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Effective Width Method for determining distortional buckling strength of cold-formed steel flexural C and Z sections

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ABSTRACT

This paper proposes a design method, based on the Effective Width Method, for determining the nominal distortional buckling strength of typical cold-formed steel C and Z sections subjected to bending. The method can be integrated into the classic effective width design provisions specified in AISI S100, and it allows the conventional design approach to cover more comprehensive limit states. The proposed method is calibrated by the flexural distortional buckling strength predicted by the Direct Strength Method. Comparison with experimental results indicates that the proposed method yields reasonable predictions for the flexural distortional buckling strength of industrial standard C and Z sections. The method offers the same level of accuracy and reliability as the Direct Strength Method.

1. Introduction

Cold-formed steel flexural members may fail in local buckling, distortional buckling, or lateral–torsional buckling. Fig. 1 illustrates the three elastic buckling shapes of a typical cold-formed steel Z section subjected to a uniform bending moment. The local buckling mode is characterized by relatively short and repeated buckling waves of the compressive built-up plate elements (e.g. web, compression flange and lip stiffener). The four corners of the cross section have no relative movement. The distortional buckling mode occurs at an intermediate length of the buckling waves. In the distortional mode, the section distorts and the compression flange-lip component rotates about the web–flange junction. This phenomenon is commonly caused by buckling of the compression flange-lip component, but it also can be driven by buckling of the web. Lateral–torsional buckling occurs at relatively long wavelengths, and the entire cross section translates and rotates as a rigid-body without significant changes in the cross-sectional shape.

The distortional buckling most often occurs in sections where lateral deformations (i.e. lateral–torsional buckling) are prevented by intermittent bracing [1]. When the compression flange is not restrained by attachment to sheathing or paneling, such as in negative bending of continuous members (joists, purlins, etc.), members are prone to distortional failures. Yu [2] conducted a series of flexural tests on industrial standard cold-formed steel C and Z sections that had intermediate lengths of unbraced members. The distortional buckling failure was observed in a majority of the tested Z sections and some of the tested C sections. Fig. 2 shows a typical distortional buckling mode of a cold-formed steel C section observed in Yu [2]. The experimental results on the distortional buckling failure are specifically addressed in Yu and Schafer [3].

The Effective Width Method, introduced by von Karman et al. in 1932 [4] and subsequently modified by Winter [5], has been the primary design approach for the cold-formed steel members in the AISI Specifications including the latest edition of North American Specification for the Design of Cold-Formed Steel Structural Members [6]. However, the Effective Width Method does not have sufficient procedures for predicting the distortional buckling failure. The AISI S100 attempts to account for the distortional buckling through a reduced plate buckling coefficient, k, for the compressive flange element [7]. However, the experimental work [8] carried out for determining the reduced buckling coefficient, k, concentrated on flange local buckling instead of the distortional buckling, as the test setup strongly restricted the buckling in web and partially restricted distortional buckling. The empirical k values do not agree with the actual elastic distortional buckling stress, and this oversight has been highlighted by experiments conducted by Willis and Wallace [9], Schuster [10], Moreyra [11], Ellifritt et al. [12], Rogers and Schuster [13], Yu [2], and Yu and Schafer [3]. Yu [2] concluded that the Effective Width Method in AISI Specifications yielded average 12% non-conservative flexural strength predictions for distortional buckling. It also was indicated by Yu [2] that the Direct Strength Method, Australian/New Zealand codes, and European standards provide reasonable predictions for the distortional buckling strength.

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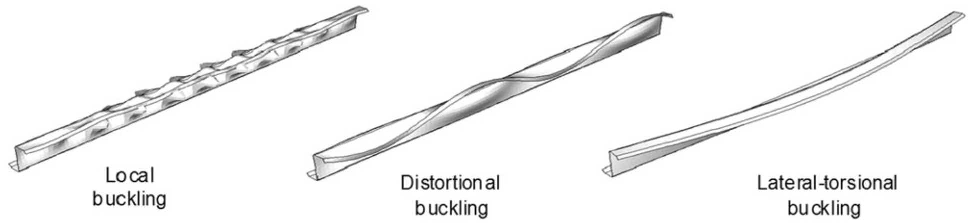

Fig. 1. Buckling modes of a cold-formed steel Z section in bending.

