Direct Strength Method for Cold-Formed Steel

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In 2004, *The North American Specification for the Design of Cold-Formed Steel Structural Members* adopted a new alternative design approach as Appendix 1, *Design of Cold-Formed Steel Structural Members Using Direct Strength Method*. Subsequently, a *Direct Strength Method Design Guide* was published to help engineers and researchers to better understand and apply this method. This article will introduce the Direct Strength Method from a practical approach and provide a brief description of what is included in the *Direct Strength Method Design Guide*.

What is the Direct Strength Method?

The Direct Strength Method (DSM) predicts the strength of a cold-formed member by consideration of the member buckling loads in local, distortional and global buckling under a given loading, bracing and supporting condition. Different from the Effective Width Method, the DSM does not need to calculate the effective section properties; instead, a cross-section elastic buckling analysis is needed. The elastic buckling analysis can be accomplished with manual calculation or computer aided numerical analysis.

Some Basic Knowledge About Member Buckling

Since cross-section elastic buckling analysis is an important and integral part of the DSM, it is necessary for the engineer to understand the cause of the buckling modes and the different types of buckling modes.

When the thin elements of a cold-formed member is subjected to compressive stress, which may be caused by a bending moment or an axial load, the element will tend to respond in-plane to the compressive stress, but also out-of-plane due to the low bending rigidity of the element. The out-of-plane movement is strongly associated with the elastic buckling stress of the element. When all of the elements of a member are considered together as a cross-section, several different potential buckling modes are potentially associated with the member:

a) local buckling – involves primarily plate bending of the elements; and, with respect to the cross-section deformations, the fold lines of the elements do not translate but merely rotate as each compression element buckles out-of-plane. The half-wavelength of local buckling, i.e., the length at which the buckling shape repeats along the member length, is usually shorter than or equal to the largest dimension of the member under compressive stress.

b) global buckling – involves buckling where the whole cross section, without distortion, starts to bend laterally (flexural buckling), rotate (torsional buckling), or bend and rotate simultaneously (flexural-torsional buckling). Global buckling is also called Euler buckling. The half-wavelength of the global buckling is determined by the member's unbraced length.

c) distortional buckling – involves deformations which vis ually appears as a combination of local and global buckling, where part of the cross-section (e.g., the flange) responds rigidly by twisting or translating about a point (e.g., the flange/web junction) and another part of the cross-section (e.g., the web) undergoes plate bending. The half-wavelength of distortional buckling falls between the half-wavelengths of local and global buckling. It is possible that a member that is fully braced from global buckling (i.e., no global buckling) may still be subjected to distortional buckling.

The elastic buckling modes and the corresponding buckling loads can be determined manually, or numerically. A detailed discussion can be found in the DSM *Design Guide*.

What are the Advantages in Using Direct Strength Method?

The DSM provides a consistent approach in determining member flexural and compression strengths disregarding what cross section the member may have. The advantages of this method may be summarized as follows:

1) The DSM enables the engineer to readily consider the distortional buckling. This feature is especially important for members that have their strength controlled by distortional buckling.

2) The Direct Strength enables the engineer to predict the strength of cold-formed members with optimized cross sections such as the ones shown in *Figure 1*.

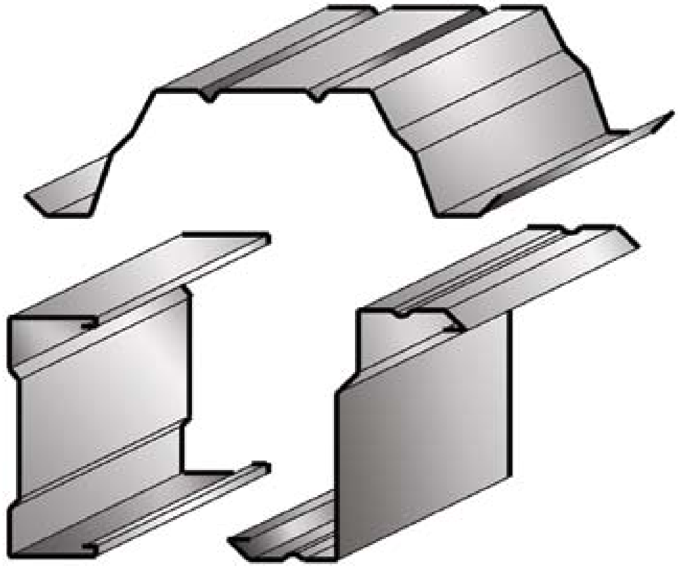

Figure 1: Optimized Sections for Cold-Formed Members

With computer-aided elastic buckling analysis, it is possible to obtain the buckling loads for members with any type of cross section. The DSM is a new and viable choice for developing or optimizing cold-formed steel products.

