Effective Width Method Based Design for Distortional Buckling

Cheng Yu

Trevor Lokie

Eighteenth International Specialty Conference on Cold-Formed Steel Structures
Orlando, Florida, U.S.A, October 26 & 27, 2006

Effective Width Method Based Design for Distortional Buckling of Cold-Formed Steel Beams

Cheng Yu[1], Trevor Lokie[2]

Abstract

This paper presents an Effective Width concept based design method against the distortional buckling of cold-formed steel Z and C-section beams. The distortional buckling may be the predominant buckling mode for many cold-formed steel studs, joists, purlins, or girts, unless the compression flange is fully restrained by attachment to sheathing or paneling. However the distortional buckling remains a largely unaddressed problem in the main body of the current North American Specification for the Design of Cold-Formed Steel Structural Members (NAS, 2001) Edition. Experimental investigations have indicated that NAS provides unconservative predictions for the distortional buckling failures. It was also found that the Direct Strength Method and Australian/New Zealand code work well for distortional buckling, but they demonstrate limited applicability for today's industry due to the need of advanced computation tools to determine the elastic buckling behavior of sections. The proposed method in this paper was based on the current design procedure in NAS (2001), it enables engineers to predict the distortional buckling strength of cold-formed steel Z or C-section beams using the existing design method, Effective Width Method, with limited modifications. The new method shows good agreements with experimental results as well as the Direct Strength Method predictions.

[1] Assistant Professor, University of North Texas (cyu@unt.edu)
[2] Research Assistant, University of North Texas (trevor_lokie@yahoo.com)

Introduction

Cold-formed steel flexural members may fail in local buckling, distortional buckling, or lateral-torsional buckling. Figure 1 illustrates a finite strip analysis of a Z-section in restrained flexure with web height 8.5 in. (216 mm), flange width 2.5 in. (64 mm), material thickness 0.073 in. (1.85 mm), and material yield stress of 55 ksi (379 MPa). The results are shown in a plot of buckling half wavelength vs. critical buckling moment - to - yield moment ratio. Three different buckling modes are identified in the finite strip results. The first minimum, at a half-wavelength of 5 in. (127 mm), is the local buckling mode which is characterized by the relatively short and repeated wavelength buckling of individual plate elements (web, compression flange and lip stiffener) with no relative movement of the nodes at corners (e.g., web-flange, flange-stiffener). The distortional buckling mode occurs at the second minimum point of the half-wavelength curve (at approximately 20 in. (508 mm)). 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 can also be driven by buckling of the web. Lateral-torsional buckling occurs at relatively long wavelengths, in which the section translates and rotates as a rigid-body without any change in the cross-sectional shape.

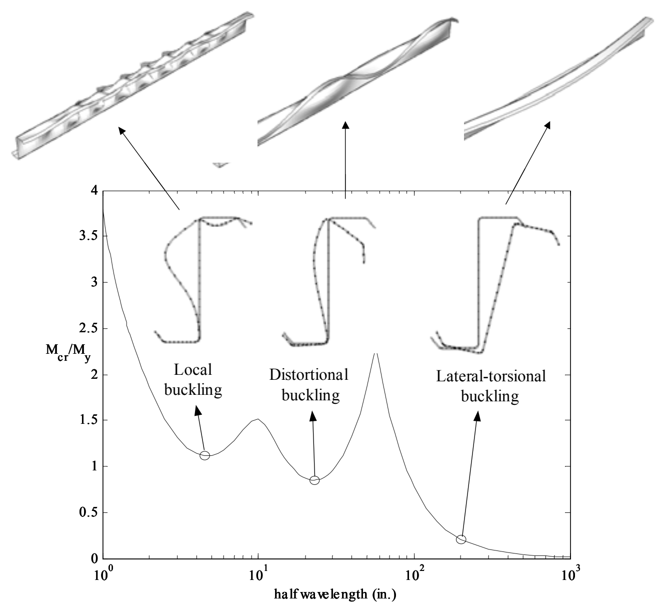

Figure 1 Buckling modes of a cold-formed steel Z-section in bending

For the analyzed Z-section in Figure 1, lateral-torsional buckling will be the first (lowest) elastic buckling mode if the unbraced length of the member is longer than approximately 100 in. (2540 mm). When the unbraced length is less than 10 in. (254 mm), the local buckling becomes the lowest mode. For other cases, the distortional buckling controls (final determination of the controlling mode requires examination of the post-buckling strength, but the elastic results do provide a helpful first indicator). Distortional buckling most often occurs in sections where lateral deformations (i.e. lateral-torsional buckling) are prevented by intermittent bracing (Ellifritt et al. 1998). 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.

