COMMENTARY

C3.1.6 Distortional Buckling Strength [Resistance]

Distortional buckling is an instability that may occur in members with edge stiffened flanges, such as lipped C- and Z-sections. As shown in Figure C-C3.1.6-1, this buckling mode is characterized by instability of the entire flange, as the flange along with the edge stiffener rotates about the junction of the compression flange and the web. The length of the buckling wave in distortional buckling is considerably longer than local buckling, and noticeably shorter than lateral-torsional buckling. The *Specification* provisions of Section B4.2 partially account for distortional buckling, but research has shown that a separate limit state check is required (Ellifritt, Sputo, and Haynes 1992, Hancock, Rogers, and Schuster 1996, Kavanagh and Ellifritt 1994, Schafer and Peköz 1999, Hancock 1997, Yu and Schafer 2003, 2006). Thus, in 2006 Section C3.1.6 was added to address distortional buckling as a separate limit state.

Determination of the nominal strength in distortional buckling (*Specification* Equation C3.1.6-2) was validated by testing. Results of one such study (Yu and Schafer 2006) are shown in Figure C-C3.1.6-2. The Direct Strength Method of Appendix 1 of the *Specification* also uses Equation C3.1.6-2. In addition, the Australian / New Zealand Specification (AS / NZS 4600) has used Equation C3.1.6-2 since 1996. Calibration of the safety and resistance factors for Equation C3.1.6-2 is provided in the commentary to Appendix 1.

Distortional buckling is unlikely to control the strength if (a) edge stiffeners are sufficiently stiff and thus stabilize the flange (as is often the case for C-sections, but typically not for Z-sections due to the use of sloping lips), (b) unbraced lengths are long and lateral-torsional buckling strength limits the capacity, or (c) adequate rotational restraint is provided to the compression flange from attachments (panels, sheathing, etc.).

The primary difficulty in calculating the strength in distortional buckling is to efficiently estimate the elastic distortional buckling stress, F_d. Recognizing the complexity of this calculation this section provides three alternatives: C3.1.6(a) provides a conservative prediction for unrestrained C- and Z-sections, C3.1.6(b) provides a more comprehensive method for C- and Z-Section members and any open section with a single web and single edge stiffened compression flange, and C3.1.6(c) offers the option to use rational elastic buckling analysis, e.g., see the Appendix 1 commentary. The equations of C3.1.6(a) assume the compression flange is unrestrained; however, the methods of C3.1.6(b) and (c) allow for a rotational restraint, k_ϕ, to be included to account for attachments which restrict flange rotation.

While it is always conservative to ignore the rotational restraint, k_ϕ, in many cases it may be beneficial to include this effect. Due to the large variety of possible conditions, no specific method is provided for determining the rotational restraint. Instead, per Section A1.1 of the *Specification*, k_ϕ may be estimated by testing or rational engineering analysis. Test determination of k_ϕ may use AISI TS-1-02 (AISI 2002). K from this method is a lower bound estimate of k_ϕ. The member lateral deformation may be removed from the measured lateral deformation to provide a more accurate estimate of k_ϕ.

Testing on 8 and 9.5 in. (203 and 241 mm) deep Z-sections with a thickness between

0.069 (1.75 mm) and 0.118 in. (3.00 mm), through-fastened 12 in. (205 mm) o.c., to a 36 in. (914 mm) wide, 1 in. (25.4 mm) and 1.5 in. (38.1 mm) high steel panels, with up to 6 in. (152 mm) of blanket insulation between the panel and the Z-section, results in a k_ϕ between 0.15 to 0.44 kip-in./rad./in. (0.667 to 1.96 kN-mm/rad./mm) (MRI 1981).

Additional testing on C- and Z-sections with pairs of through-fasteners provides considerably higher rotational stiffness: for 6 and 8 in. (152 and 203 mm) deep C-sections with a thickness between 0.054 and 0.097 in. (1.27 and 2.46 mm), fastened with pairs of fasteners on each side of a 1.25 in. (31.8 mm) high steel panel flute at 12 in. (305 mm) o.c., k_ϕ is 0.4 kip-in./rad./in. (1.78 kN-mm/rad./mm); and for 8.5 in. (216 mm) deep Z-sections with a thickness between 0.070 and 0.120 in. (1.78 to 3.05 mm), fastened with pairs of fasteners on each side of 1.25 in. (31.8 mm) high steel panel flute at 12 in. (305 mm) o.c., k_ϕ is 0.8 kip-in./rad./in. (3.56 kN-mm/rad./mm) (Yu and Schafer 2003, Yu 2005).