3) The DSM design approach, which focuses on member elastic buckling instead of effective width calculations, may also help engineers to better understand the behavior of cold-formed steel members so that an adequate method may be selected to increase the member strength or reinforcing the member in retrofitting.

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The application of the Direct Strength Method will be explained in the following design example:

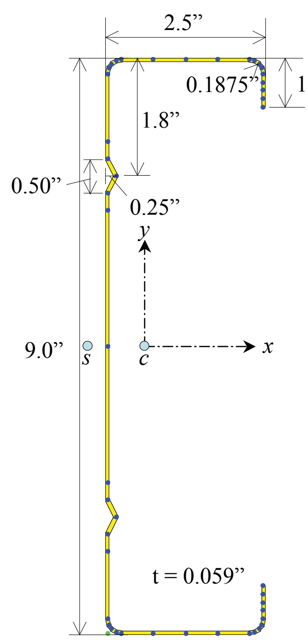


Figure 2: Geometry of Modified C-Section

Determine the flexural and compression strengths for a fully braced member with the cross section shown in *Figure 2*. The yield stress is 55 ksi. CUFSM is used to obtain the elastic buckling loads. The program also provides the unreduced section properties as follows:

Area:	A	=	0.933	in.^{2}
Moment of inertia about x-axis:	I_x	=	10.818	in.^{4}
Moment of inertia about y-axis:	I_y	=	0.781	in.^{4}
Distance between web and centroid:	x_c	=	0.659	in.
Distance between web and the shear center:	m	=	1.078	in.
Coordinate of shear center:	x_o	=	-1.859	in.
Shear constant:	J	=	0.00108	in.^{4}
Warping constant:	C_w	=	13.33	in.^{6}

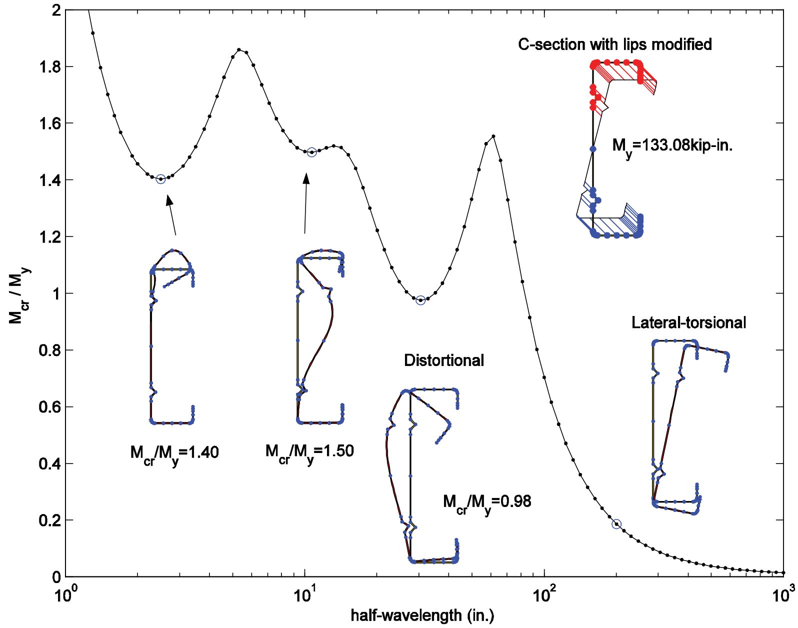
It should also be noted that a fully braced member means that the member will not be subject to global buckling. However, the member may still be subject to local and distortional buckling.