However, the main body of North American Specification for the Design of Cold-Formed Steel Structural Members (NAS 2001) does not have sufficient procedures for design against distortional buckling. The NAS attempts to account for distortional buckling through an empirical reduction of the plate buckling coefficient (k) when calculating the effective width of the compression element (Schafer and Peköz 1998). However, the experimental work (Desmond et al. 1981) carried out for determining the empirical k expressions concentrated on flange local 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 (1990), Schuster (1992), Moreyra (1993), Ellifritt (1997), and Rogers and Schuster (1997). A series of distortional buckling tests on cold-formed steel lipped Z and C-section beams were recently conducted at the Structures Lab of Johns Hopkins University (Yu and Schafer 2004, 2006). The test results indicated that the current design method in NAS (2001) yielded average 12% unconservative flexural strength predictions for distortional buckling. It also indicated that the Direct Strength Method, Australian/New Zealand code, and European standard provide reasonable predictions for the distortional buckling failures.

The Direct Strength Method (DSM), adopted by American Iron and Steel Institute (AISI) as an alternative design procedure (NAS 2004), 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, regarded as the next generation design method, is still under development towards a comprehensive design procedure. Furthermore advanced numerical analysis tools such as finite strip or finite element software are generally required for determining the elastic buckling behavior of cross-sections. The effective width concept based design procedures of NAS (2001) is still widely utilized by today's engineers.

Therefore it is of importance to develop an effective width method for considering distortional buckling to add into the current Specification (NAS 2001). Although the Eurocode 3 (EC 2002) offers an effective width method against distortional buckling failures, the procedure involves complicate computation of the reduced thickness, and an additional iteration for edge stiffener is generally required, plus the test results showed EC3 provided unconsevative and relatively scattered predictions. In the paper, a simple and accurate effective width method is proposed to determine the flexural strength of distortional buckling for typical cold-formed steel lipped Z and C-section beams. The new method is examined by DSM and previously conducted tests.

Existing Design Methods for Flexural Strength of Distortional Buckling

Direct Strength Method and Australian/New Zealand Standard

The Direct Strength Method (NAS 2004) and the Australian/New Zealand Standard – Cold-Formed Steel Structures (AS/NZS 4600, 1996) employ similar equations for the distortional buckling of laterally braced cold-formed steel beams.

The nominal flexural strength, M_{nd}, for distortional buckling is

for $\lambda_d \leq 0.673$ (DSM); $\lambda_d \leq 0.674$ (AS/NZS 4600)

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

for $\lambda_d > 0.673$ (DSM); $\lambda_d > 0.674$ (AS/NZS 4600)

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

where $\lambda_d = \sqrt{M_y / M_{crd}}$, (3)

M_y is the yield moment, M_{crd} is the critical elastic distortional buckling moment.

The test results reported in Yu and Schafer (2004, 2006) showed that DSM and AS/NZS 4600 provided reasonable and conservative predictions for distortional buckling of cold-formed steel beams, the average test-to-predicted ratio was 1.02 with an standard deviation of 0.07 for both methods.

European Standard: Eurocode 3

The Eurocode 3 (EC3, 2002) provides specific provisions against distortional buckling strength for cold-formed steel beams. The method adopted in EC3 is essentially based on effective width concept, it 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:

$$\chi_d = 1.0, \quad \text{if } \overline{\lambda_d} \le 0.65 \tag{4}$$

$$\chi_d = 1.47 - 0.732\overline{\lambda_d}, \quad \text{if } 0.65 < \overline{\lambda_d} < 1.38 \tag{5}$$

$$\chi_d = \frac{0.66}{\overline{\lambda_d}}, \quad \text{if } \overline{\lambda_d} \ge 1.38 \tag{6}$$

where $\overline{\lambda_d} = \sqrt{f_{yb} / \sigma_{cr,s}}$, (7)

f_{yb} is the material yield strength, $\sigma_{cr,s}$ is the elastic critical stress for the stiffener.