Fig. 2. Distortional buckling modes of a cold-formed steel C section in bending [2].

The Direct Strength Method (DSM), adopted by both AISI S100 and Australia/New Zealand Standards—Cold-Formed Steel Structures [14], uses the entire cross-section in the elastic buckling determination and offers specific provisions for local, distortional and global buckling strength without effective width calculations and iteration. However, DSM is still being developed to become a comprehensive design procedure to replace the Effective Width Method. Furthermore, elastic critical buckling solutions are required by the DSM approach, and those solutions have to be obtained by advanced computational analyses such as finite strip or finite element analysis. The DSM equations for the nominal flexural distortional buckling strength, M_{nd}, are listed as follows.

for $\lambda_d \leq 0.673$ [6], $\lambda_d \leq 0.674$ [14]

$$M_{nd} = M_y \tag{1}$$

for $\lambda_d > 0.673$ (DSM), $\lambda_d > 0.674$ [14]

$$M_{nd} = \left(1-0.22\left(\frac{M_{crd}}{M_y}\right)^{0.5}\right)\left(\frac{M_{crd}}{M_y}\right)^{0.5} M_y \tag{2}$$

where $\lambda_d = \sqrt{M_y/M_{crd}}$, M_y is the yield moment, and M_{crd} is the critical elastic distortional buckling moment.

The Eurocode 3 [15] provides specific provisions for the distortional buckling strength of cold-formed steel flexural members. The method adopted in EC3 essentially is based on the effective width concept, and the procedure involves complicated computation of the reduced thickness. The method considers the distortional buckling by using a reduced thickness in the calculation of the effective area of the edge stiffener and the distorted part of the compression flange. The reduction factor of thickness for distortional buckling depends on the elastic buckling stress of the edge stiffener and the material yield strength; the factor can be refined by an optional iteration procedure. The equations to calculate the reduction factor χ_d are as follows:

$$\chi_d = 1.0 \quad \text{if } \overline{\lambda_d} \leq 0.65 \tag{3}$$

$$\chi_d = 1.47 - 0.723\overline{\lambda_d} \quad \text{if } 0.65 < \overline{\lambda_d} < 1.38 \tag{4}$$

$$\chi_d = \frac{0.66}{\overline{\lambda_d}} \quad \text{if } \overline{\lambda_d} \geq 1.38 \tag{5}$$

where $\overline{\lambda_d} = \sqrt{f_{yb}/\sigma_{cr,s}}$, f_{yb} is the material yield strength, and $\sigma_{cr,s}$ is the elastic critical stress for the stiffener. A hand solution of the elastic buckling stress of edge stiffeners in Z or C sections is given in EC3. The test results by Yu [2] indicated that EC3 provided slightly non-conservative predictions for the flexural distortional buckling failures of typical cold-formed steel Z and C sections; the average test-to-predicted ratio is 0.96.

A reliable and efficient design approach for determining the distortional buckling strength is must-needed to the existing Effective Width Method based design provisions. The paper presents a proposed design method for the flexural distortional buckling of industrial standard cold-formed steel C and Z sections; the new method is designed to be integrated in the existing Effective Width Method specified in AISI S100.

2. Proposed design method for flexural strength of distortional buckling

When the cold-formed steel Z or C section beams buckle in distortional buckling mode, as shown in Fig. 1, the compression flange and edge stiffener rotate against the junction between the web element and the flange, while at the same time the plate buckling occurs on the compression portion of the web element. The rotation of flange-stiffener component would change both the effective widths and the neutral axis location of the flange-stiffener component. Given the fact that the effective width of the compressive flange affects the bending resistance of the whole section, the proposed method attempts to use revised formulae for the buckling coefficient of the compressive flange to account for the distortional buckling behavior of the entire cold-formed steel section. The new method employs the same design procedure and equations in Section C3.1.1 of AISI S100, which calculates the nominal section strength of flexural members, except that Eqs. (6) and (7) listed below will be adopted for determining the plate buckling coefficient of the compression flange