To obtain good Finite Strip analysis results, it is recommended that:

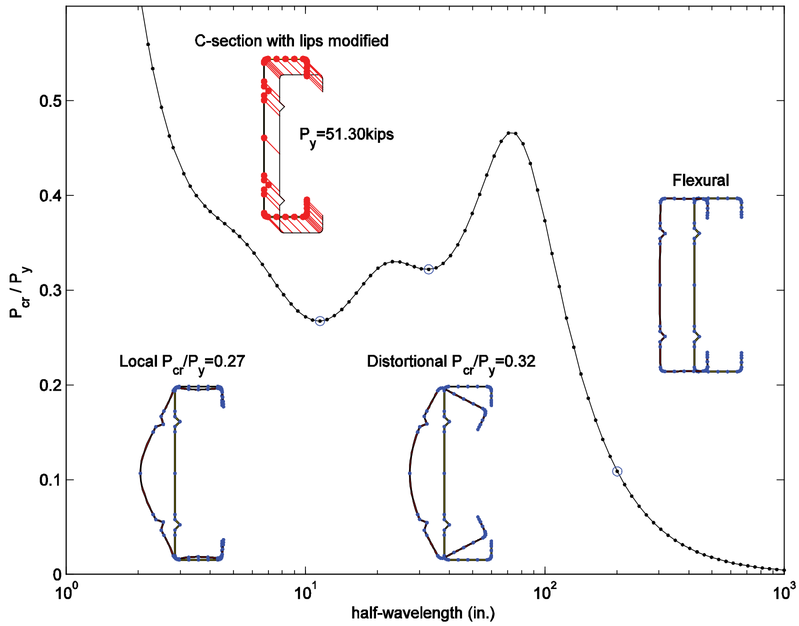
1) The nodal points should be selected along the centerline of the cross section. At least two elements should be used in any portion of a plate that is subjected to compression. A smooth corner should be modeled with at least four nodal points. The small dots along the member cross-section profile in *Figure 2* are the nodal points used for this example.

2) To determine the buckling half-wavelengths, different wavelengths (from small to large) should be selected and smaller increments should be used in the ranges with the minimum load factors as shown on the half-wave length vs. load factor curve in *Figures 3 (a)* and *(b)*.

Detailed information on using the Finite Strip Method and sample examples can be found in the DSM *Design Guide*.



(a) Bending



(b) Compression

Figure 3: Elastic Analysis Results

The following buckling loads are obtained from the FSM analysis as shown in *Figure 3*:

Bending:

Yield moment: $M_y = S_xF_y = \frac{I_y}{h/2}F_y = \frac{10.818}{4.5} x55 = 132.22$ kip-in

Local buckling in flange: $M_{cr\ell} = 1.4\ M_y$ (controls for local buckling)

Local buckling in web: $M_{cr\ell} = 1.5\ M_y$

Distortional buckling: $M_{crd} = 0.98\ M_y$

Global buckling: Since the member is fully braced, global buckling will not occur. Therefore:

$$M_{ne} = M_y$$

Compression:

Squash load: $P_y = A\ F_y = 0.933 \text{ x } 55 = 51.32$ kips

Local buckling in web: $P_{cr\ell} = 0.27\ P_y$

Distortional Buckling: $P_{crd} = 0.32\ P_y$

Global buckling: will not occur for fully braced member. Therefore:

$$P_{ne} = P_y$$

Flexural Strength

In accordance with DSM Section 1.2.2, the nominal strength, M_n, is the minimum of nominal strength due to global buckling (M_{ne}), local buckling ($M_{n\ell}$) and distortional buckling (M_{nd}). The corresponding buckling strengths are calculated as follows:

Local Buckling Strength in accordance with DSM Section 1.2.2.2:

$$\lambda_\ell = \sqrt{\frac{M_{ne}}{M_{cr\ell}}} = \sqrt{\frac{M_y}{1.4M_y}} = 0.845$$

For $\lambda_\ell > 0.776$

$$M_{n\ell} = \left[1 - 0.15\left(\frac{M_{cr\ell}}{M_{ne}}\right)^{0.4}\right]\left(\frac{M_{cr\ell}}{M_{ne}}\right)^{0.4} M_{ne} = \left[1 - 0.15\left(\frac{1.4M_y}{M_y}\right)^{0.4}\right]\left(\frac{1.4M_y}{M_y}\right)^{0.4} M_y$$