EC3 assumes that the edge stiffener behaves as a compression member with continuous partial restraint, with a spring stiffness that depends on the boundary conditions and the flexural stiffness of the adjacent plane elements. Figure 2 shows the analysis model in EC3 to determine the rotational spring stiffness of the stiffener for Z or C sections. A hand solution of the elastic buckling stress of edge stiffeners in Z or C-sections is given in EC3.

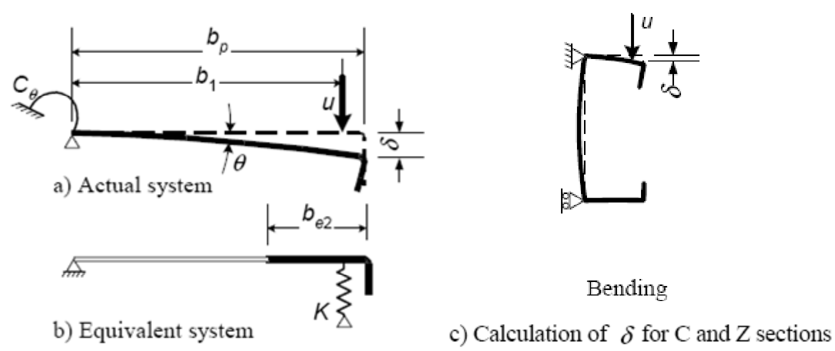

Figure 2 Model for calculating the rotational spring stiffness in EC3

The test results by Yu and Schafer (2004, 2006) indicated that EC3 provided slightly unconsevative predictions for the distortional buckling failures of cold-formed steel Z and C-section beams, the average test-to-predicted ratio is 0.96. EC3 also demonstrated relatively large deviation in the strength predictions. The standard deviation of the test-to-predicted ratio is 0.09.

Proposed Design Method for Flexural Strength of Distortional Buckling

The proposed design method was based on the effective width concept and was developed according to the current design procedure in NAS (2001) as well as the Direct Strength Method (NAS 2004).

When the cold-formed steel Z or C-section beams buckle in distortional buckling mode, as shown in Figure 1, the compression flange and edge stiffener rotate against the junction between the web element and the flange, at the same time plate buckling occurs on the compression portion of the web element. The rotation of flange-stiffener component in distortional buckling mode would change the effective widths in the three compression components (flange, edge stiffener, web) and the location of neutral axis compared to those of the local buckling mode. In EC3, the changes of the neutral axis location by the rotation of flange-stiffener component is not specifically addressed; the effect must be included in the calculation of reduced thickness for the edge stiffener. EC3 also ignores the changes in the formula for calculating the effective width of the web element from local buckling to distortional buckling, due to the fact that the effective width in the flange and edge stiffer play the more significant role in determining the flexural resistance of thin-walled, cold-formed steel sections than the web element does.

The proposed method adopts the above two assumptions of EC3 and employs the same design procedure/equations in Section C3.1.1 of NAS (2001) for the nominal section strength of flexural members, except for the provisions to determine the effective width of the compression flange. Eqs. 8 and 9 listed below are developed herein to calculate the buckling coefficient k of the compression flange. Therefore the proposed provisions to determine the effective width of compression flange for the flexural distortional buckling strength are same as NAS Section B4.2 except for using Eqs. 8 and 9 instead of Table B4.2 of NAS to calculate k.

$$k = 4.0, \qquad \text{if } \alpha \le 0.6 \tag{8}$$

$$k = 0.43 + \frac{3.57}{(\alpha + 0.4)^{3.5}} \qquad \text{if } \alpha > 0.6 \tag{9}$$

Where $\alpha = \frac{tb}{d\sin(\theta)} h^{0.9}$; (10)

b = out-to-out compression flange width;

d = out-to-out compression flange lip stiffener length;

h = out-to-out web depth;

t = base material thickness;

θ = compression flange stiffener angle from horizontal. (the dimensions refer to Figure 3)

Eqs. 8, 9 indicate that the proposed k values vary from 0.043 to 4.0. When the flange width goes to infinity or the stiffener is significantly small ($\alpha \rightarrow \infty$), 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 closed to 4.0.