Examples of rational engineering analysis to estimate the rotational stiffness are provided in the Direct Strength Method Design Guide (2006). For a flexural member, k_ϕ can be approximated as:

$$k_\phi \approx EI/(W/2) \qquad \text{(C-C3.1.6-1)}$$

where E is the modulus of the attached material, I is the moment of inertia of the engaged attachment, and W is the member spacing. The primary complication in such a method is determining how much of the attachment (decking, sheathing, etc.) is engaged when the flange attempts to deform. For the Z-sections tested in Yu (2005) experimental k_ϕ is 0.8 kip-in./rad./in. (3.56 kN-mm/rad./mm). Using an estimate of EI/(W/2) the rational engineering values are k_ϕ of 9 kip-in./rad/in. (40.0 kN-mm/rad./mm) if the entire panel, flutes and all, are engaged; k_ϕ of 1.2 kip-in./rad/in. (5.34 kN-mm/rad./mm) if only the corrugated bottom panel, but not the flutes, is engaged; and k_ϕ of 0.003 kip-in./rad./in. (0.0133 kN-mm/rad./mm) if plate bending of the t = 0.019 in. (0.483 mm) panel occurs. The observed panel engagement is between the last two estimates, and assuming the corrugated bottom pan, but not the 1.25 in. (31.8 mm) high flutes is engaged is reasonable.

For members with wood sheathing attached, little experimental information is available. The problem has been studied numerically using the same paired fastener detail as in Yu's (2005) and Yu and Schafer (2003) tests but replacing the steel panel with a simulated wood member, thickness = 0.5 in. (12.7 mm), E = 1000 ksi (6900 MPa), and μ = 0.3. The calculated k_ϕ is 5.1 kip-in./rad./in. (22.7 kN-mm/rad./mm) for 6 and 8 in. (152 to 203 mm) deep C-sections with a thickness between 0.054 and 0.097 in. (1.37 and 2.46 mm); and k_ϕ is 4.1 kip-in./rad./in. (18.2 kN-mm/rad./mm) for 8.5 in. (216 mm) deep Z-sections with thickness between 0.070 and 0.120 in. (1.78 mm and 3.05 mm). From calculations assuming a fully engaged ½ in. (12.7 mm) thick wood sheet on top of C- or Z-section members spaced 12 in. (305 mm) apart, k_ϕ is predicted to be 1.7 kip-in./rad./in. (7.56 kN-mm/rad./mm). Thus, use of EI/(W/2) provides a reasonably conservative approximation, with I calculated assuming the full engagement of wood sheet.

The presence of moment gradient can also increase the distortional buckling moment (or equivalently stress, F_d). However, this increase is lessened if the moment gradient occurs over a longer length. Thus, in determining the influence of moment gradient (β) the ratio of the end moments, M_1/M_2, and the ratio of the critical distortional buckling length to the unbraced length, L/L_m, should both be accounted for. Yu (2005) performed elastic buckling analysis with shell finite element models of C- and Z-sections under different moment gradients to examine this problem. Significant scatter exists in the results, therefore a lower bound prediction (*Eq.* C3.1.6-11) for the increase was selected.

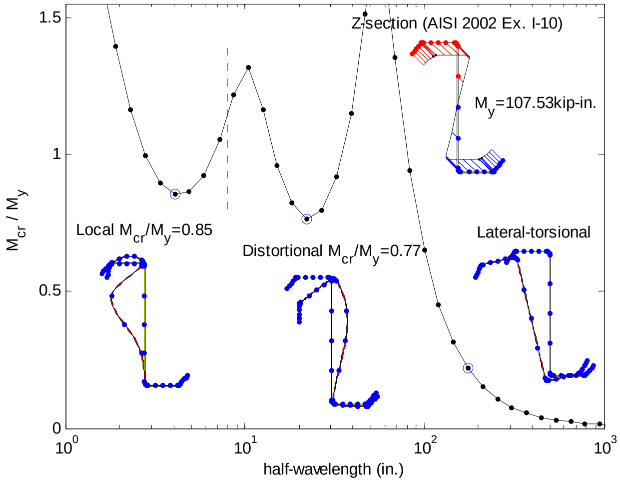


Figure C-C3.1.6-1 Rational Elastic Buckling Analysis of a Z-Section under Restrained Bending Showing Local, Distortional, and Lateral-Torsional Buckling Modes

(a) Simplified Provision for Unrestrained C- and Z-sections with simple lip stiffeners

The provision of C3.1.6(a) provides a conservative approximation to the distortional buckling length, L_{cr}, and stress, F_d, for C- and Z-sections with simple lip stiffeners bent about an axis perpendicular to the web. The provision ignores any rotational restraint, which would restrain distortional buckling. The expressions were specifically derived as a conservative simplification to those provided in section C3.1.6(b) and (c).

(b) For C- and Z-sections or any open section with a stiffened compression flange extending to one side of the web where the stiffener is either a simple lip or a complex edge stiffener

The provisions of C3.1.6(b) provide a general method for calculation of the distortional buckling stress, F_d, for any open section with an edge stiffened compression flange, including complex edge stiffeners. The provisions of C3.1.6(b) also provide a more refined answer for any C- and Z-section including those meeting the criteria of C3.1.6(a). The expressions employed here are derived in Schafer and Peköz (1999) and verified for complex stiffeners in Schafer et al. (2006). The equations used for the distortional buckling stress, F_d, in AS / NZS 4600 are also similar to those in *Specification* Section C3.1.6 (b), except that when the web is very slender and is restrained by the flange, AS / NZS 4600 uses a simpler, conservative treatment. Since the provided expressions can be complicated, solutions for the geometric properties of C- and Z-sections based on centerline dimensions are provided in Table C-C3.1.6(b)-1.