$$k = 4.0 \quad \text{if } \alpha \leq 0.6 \tag{6}$$

$$k = 0.43 + \frac{3.57}{(\alpha+0.4)^{3.5}} \quad \text{if } \alpha > 0.6 \tag{7}$$

where $\alpha = (tb/d\sin(\theta))h^{0.9}$ for unit in inch, $\alpha = (0.0021tb/d\sin(\theta))\,h^{0.9}$ for unit in mm, b is the out-to-out compression flange width, d is the out-to-out compression flange lip stiffener length, h is the out-to-out web depth, t is the base material thickness, and θ is the compression flange stiffener angle from horizontal. The definition of these dimensions is illustrated in Fig. 3.

The proposed formulae of k values vary from 0.43 to 4.0. When the flange width goes to infinity or the stiffener is significantly small ($\alpha \to \infty$), the flange-stiffener component will behave as an unstiffened element, thus the buckling coefficient approaches to 0.43. On the other hand, if the stiffener is relatively large so that it provides strong restraint to the compression flange, the flange will behave similarly to a stiffened element; therefore the buckling coefficient will be close to 4.0.

Eqs. (6) and (7) are developed by a parameter study based on the industrial standard cold-formed steel Z and C sections tested by Yu [2], which includes a broad range of configurations in terms of

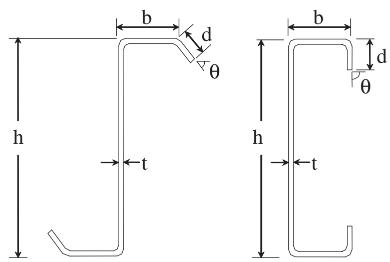

Fig. 3. Definitions for dimensions of Z and C sections.

the material thickness, the web height, and the flange width. Table 1 summarizes the geometries of the tested sections and the results by the parameter study. In Table 1, the denotation of specimen label refers to Yu [2]; only the dimensions of interest are included; f_y is the material yield stress; M_{DSd} is the nominal flexural strength of distortional buckling calculated by the Direct Strength Method (Eqs. (1) and (2) AISI S100 approach). The k_o in Table 1 is the exact (theoretical) plate buckling coefficient for the compression flange in order to allow the Effective Width Method in Section C3.3.1 of AISI S100 to match the results of the Direct Strength Method for the nominal distortional buckling strength of the analyzed sections. The k in Table 1 is the plate buckling coefficient computed by the proposed empirical equations (Eqs. (6) and (7)). M_k is the nominal flexural distortional buckling strength predicted by the proposed design method.

Fig. 4 shows a comparison of the proposed equations for k (Eqs. (6) and (7)) with the theoretical values k_o. The comparison indicates that the proposed equations match the theoretical values fairly well.

Table 1
Geometry of sections and results of parameter study.