Eqs. 8, 9 were developed by a parameter study based on the cold-formed steel Z and C-section beams conducted by Yu and Schafer (2004, 2006). Table 1 summarizes the geometries of the analyzed sections and the results by the parameter study. Only the dimensions of interest are included in Table 1, for the completed dimensions, refer to Yu and Schafer (2006). Figure 3 illustrates the definitions for dimensions used for Z and C-sections.

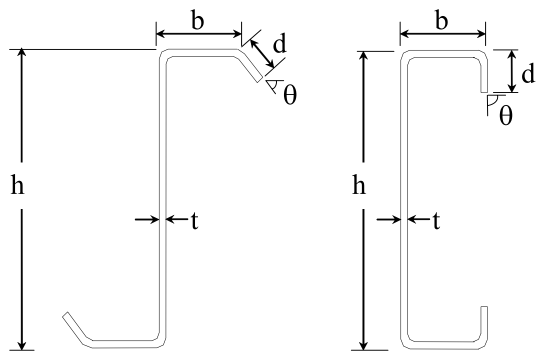

Figure 3 Definitions for dimensions of Z and C sections

In Table 1, "M_{DSd}" is the nominal flexural strength of distortional buckling calculated by the Direct Strength Method (Eqs. 1-3). The first step of the parameter study is to calculate the required buckling coefficient ("k_o" in Table 1) for the compression flange in order to allow the current NAS method (Chapter C3.1.1, NAS 2001) matches the results of the Direct Strength Method for the distortional buckling strength of the analyzed sections. The second step is to develop an empirical equation (Eqs. 8, 9) to approximate the "theoretical" k_o. The column "k" in Table 1 summarizes the results by Eqs. 8, 9 and "M_k" is the nominal strength by the proposed method for the distortional buckling of the analyzed sections.

