurate in comparison with the current S136[1] procedure when the Waterloo[4] and available test data[8,9,10,11,12] were combined, excluding the sections which failed by distortional buckling. This comparison of test-to-predicted bending moment ratios produced a mean of 1.09, a standard deviation of 0.096 and a coefficient of variation of 0.095 for the Dinovitzer method and a mean of 1.11, a standard deviation of 0.104 and a coefficient of variation of 0.101 for the S136 procedure (see Table 6).

Table 6 - Statistical Comparison of M_T/M_P Ratios

Test Specimen		Dinovitzer	S136
Waterloo Data	Mean	1.04	1.06
(7 Tests)	S.D.	0.090	0.097
	C.o.V.	0.106	0.111
Available Data	Mean	1.00	1.01
(20 Tests)	S.D.	0.147	0.158
	C.o.V.	0.090	0.166
Available Data	Mean	1.13	1.15
w/o Dist. Bckl.	S.D.	0.087	0.100
(9 Tests)	C.o.V.	0.090	0.101
Waterloo &	Mean	1.01	1.02
Available Data	S.D.	0.134	0.145
(27 Tests)	C.o.V.	0.138	0.147
Waterloo &	Mean	1.09	1.11
Available Data	S.D.	0.096	0.104
w/o Dist. Bckl.	C.o.V.	0.095	0.101
(16 Tests)			

6 CONCLUSIONS

The Dinovitzer[3] exponent method used to calculate the plate buckling coefficient of an inadequately supported compressive flange was more accurate than the current S136[1] procedure for all applicable Waterloo[4] and available test data[8,9,10,11,12]. Since the Dinovitzer flange method is more accurate than the current S136 procedure and it simplifies the current plate buckling coefficient equations, it is recommended that the Dinovitzer flange method be used to revise the North American Design Standards[1,2].

ACKNOWLEDGEMENTS

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APPENDIX

Table A.1 - Test Specimen Dimensions and Material Properties

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.
C2-DW20-1-A,B	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-DW45-1-A,B	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-DW25-2-A,B	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-DW20-3-A,B	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-A,B	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-DW25-4-A,B	7.90	42.7	301	42.3	26.2	8.40	42.9	300	42.2	25.6	1.90	3.81	418	515	27.2
C2R-DW20-1-A,B	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

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

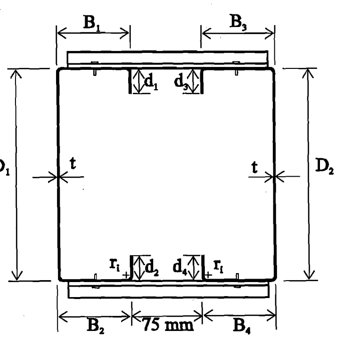

Figure A.1 - Test Specimen Cross-Section