Specimen	h (mm)	b (mm)	d (mm)	θ (deg)	t (mm)	f_y (MPa)	M_{DSd} (kN-m)	k_o	k	M_k (kN-m)	M_{DSd}/M_k
D8.5Z120-4	214.4	66.8	23.6	54.2	3.000	423	25.63	0.51	0.49	25.60	1.00
D8.5Z120-1	214.1	67.3	23.9	48.1	3.000	427	25.39	0.41	0.48	25.91	0.98
D8.5Z115-2	216.9	65.0	23.1	49.0	2.974	442	25.33	0.32	0.48	26.50	0.96
D8.5Z115-1	215.9	67.6	20.8	48.3	2.962	454	25.08	0.48	0.46	25.05	1.00
D8.5Z092-3	213.4	65.5	24.1	51.9	2.268	397	16.51	0.48	0.58	16.89	0.98
D8.5Z092-1	213.9	65.8	23.6	52.4	2.278	399	16.67	0.55	0.57	16.76	0.99
D8.5Z082-4	215.4	64.0	23.9	48.5	2.057	408	14.57	0.40	0.60	15.31	0.95
D8.5Z082-3	215.9	64.3	23.9	49.9	2.057	407	14.72	0.45	0.61	15.26	0.96
D8.5Z065-7	215.4	62.7	21.1	50.0	1.631	430	10.56	0.54	0.69	10.97	0.96
D8.5Z065-6	216.4	63.0	22.1	53.0	1.638	436	11.02	0.55	0.75	11.51	0.96
D8.5Z065-5	215.9	59.9	17.0	51.3	1.638	433	10.13	0.70	0.60	9.91	1.02
D8.5Z065-4	213.4	61.0	20.6	47.3	1.572	402	8.99	0.38	0.70	9.86	0.91
D8.5Z059-6	214.4	61.5	19.6	50.4	1.570	403	9.32	0.55	0.69	9.64	0.97
D8.5Z059-5	215.9	61.5	20.3	48.3	1.562	407	9.32	0.53	0.69	9.73	0.96
D11.5Z092-4	285.2	88.1	23.9	48.7	2.253	482	26.69	0.68	0.45	25.10	1.06
D11.5Z092-3	285.8	87.1	22.6	49.3	2.258	483	26.69	0.70	0.45	24.99	1.07
D11.5Z082-4	289.6	86.6	22.4	48.4	2.062	508	23.95	0.79	0.45	22.00	1.09
D11.5Z082-3	287.8	86.6	23.9	50.2	2.078	495	24.65	0.87	0.46	22.38	1.10
D8C097-7	206.5	54.6	16.5	80.8	2.543	587	22.46	0.45	0.55	23.04	0.97
D8C097-6	207.0	53.1	16.3	81.0	2.553	588	22.46	0.42	0.56	23.23	0.97
D8C097-5	204.7	50.8	16.8	86.7	2.535	577	21.53	0.58	0.60	21.70	0.99
D8C097-4	204.7	51.6	17.0	83.0	2.535	581	21.80	0.38	0.60	22.88	0.95
D8C085-2	204.7	50.3	16.0	86.0	2.096	364	12.09	0.80	0.70	11.93	1.01
D8C085-1	204.7	50.3	15.7	88.6	2.154	358	12.42	0.86	0.67	12.11	1.03
D8C068-6	201.7	48.5	16.8	80.0	1.798	544	12.86	1.62	0.94	11.89	1.08
D8C068-7	201.7	50.0	16.3	76.5	1.798	551	12.86	1.68	0.85	11.60	1.11
D8C054-7	203.5	51.8	13.5	83.4	1.341	281	5.29	0.70	0.95	5.58	0.95
D8C054-6	203.2	52.1	15.0	89.4	1.321	281	5.39	0.89	1.16	5.63	0.96
D8C045-1	207.8	49.5	17.0	89.0	0.884	148	2.20	4.00	3.23	2.16	1.02
D8C045-2	206.8	49.3	17.5	88.8	0.884	145	2.20	4.00	3.48	2.11	1.04
D8C043-4	203.7	51.1	13.5	87.3	1.166	313	4.64	1.36	1.23	4.59	1.01
D8C043-2	204.0	50.5	13.2	88.9	1.199	314	4.83	2.02	1.15	4.44	1.09
D8C033-2	207.0	50.5	17.3	87.1	0.856	141	1.96	3.25	3.41	1.98	0.99
D8C033-1	205.2	50.8	15.5	86.0	0.861	141	1.90	2.65	2.75	1.92	0.99
D12C068-11	305.6	51.6	13.0	82.0	1.638	227	8.55	0.53	0.52	8.58	1.00
D12C068-10	306.1	51.3	13.7	85.9	1.646	239	9.00	0.49	0.54	9.15	0.98
D12C068-2	302.8	52.1	13.2	82.5	1.687	388	12.54	0.50	0.52	12.66	0.99
D12C068-1	304.0	53.8	13.2	80.6	1.697	385	12.70	0.52	0.51	12.71	1.00
D10C068-4	256.0	50.8	12.2	83.2	1.590	152	5.30	0.78	0.57	5.14	1.03
D10C068-3	256.5	52.6	13.5	80.7	1.610	155	5.73	1.00	0.59	5.44	1.05
D10C056-3	253.7	50.0	16.8	88.0	1.445	533	11.43	1.55	0.93	10.59	1.08
D10C056-4	254.0	49.3	18.3	88.6	1.445	530	11.73	1.52	1.09	11.19	1.05
D10C048-1	252.5	52.3	15.7	86.1	1.214	352	6.76	1.44	1.04	6.45	1.05
D10C048-2	252.5	51.3	16.0	85.7	1.234	349	6.90	1.51	1.07	6.57	1.05
D6C063-2	152.1	50.5	16.0	88.7	1.468	385	5.67	1.39	1.80	5.90	0.96
D6C063-1	152.1	50.5	15.7	87.0	1.420	399	5.50	1.22	1.86	5.84	0.94
D3.62C054-4	94.7	47.8	10.4	87.0	1.410	221	1.77	2.19	2.14	1.73	1.02
D3.62C054-3	94.5	48.0	8.9	88.0	1.412	227	1.70	1.10	1.59	1.77	0.97
									Average		1.01
									Std. dev.		0.048