Table 1 Geometry of beams and results of parameter study

Specimen	h (in.)	b (in.)	d (in.)	θ (deg)	t (in.)	f_y (ksi)	M_{DSd} (kip-in)	k_o	k	M_k (kip-in)	M_{DSd}/M_k
D8.5Z120-4	8.44	2.63	0.93	54.2	0.1181	61.4	235.2	0.51	0.49	234.9	1.00
D8.5Z120-1	8.43	2.65	0.94	48.1	0.1181	61.9	233.0	0.41	0.48	237.8	0.98
D8.5Z115-2	8.54	2.56	0.91	49.0	0.1171	64.1	232.4	0.32	0.48	243.2	0.96
D8.5Z115-1	8.50	2.66	0.82	48.3	0.1166	65.8	230.1	0.48	0.46	229.9	1.00
D8.5Z092-3	8.40	2.58	0.95	51.9	0.0893	57.6	151.5	0.48	0.58	155.0	0.98
D8.5Z092-1	8.42	2.59	0.93	52.4	0.0897	57.8	153.0	0.55	0.57	153.8	0.99
D8.5Z082-4	8.48	2.52	0.94	48.5	0.0810	59.2	133.7	0.40	0.60	140.5	0.95
D8.5Z082-3	8.50	2.53	0.94	49.9	0.0810	59.0	135.1	0.45	0.61	140.0	0.96
D8.5Z065-7	8.48	2.47	0.83	50.0	0.0642	62.4	96.9	0.54	0.69	100.7	0.96
D8.5Z065-6	8.52	2.48	0.87	53.0	0.0645	63.3	101.1	0.55	0.75	105.6	0.96
D8.5Z065-5	8.50	2.36	0.67	51.3	0.0645	62.8	93.0	0.70	0.60	90.9	1.02
D8.5Z065-4	8.40	2.40	0.81	47.3	0.0619	58.3	82.5	0.38	0.70	90.5	0.91
D8.5Z059-6	8.44	2.42	0.77	50.4	0.0618	58.5	85.5	0.55	0.69	88.5	0.97
D8.5Z059-5	8.50	2.42	0.80	48.3	0.0615	59.1	85.5	0.53	0.69	89.3	0.96
D11.5Z092-4	11.23	3.47	0.94	48.7	0.0887	69.9	244.9	0.68	0.45	230.3	1.06
D11.5Z092-3	11.25	3.43	0.89	49.3	0.0889	70.1	244.9	0.70	0.45	229.3	1.07
D11.5Z082-4	11.40	3.41	0.88	48.4	0.0812	73.7	219.8	0.79	0.45	201.9	1.09
D11.5Z082-3	11.33	3.41	0.94	50.2	0.0818	71.8	226.2	0.87	0.46	205.4	1.10
D8C097-7	8.13	2.15	0.65	80.8	0.1001	85.2	206.1	0.45	0.55	211.4	0.97
D8C097-6	8.15	2.09	0.64	81.0	0.1005	85.3	206.1	0.42	0.56	213.2	0.97
D8C097-5	8.06	2.00	0.66	86.7	0.0998	83.7	197.6	0.58	0.60	199.1	0.99
D8C097-4	8.06	2.03	0.67	83.0	0.0998	84.2	200.0	0.38	0.60	210.0	0.95
D8C085-2	8.06	1.98	0.63	86.0	0.0825	52.8	110.9	0.80	0.70	109.5	1.01
D8C085-1	8.06	1.98	0.62	88.6	0.0848	51.9	114.0	0.86	0.67	111.1	1.03
D8C068-6	7.94	1.91	0.66	80.0	0.0708	78.9	118.0	1.62	0.94	109.1	1.08
D8C068-7	7.94	1.97	0.64	76.5	0.0708	79.9	118.0	1.68	0.85	106.4	1.11
D8C054-7	8.01	2.04	0.53	83.4	0.0528	40.8	48.5	0.70	0.95	51.2	0.95
D8C054-6	8.00	2.05	0.59	89.4	0.0520	40.7	49.5	0.89	1.16	51.7	0.96
D8C045-1	8.18	1.95	0.67	89.0	0.0348	21.4	20.2	4.00	3.23	19.8	1.02
D8C045-2	8.14	1.94	0.69	88.8	0.0348	21.0	20.2	4.00	3.48	19.4	1.04
D8C043-4	8.02	2.01	0.53	87.3	0.0459	45.4	42.6	1.36	1.23	42.1	1.01
D8C043-2	8.03	1.99	0.52	88.9	0.0472	45.5	44.3	2.02	1.15	40.7	1.09
D8C033-2	8.15	1.99	0.68	87.1	0.0337	20.5	18.0	3.25	3.41	18.2	0.99
D8C033-1	8.08	2.00	0.61	86.0	0.0339	20.4	17.4	2.65	2.75	17.6	0.99
D12C068-11	12.03	2.03	0.51	82.0	0.0645	32.9	78.5	0.53	0.52	78.7	1.00
D12C068-10	12.05	2.02	0.54	85.9	0.0648	34.7	82.6	0.49	0.54	84.0	0.98
D12C068-2	11.92	2.05	0.52	82.5	0.0664	56.3	115.1	0.50	0.52	116.2	0.99
D12C068-1	11.97	2.12	0.52	80.6	0.0668	55.9	116.5	0.52	0.51	116.6	1.00
D10C068-4	10.08	2.00	0.48	83.2	0.0626	22.0	48.6	0.78	0.57	47.2	1.03
D10C068-3	10.10	2.07	0.53	80.7	0.0634	22.5	52.6	1.00	0.59	49.9	1.05
D10C056-3	9.99	1.97	0.66	88.0	0.0569	77.3	104.9	1.55	0.93	97.2	1.08
D10C056-4	10.00	1.94	0.72	88.6	0.0569	76.9	107.6	1.52	1.09	102.7	1.05
D10C048-1	9.94	2.06	0.62	86.1	0.0478	51.1	62.0	1.44	1.04	59.2	1.05
D10C048-2	9.94	2.02	0.63	85.7	0.0486	50.6	63.3	1.51	1.07	60.3	1.05
D6C063-2	5.99	1.99	0.63	88.7	0.0578	55.9	52.0	1.39	1.80	54.1	0.96
D6C063-1	5.99	1.99	0.62	87.0	0.0559	57.8	50.5	1.22	1.86	53.6	0.94
D3.62C054-4	3.73	1.88	0.41	87.0	0.0555	32.1	16.2	2.19	2.14	15.9	1.02
D3.62C054-3	3.72	1.89	0.35	88.0	0.0556	32.9	15.6	1.10	1.59	16.2	0.97
									Average		1.01
									St. dev.		0.048