$= 0.95M_y = 126$ kip-in

Distortional Buckling Strength in accordance with DSM Section 1.2.2.3:

$$\lambda_d = \sqrt{\frac{M_y}{M_{crd}}} = \sqrt{\frac{M_y}{0.98M_y}} = 1.01$$

For $\lambda_d > 0.673$

$$M_{nd} = \left[1 - 0.22\left(\frac{M_{crd}}{M_y}\right)^{0.5}\right]\left(\frac{M_{crd}}{M_y}\right)^{0.5} M_y = \left[1 - 0.22\left(\frac{0.98M_y}{M_y}\right)^{0.5}\right]\left(\frac{0.98M_y}{M_y}\right)^{0.5} M_y$$

$= 0.77M_y = 102$ kip-in

The predicted flexural strength in accordance with DSM Section 1.3 is:

M_n = minimum (M_{ne}, $M_{n\ell}$, M_{nd}) = minimum (M_y, 0.95 M_y, 0.77 M_y)
= 0.77 M_y = 102 kip-in.

The above analysis indicates that the distortional buckling strength controls in this example.

Since the geometry of the section does not fall within the pre-qualified sections as defined in DSM Section 1.1.1.2, the safety and the resistance factors for rational engineering analysis should be used in accordance with Specification Section A1.1(b). Thus the available strengths of the member are:

LRFD: $\phi_b = 0.8$ $\phi_b M_n = 0.8 \times 102 = 81.6$ kip-in.

ASD: $\Omega_b = 2.00$ $\frac{M_n}{\Omega_b} = \frac{102}{2.00} = 51$ kip-in.

Compression Strength

In accordance with DSM Section 1.2.1, the nominal strength, P_n, is the minimum of nominal strength due to global buckling (P_{ne}), local buckling ($P_{n\ell}$) and distortional buckling (P_{nd}). The corresponding buckling strengths are calculated as follows:

Local buckling strength in accordance with DSM Section 1.2.1.2:

$$\lambda_\ell = \sqrt{\frac{P_{ne}}{P_{cr\ell}}} = \sqrt{\frac{P_y}{0.27P_y}} = 1.925$$

For $\lambda_\ell > 0.776$

$$P_{n\ell} = \left[1 - 0.15\left(\frac{P_{cr\ell}}{P_{ne}}\right)^{0.4}\right]\left(\frac{P_{cr\ell}}{P_{ne}}\right)^{0.4} P_{ne} = \left[1 - 0.15\left(\frac{0.27P_y}{P_y}\right)^{0.4}\right]\left(\frac{0.27P_y}{P_y}\right)^{0.4} P_y$$

$= 0.54P_y = 27.7$ kips

Distortional buckling strength in accordance with DSM Section 1.2.1.3:

$$\lambda_d = \sqrt{\frac{P_y}{P_{crd}}} = \sqrt{\frac{P_y}{0.32P_y}} = 1.768$$

For $\lambda_d > 0.673$

$$P_{nd} = \left[1 - 0.25\left(\frac{P_{crd}}{P_y}\right)^{0.6}\right]\left(\frac{P_{crd}}{P_y}\right)^{0.6} P_y = \left[1 - 0.25\left(\frac{0.32P_y}{P_y}\right)^{0.6}\right]\left(\frac{0.32P_y}{P_y}\right)^{0.6} P_y$$

$= 0.44P_y = 22.6$ kips

The predicted compression strength in accordance with DSM Section 1.2 is:

P_n = minimum (P_{ne}, $P_{n\ell}$, P_{nd}) = minimum (P_y, 0.54P_y, 0.44P_y)
= 0.44 P_y = 22.6 kips

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The previous analysis (see pages 30-31) indicates that the distortional buckling strength controls compression strength of the member as well.

As indicated in the flexural strength calculation, the safety and the resistance factors in Specification section A1.1(b) should be applied. therefore, the available strengths of the section are:

$$\text{LRFD: } \phi_b = 0.8 \quad \phi_b P_n = 0.8 \times 22.6 = 18.1 \text{ kips}$$

$$\text{ASD: } \Omega_b = 2.00 \quad \frac{P_n}{\Omega_b} = \frac{22.6}{2.00} = 11.3 \text{ kips}$$

How Does the DSM Work?