The proposed method produces similar results to the Direct Strength Method; the average ratio of DSM to the proposed method is 1.01 with a standard deviation of 0.048.

The proposed design procedure for the flexural distortional buckling is identical to the procedure for determining the flexural section strength stipulated in AISI S100 except that the proposed Eqs. (6) and (7) shall be used to replace Table B4-1 of AISI S100 in calculating the plate buckling coefficient k of the compression flange.

The proposed design equations are based on selected cold-formed steel sections, therefore limitations on pre-qualified sections shall be applied when the new design approach is used. The geometric limitations are listed as follows:

$h/t < 183$
$b/t < 60$
$0 < d/t < 20$
$47^\circ < \theta < 90^\circ$
$0.18 < d/b < 0.37$

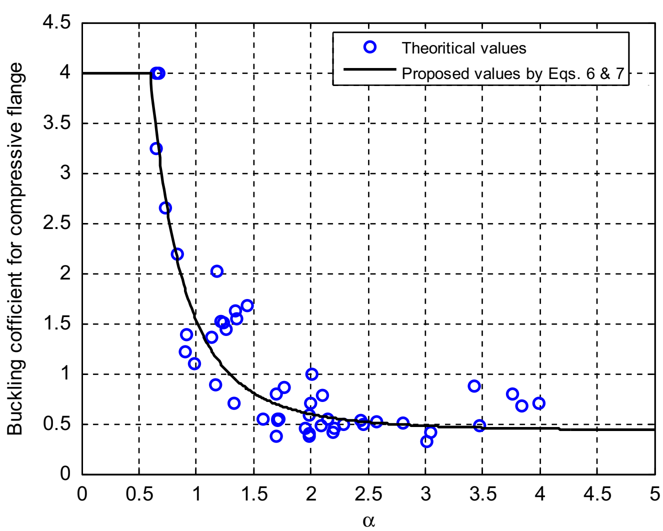

Fig. 4. Comparison of the proposed equations with the theoretical values.

3. Comparison with experimental results

Among the series of distortional buckling tests reported in Yu and Schafer [3], 17 out of 24 tests failed in distortional buckling. In each test, two nominally identical Z or C section members were attached at the loading points and both ends to restrict lateral–torsional buckling. The member with lower AISI S100 predicted flexural section strength in each test was regarded as the controlling specimen. The data of the controlling specimens are used herein to examine the proposed design method, the Direct Strength Method, the current design method in AISI S100, and the Eurocode 3 [15]. Table 2 lists the comparison. Since the Australian/New Zealand Standard [14] is essentially the same as DSM, only the results by DSM are listed. Table 2 shows that, in general, the proposed design method, DSM, EC3 and AS/NZS 4600 provide good agreements with the test results. The results by the proposed method are conservative and similar to results by DSM in terms of the average, the maximum and the minimum values. The standard deviation of the provided method is same as that for EC3.

Based on the experimental data listed in Table 2, the resistance factor, ϕ, for LRFD design and the factor of safety, Ω, for ASD design for the proposed design method can be determined using the provisions specified in Chapter F of AISI S100 with a target reliability index, β, of 2.5. The following equation is used to compute the resistance factors, ϕ:

$$\phi = C_\phi (M_m F_m P_m) e^{-\beta\sqrt{V_M^2+V_F^2+C_P V_P^2+V_Q^2}} \quad (8)$$

where C_ϕ is the calibration coefficient (1.52 for LRFD), M_m is the mean value of material factor, F_m is the mean value of fabrication factor, P_m is the mean value of professional factor, β is the target reliability index, V_M is the coefficient of variation of material factor, V_F is the coefficient of variation of fabrication factor, C_p is the coefficient factor, V_P is the coefficient of variation of test results and V_Q is the coefficient of variation of load factor (0.21 for LRFD).