Note: the denotation of specimen label refers to Yu (2005). f_y – yield stress; M_{DSd} – nominal flexural strength of distortional buckling by Direct Strength Method; M_k – nominal flexural strength of distortional buckling by the proposed design method; k_o – theoretical values of buckling coefficient for compression flange; k – values of buckling coefficient for compression flange by Eqs. 8 and 9.

Figure 4 shows a comparison of the proposed equations for k with the theoretical values k_o. It indicates that the proposed equations match the theoretical values fairly well. The strengths calculated by the proposed method have a good agreement with the Direct Strength Method, the average ratio of DSM-to- the proposed method is 1.01 with a standard deviation 0.048.

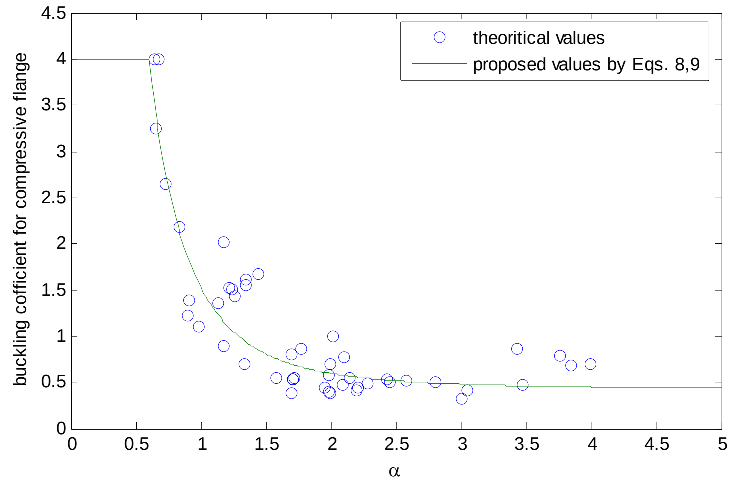

Figure 4 Comparison of the proposed equations with the theoretical values

The proposed design procedure for the flexural distortional buckling can be simply expressed as below.

Step 1: calculate the effective width of the compression flange following Section B4.2 of NAS (2001). Use the proposed equations (Eqs. 8 and 9) to determine the buckling coefficient k instead of using Table B4.2 of NAS (2001);

Step 2: calculate the effective width of the edge stiffener following Section B3.2-a of NAS (2001);

Step 3: calculate the initial effective width of the web element following Section B2.3 of NAS (2001) 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 element following Section B2.3 of NAS (2001) till the desired accuracy is reached; an updated neutral axis location shall be used in each iteration; the effective section modulus shall be obtained at the end.

Step 5: calculate the nominal strength by using the material yield stress and the effective section modulus.

Comparison with Experimental Results

In the series of distortional buckling tests reported in Yu and Schafer (2004, 2006), 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 NAS (2001) predicted flexural section strength in each tests was regarded as the controlling specimen. The data of the controlling specimens are used herein to examine the proposed design method as well as the Direct Strength Method (NAS 2004), the current design method in NAS (2001), and the Eurocode 3 (EC3, 2002). Since the Australian/New Zealand Standard (AS/NZS 4600, 1996) is essentially the same as DSM, only results by DSM are listed in Table 2. The results show that in general the proposed design method, DSM, EC3 and AS/NZS 4600 provide good agreements with the test results. However EC3 demonstrates an average of 4% unconservativeness along with large variance compared to DSM. 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.

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_{NAS}	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 (2004, 2006); M_{NAS} – nominal flexural strength by NAS (2001); M_{EC3} – nominal flexural strength by Eurocode 3 (2002).