The DSM shows that member strength (M_n) is the minimum of the nominal strengths due to local buckling ($M_{n\ell}$), distortional buckling (M_{nd}) and global buckling (M_{ne}). With the buckling loads determined by the elastic buckling analysis, the nominal strengths of $M_{n\ell}$, M_{nd}, and M_{ne} can be determined using the design equations as provided in the Appendix 1 of the AISI *Specification*.

Since the DSM can virtually be used for any cold-formed steel members, safety and resistance factors have been developed both for pre-qualified members and for non-qualified members. Pre-qualified members represent the range of sections used in the development of the DSM design equations and Tables are provided summarizing these dimensions in Appendix 1 of the AISI *Specification*. For non-qualified members, the safety and resistance factors provided in AISI *Specification* Chapter 1.1(b) for rational engineering analysis should be used.

What are the Limitations of the Direct Strength Method?

The Direct Strength Method predicts the member strength based on the member's elastic buckling loads. If a member section contains very slender elements, the local buckling load would be very low. The strength calculated based on DSM would be overly conservative in this case. However, members with very slender element are inefficient and prone to serviceability problems. If folded longitudinal stiffeners are provided, the strength will be increased and the predicted strength with the DSM will be improved greatly.

In addition, the DSM does not provide provisions for shear, web crippling, members with holes, etc. The existing provisions in the AISI *Specification* can be used in conjunction with the DSM.

What is Included in the Direct Strength Method Design Guide?

The *Direct Strength Method Design Guide* was developed by Dr. Ben Schafer, who is also the original developer of the Direct Strength Method. The *Design Guide* is aimed at providing practical guidance to design engineers. Extensive materials are provided:

1) Elastic Buckling Analysis: Closed-form solutions and numerical solutions are provided with the emphasis on the Finite Strip Analysis Method (FSM). Detailed discussion and techniques are provided on how to interpret the FSM results and differentiate buckling modes.

2) Design Examples: 14 examples are provided which cover cold-formed members with typical and modified C- and Z-sections, hat and angle sections, rack type section and wall panels. In each example, the Guide provides (a) elastic buckling analysis results by FSM, (b) member strength using the DSM, and comparison with the results from the Effective Width Method. In addition, Mathcad files for all the design examples are provided.

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3) Charts: Prescriptive guidelines are provided for developing beam and column charts. Examples are provided to show step-by-step how the charts are developed. The information provided can be used to create span and load tables based on the DSM.

4) Special treatments are provided on how to take into consideration moment gradient, rotational restraint to members, members with holes, and support conditions that are not pinned.

What Materials and Tools are Needed for Using the Direct Strength Method?

The following materials are needed or recommended for using the Direct Strength design:

1) *North American Specification for the Design of Cold-Formed Steel Structural Members*, 2001 edition.

2) Appendix 1, Design of Cold-Formed Steel Structural Members Using Direct Strength Method. This document is included in *Supplement 2004 to the North American Specification for the Design of Cold-Formed Steel Structural Members*, 2001 edition.

3) A computer-aided elastic analysis software is recommended. One of such software is the freely available open source software, CUFSM, can be downloaded from the link **www.ce.jhu.edu/bschafer/cufsm**. A tutorial for using this software can be found from the link **www.ce.jhu.edu/bschafer/cufsm/#Tutorials**.

4) The *Direct Strength Method Design Guide*. It is a recommended document for engineers to better understand and utilize the method.

The documents listed in items 1, 2 and 4 can be obtained from the AISI online store at (**www.steel.org**).

Future Research

Although the Direct Strength Method has been adopted as the alternative method by the Cold-Formed Steel Specification, research work continues in the areas on how to apply this method to perforated members, how to effectively count on the member strength in combined bending and compression (i.e., produce more accurate capacities than that from the traditional beam-column interaction equations), and how to develop a method to expand the ranges for pre-qualified members. This future research work will certainly make the Direct Strength design an even more comprehensive and robust design method.▪

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