(c) Rational elastic buckling analysis

Rational elastic buckling analysis consists of any method following the principles of mechanics to arrive at an accurate prediction of the elastic distortional buckling stress (moment). It is important to note that this is a rational **elastic buckling** analysis and not simply an arbitrary rational method to determine ultimate strength. A variety of rational computational and analytical methods can provide the elastic buckling moment with a high degree of accuracy. Complete details are provided in section 1.1.2 of the commentary to Appendix 1 of the *Specification*. The safety and resistance factors of this section have been shown to apply to a wide variety of cross-sections undergoing distortional buckling (via the methods of Appendix 1). As long as the member falls within the geometric limits of main *Specification* B1.1 the same safety and resistance factors have been assumed to apply. Application of the β expression, to account for moment gradient, as provided in C3.1.6(b) is a rational extension to solutions which do not typically account for moment gradient such as the finite strip method.

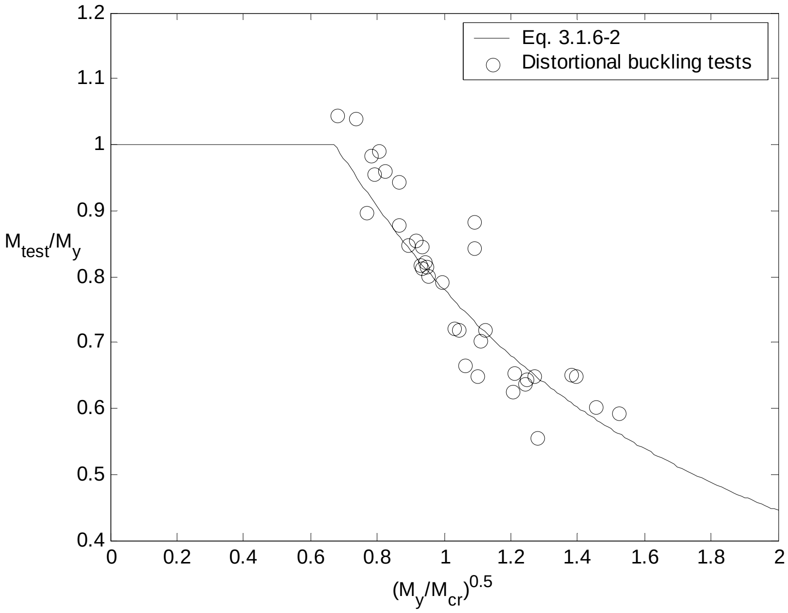
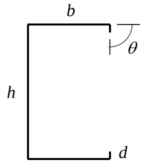
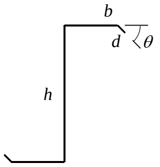


Figure C-C3.1.6-2 Performance of Distortional Buckling Prediction with Test Data on Common C- and Z-sections in Bending (Yu and Schafer 2004)

Table C-C3.1.6(b)-1 Geometric flange properties for C- and Z-sections

	
$A_f = (b+d)t$	$A_f = (b+d)t$
$J_f = \frac{1}{3}bt^3 + \frac{1}{3}dt^3$	$J_f = \frac{1}{3}bt^3 + \frac{1}{3}dt^3$
$I_{xf} = \dfrac{t\left(t^2b^2 + 4bd^3 + t^2bd + d^4\right)}{12(b+d)}$	$I_{xf} = \dfrac{t\left(t^2b^2 + 4bd^3 - 4bd^3\cos^2(\theta) + t^2bd + d^4 - d^4\cos^2(\theta)\right)}{12(b+d)}$
$I_{yf} = \dfrac{t\left(b^4 + 4db^3\right)}{12(b+d)}$	$I_{yf} = \dfrac{t\left(b^4 + 4db^3 + 6d^2b^2\cos(\theta) + 4d^3b\cos^2(\theta) + d^4\cos^2(\theta)\right)}{12(b+d)}$
$I_{xyf} = \dfrac{tb^2d^2}{4(b+d)}$	$I_{xyf} = \dfrac{tbd^2\sin(\theta)(b + d\cos(\theta))}{4(b+d)}$
$C_{wf} = 0$	$C_{wf} = 0$
$x_o = \dfrac{b^2}{2(b+d)}$	$x_o = \dfrac{b^2 - d^2\cos(\theta)}{2(b+d)}$
$h_x = \dfrac{-\left(b^2 + 2db\right)}{2(b+d)}$	$h_x = \dfrac{-\left(b^2 + 2db + d^2\cos(\theta)\right)}{2(b+d)}$
$h_y = y_o = \dfrac{-d^2}{2(b+d)}$	$h_y = y_o = \dfrac{-d^2\sin(\theta)}{2(b+d)}$

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