Figure 5 shows a comparison of the test-to-predicted ratio for the analyzed design methods. The x-axis is the section slenderness $(M_y/M_{crd})^{0.5}$ where M_y is the yield moment and M_{crd} is the critical elastic distortional buckling moment. The plot illustrates the majority of the NAS predictions are below the line y=1 which means the predictions are unconservative. It also shows that the results for the slender sections ($(M_y/M_{crd})^{0.5} > 1$) by all the methods are more scattered than the unslender sections. EC3 tends to yield unconservative predictions for unslender sections, and the proposed method tends to give over-conservative predictions for highly slender sections.

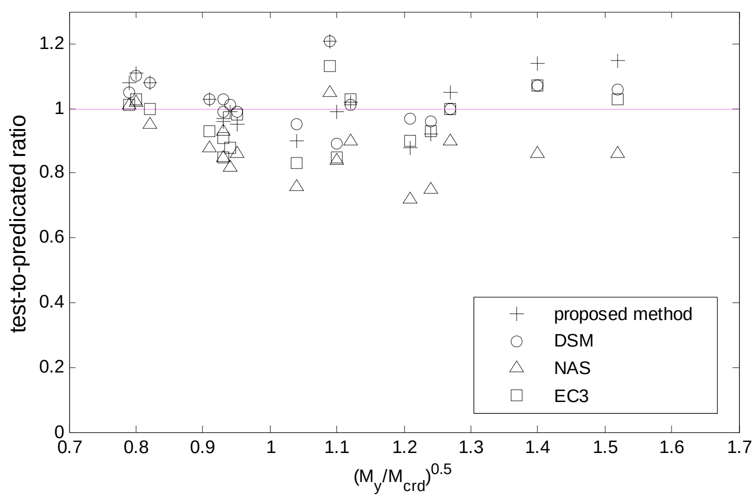

Figure 5 Comparison of the test-to-predicted for analyzed design methods

Design Example

To illustrate the potential impact of the findings of this paper in design, the nominal distortional buckling strength of a NAS standard section 8ZS2.25x059 in flexure (Example I-10 of AISI 2002) as shown in Figure 6 is considered herein. The material yield stress is 55 ksi.

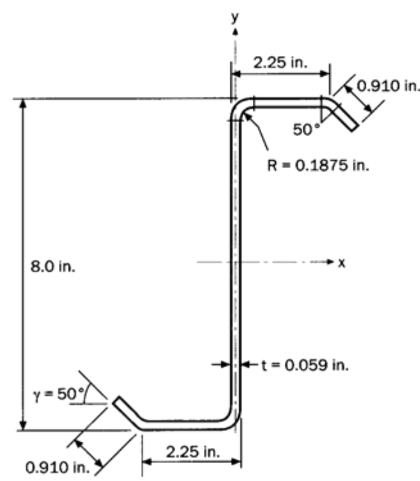

Figure 6 Cross-section of 8ZS2.25x059

The brief calculation procedure is as follows:

Step 1: calculate the effective width b of the compression flange.

$$w / t = 1.889 / 0.059 = 32.0 > 0.328S = (0.328)(29.6) = 9.7$$

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

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

$$F_{cr} = k \frac{\pi^2 E}{12(1-\mu^2)} \left(\frac{t}{w}\right)^2 = 1.066 \frac{(3.14)^2 (29500)}{12(1-(-0.3)^2)} \left(\frac{0.059}{1.889}\right) = 27.7 \text{ ksi}$$

$$\lambda = \sqrt{\frac{f}{F_{cr}}} = \sqrt{\frac{55}{27.7}} = 1.408 > 0.673$$

$$b = \rho w = (1 - 0.22 / \lambda) / \lambda w = (1 - 0.22 / 1.408) / (1.408)(1.889) = 1.131 \text{ in.}$$

Step 2: calculate the effective width of the edge stiffener following Section B3.2-a of NAS (2001). The calculation is same as Example I-10 in AISI (2002) therefore omitted herein. The results are $d_s' = 0.657$ in. $d_s = 0.610$ in.

Step 3 is to calculate the initial effective width of the web by following Section B2.3 of NAS (2001) and then determine the initial location of neutral axis. Step

4 is to iterate the computation of the location of the neutral axis and the effective width of the web following Section B2.3 of NAS (2001) till the desired accuracy is reached. Step 3 and Step 4 follows the common design procedure specified by NAS (2001), the detailed calculations are ignored here. The resulting effective section modulus is $S_e = 1.545 \text{ in}^3$.