The values of M_m, V_M, F_m and V_F were taken from Table F1 in AISI S100 using Flexural Member—Bending Strength as the type of component. The safety factor for ASD design can be determined by the following equation as specified in AISI S100:

$$\Omega = \frac{1.6}{\Phi} \quad (9)$$

Table 2
Comparison of the design methods with tests for distortional buckling of beams.

Specimen	λ	M_{test} (kip-in)	M_{test}/M_{DSd}	M_{test}/M_k	M_{test}/M_{AISI}	M_{test}/M_{EC3}
D8.5Z120-4	0.82	254	1.08	1.08	0.95	1.00
D8.5Z115-1	0.91	237	1.03	1.03	0.88	0.93
D8.5Z092-3	0.94	153	1.01	0.99	0.82	0.88
D8.5Z082-4	1.04	127	0.95	0.90	0.76	0.83
D8.5Z065-7	1.24	93	0.96	0.92	0.75	0.93
D8.5Z065-4	1.21	80	0.97	0.88	0.72	0.90
D11.5Z092-3	1.40	262	1.07	1.14	0.86	1.07
D11.5Z082-4	1.52	233	1.06	1.15	0.86	1.03
D8C097-6	0.93	204	0.99	0.96	0.85	0.91
D8C085-2	0.80	122	1.10	1.11	1.02	1.03
D8C068-7	1.10	105	0.89	0.99	0.84	0.85
D8C054-6	0.95	49	0.99	0.95	0.86	0.98
D8C043-4	1.12	43	1.01	1.02	0.90	1.03
D12C068-11	1.09	95	1.21	1.21	1.05	1.13
D10C068-4	0.79	51	1.05	1.08	1.01	1.01
D10C048-1	1.27	62	1.00	1.05	0.90	1.00
D6C063-1	0.93	52	1.03	0.97	0.93	0.85
Average			**1.02**	**1.03**	**0.88**	**0.96**
Standard deviation			0.07	0.09	0.09	0.09
Max. value			1.21	1.21	1.05	1.13
Min. value			0.89	0.88	0.72	0.83

Note: $\lambda=(M_y/M_{crd})^{0.5}$; M_y—yield moment; M_{crd}—critical elastic distortional buckling moment; M_{test}—tested flexural strength by Yu and Schafer [3]; M_{AISI}—nominal flexural strength by AISI S100; M_{EC3}—nominal flexural strength by EC3.

Table 3
Resistance factors and safety factors for proposed design method.

	New method #1	
Quantity	17	
Mean	1.03	
Std. dev.	0.09	
COV	0.087	
M_m	1.10	
V_m	0.10	
F_m	1.00	
P_m	1.03	
V_f	0.05	
β (LRFD)	2.5	
V_Q	0.21	AISI S100
ϕ (LRFD)	0.91	0.90
Ω (ASD)	1.76	1.67

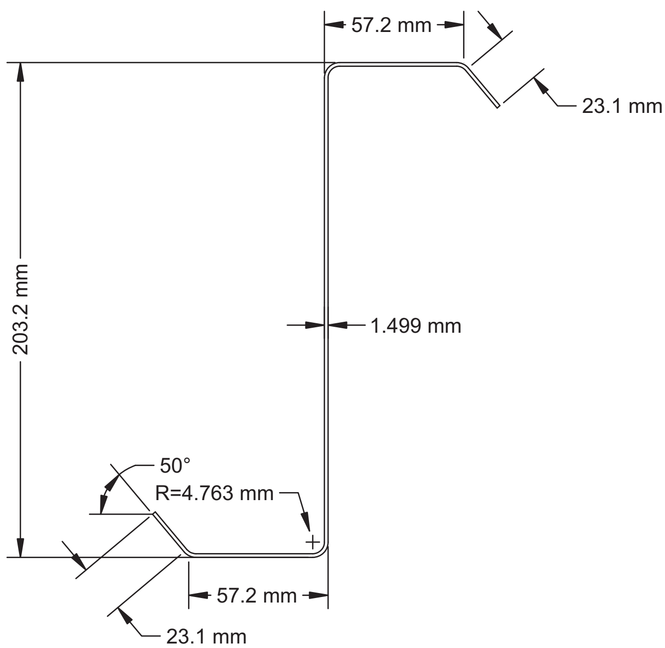

Fig. 5. Cross-section of 8ZS2.25 × 059.

Table 3 summarizes the calculated resistance factor and safety factor as well as the adopted factors for Eq. (8). The results show that the proposed method yields a slightly greater resistance factor than the value specified by AISI S100 for DSM for the flexural distortional buckling strength computed by DSM (0.91 vs. 0.90), which indicates that the proposed method has the same reliability as the adopted DSM design approach in AISI S100.

4. Design example

To illustrate the procedure of the proposed design method, an example is provided herein. The example is to calculate the nominal distortional buckling strength of a standard cold-formed steel Z section 8ZS2.25 × 059 in flexure as shown in Fig. 5. The material yield stress is 379 MPa. The Z section is identical to Example I-10 in AISI Cold-Formed Steel Design Manual [16].

The brief calculation procedure is as follows:

Step 1: Calculate the effective width b of the compression flange:

$$w/t = 48.0/1.499 = 32.0 > 0.328S = (0.328)(29.6) = 9.7$$

$$\alpha = \frac{0.0021tb}{d\sin(\theta)}h^{0.9} = \frac{(0.0021)(1.499)(57.2)}{(23.1)(\sin(50))}203^{0.9} = 1.237$$

$$\alpha = \frac{tb}{d\sin(\theta)}h^{0.9} = \frac{(0.059)(2.25)}{(0.910)(\sin(50))}8^{0.9} = 1.237$$

$$k = 0.43 + \frac{3.57}{(\alpha+0.4)^{3.5}} = 0.43 + \frac{3.57}{(1.237+0.4)^{3.5}} = 1.066$$

$$F_{cr} = k\frac{\pi^2 E}{12(1-\mu^2)}\left(\frac{t}{w}\right)^2 = 1.066\frac{(3.14)^2(203395)}{12(1-(0.3)^2)}\left(\frac{1.499}{48.0}\right)^2 = 191\,\text{MPa}$$

$$\lambda = \sqrt{\frac{f}{F_{cr}}} = \sqrt{\frac{379}{191}} = 1.409 > 0.673$$

$$b = \rho w = (1-0.22/\lambda)/\lambda w = (1-0.22/1.409)/(1.409)(48.0) = 28.7\,\text{mm}$$

Step 2: Calculate the effective width of the edge stiffener following Section B3.2 of AISI S100. The calculation is the same as Example I-10 in AISI [16] and therefore the equations are omitted herein. The results are $d_s' = 16.7$ mm, $d_s = 15.5$ mm.

Step 3: Calculate the initial effective width of the web by following Section B2.3 of AISI S100 and then determine the initial location of neutral axis.

Step 4: Iterate the computation of the location of the neutral axis and the effective width of the web following Section B2.3 of AISI S100 until the desired accuracy is reached. Steps 3 and 4 follow the common design procedure specified by AISI S100; the detailed calculations are ignored here. The resulting effective section modulus is $S_e = 25.32 \times 10^3\,\text{mm}^3$.

The last step is to calculate the nominal distortional buckling strength in flexure. $M_n = S_e F_y = (25.32 \times 10^3)(379) = 9.60$ KN-m

5. Conclusions

This paper presents an Effective Width Method for calculating the nominal distortional buckling strength of flexural cold-formed steel Z and C sections. The proposed method employs the current design procedure for flexural section strength in AISI S100 using the new equations of plate buckling coefficient to account for the distortional buckling mode. The proposed method is calibrated by the Direct Strength Method and has shown a similar performance to DSM when compared to experimental results. The proposed method allows engineers to examine the flexural distortional buckling strength using the existing design procedure in AISI S100 with simplified modifications.

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