Last step is to calculate the nominal distortional buckling strength in flexure. $M_n = S_e F_y = (1.545)(55) = 85.0$ kip-in.

Conclusions

This paper presents an effective width method for calculating the distortional buckling strength of cold-formed steel Z and C-section beams. The proposed method employs the current design procedure for flexural section strength in NAS (2001) except for using specific equations to determine the effective width of the compression flange to account for the distortional buckling mode. The proposed method was calibrated by the Direct Strength Method and has shown a similar performance to DSM. Compared to the European code, the proposed method yields better strength prediction and does not need iteration of calculation on the edge stiffener. The proposed method was developed in order to overcome the unaddressed distortional buckling problem in the main body of NAS (2001), thus allow engineers to examine the flexural distortional buckling strength using the existing design procedure in NAS (2001) with minimum modifications.

Acknowledge

The presented work is sponsored by University of North Texas through a Faculty Research Grant.

References

AISI (2002). “AISI Cold-Formed Steel Design Manual, 2002 Edition”, American Iron and Steel Institute, Washing DC.

AS/NZS 4600 (1996). “AS/NZS 4600: 1996 Cold-Formed Steel Structures”, Standards Australia and the Australian Institute of Steel Construction.

Desmond T.P., Peköz, T. and Winter, G. (1981). “Edge Stiffeners for Thin-Walled Members”, *Journal of the Structural Division*, ASCE, Feb. 1981.

EC3 (2002). “European Standard EN1993-1-3. Eurocode 3: Design of steel structure”, European Committee for Standardization.

Ellifritt, D. S., Glover, R.L., and Hren, J.D. (1997). "Distortional Buckling of Channels and Zees Not Attached to Sheathing", *Report for the American Iron and Steel Institute*.

Ellifritt, D. S., Glover, R.L., and Hren, J.D. (1998). "A Simplified Model for Distortional Buckling of Channels and Zees in Flexure", *Proceedings of the 14th International Specialty Conference on Cold-Formed Steel Structures*, St. Louis MO., October 15-16, 1998.

Moreyra, M.E. (1993). "The Behavior of Cold-Formed Lipped Channels under Bending", *M.S. Thesis*, Cornell University, Ithaca, New York.

NAS (2001). "North American Specification for the Design of Cold-Formed Steel Structural Members 2001 Edition", American Iron and Steel Institute, Washington, D.C..

NAS (2004). "North American Specification for the Design of Cold-Formed Steel Structural Members: Appendix 1, Design of Cold-Formed Steel Structural Members Using the Direct Strength Method", American Iron and Steel Institute, Washington, D.C.

Rogers, C.A., Schuster, R.M. (1997). "Flange/web distortional buckling of cold-formed steel sections in bending", *Thin-Walled Structures*, Vol. 27, No. 1, 13-29.

Schafer, B.W., Peköz, T. (1998). "Direct Strength Prediction of Cold-Formed Steel Members using Numerical Elastic Buckling Solutions", *Proceedings of the 14th International Specialty Conference on Cold-Formed Steel Structures*, St. Louis, MO, October 15-16, 1998.

Willis, C.T., Wallace, B. (1990). "Behavior of Cold-Formed Steel Purlins under Gravity Loading", *Journal of Structural Engineering*, ASCE, 116(8).

Schuster, R.M. (1992). "Testing of Perforated C-Stud Sections in Bending", *Report for the Canadian Sheet Steel Building Institute*, University of Waterloo, Waterloo, Ontario.

Yu, C., Schafer, B.W. (2004). "Distortional Buckling Tests on Cold-Formed Steel Beams", *Proceedings of the 17th International Specialty Conference on Cold-Formed Steel Structures*, Orlando, FL, November 4-5, 2004.

Yu, C. (2005). "Distortional buckling of cold-formed steel members in bending", *PhD Thesis*, Johns Hopkins University, Baltimore, MD.

Yu, C., Schafer, B.W. (2006). "Distortional Buckling Tests on Cold-Formed Steel Beams", ASCE, *Journal of Structural Engineering*. 132 (4) 515-528.