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DISTORTIONAL BUCKLING FORMULAE FOR THIN WALLED CHANNEL AND Z-SECTIONS WITH RETURN LIPS

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SUMMARY

Cold-formed Channel- and Z-sections subject to both flexure and torsion may undergo distortional buckling where the flange and lip rotate about the flange/web junction. This mode of failure is prevalent in purlin sections when lateral deformation of the section is prevented and when the sections are manufactured from high strength steel. In an attempt to prevent distortional buckling, some manufacturers have added additional return lips to the flange lips to produce complex edge stiffeners.

The Australian/New Zealand Standard for Cold-Formed Steel Structures includes design rules for determining the distortional buckling strength of cold-formed beam and column sections. These design rules require the computation of the elastic distortional buckling stress. Appendix D of AS/NZS 4600 provides design rules for computing the elastic distortional buckling stress of general channels in compression, simple lipped channels in compression and simple lipped Channel- and Z-sections in bending about an axis perpendicular to the web.

The paper describes general formulations for computing the elastic distortional buckling stresses of sections with return lips including those with sloping lips and return lips. The accuracy of the formulations is compared with the results for a large range of section geometries using a finite strip buckling analysis which can be regarded as providing accurate solutions for distortional buckling stress. Explicit expressions are presented in the paper for the flange properties.

1. INTRODUCTION

Cold-formed thin-walled steel sections are susceptible to instability in a variety of modes which can be described generically as local buckling, distortional buckling and overall buckling. Local buckling is characterised by internal buckling of the elements of the section in which there is no relative movement of the nodes. Overall buckling is a rigid body translation of a cross-section without any change in cross-sectional shape.

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Distortional buckling involves the movement of the nodes relative to one another and occurs at half-wavelengths intermediate between the two. The flange and lip rotate about the flange/web junction so that the mode is called flange-distortional buckling. The mode is most common for edge-stiffened channel- and Z-sections, such as those used for storage racks and purlins. For many section geometries, distortional buckling will be the controlling mode, and consequently an accurate estimation of the stress at which distortional buckling occurs will form a critical part of the design.

Rigorous analytical expressions for the elastic distortional buckling stress of sections in compression have been developed by Lau and Hancock[1], and for sections in flexure by Hancock[2], both of which have been recently included in the Australian/New Zealand Standard for Cold-Formed Steel Structures[3]. These formulae have been tested against accurate solutions based on the finite strip method, for channel-sections with a simple lip stiffener in compression and flexure. However, with recent developments of channel- and Z-sections including inclined and return lips, it has become apparent that further research is required into the accuracy of these formulae and possible limits that may be required when designing such sections.

It is the purpose of this paper to present analytical expressions for the elastic flange-distortional buckling stress. These expressions are compared with accurate solutions using a finite strip buckling analysis[4] based on the theory developed by Plank and Wittrick[5] to determine their accuracy.

2. ELASTIC BUCKLING MODES OF THIN-WALLED MEMBERS

2.1 Sections with shallow lip stiffeners

When shallow lip stiffeners are used for channel- and Z-sections, the graph of buckling stress versus half-wavelength is as shown in Fig. 1. The graph shows an additional minimum at Point C.

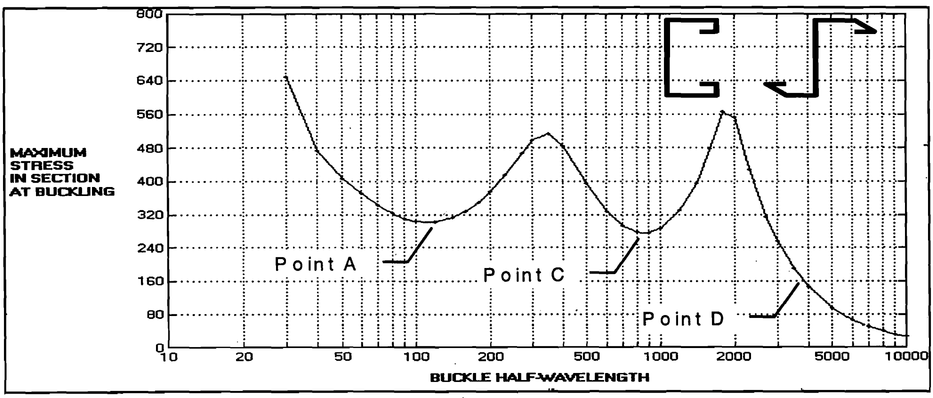


Figure 1 Buckling stress vs Half-wavelength for sections with shallow lip stiffeners

Points A and D correspond to the local and flexural-torsional buckling modes shown in Fig. 2, and Point C occurs at an intermediate half-wavelength and corresponds to the flange-distortional buckling mode, as also shown in Fig. 2.

Flange-distortional buckling of compression members involves rotation of each flange and lip about the flange/web junction in opposite directions as shown in Fig. 2(a). The web undergoes single curvature flexure at the same half-wavelength as the flange buckle, and the whole section may translate in a direction normal to the web also at the same half-wavelength as the flange and web buckling deformations.

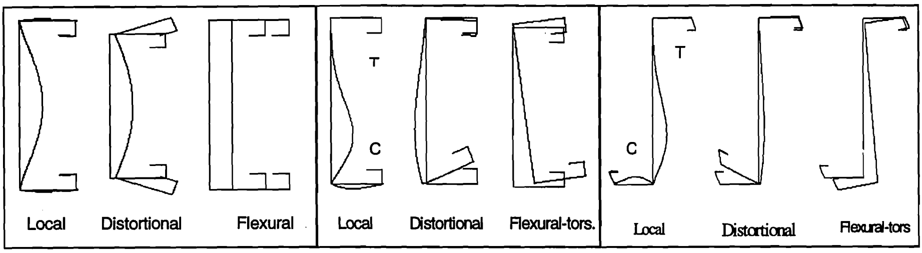


Figure 2(a) Channel in Compression **Figure 2(b) Channel in Flexure** **Figure 2(c) Z-section in Flexure**

Figure 2 Buckling modes

Flange-distortional buckling of flexural members involves rotation of only the compression flange and lips about the flange/web junction as shown in Figs 2(b) and (c). The web undergoes double curvature flexure at the same half-wavelength as the flange buckle, and the compression flange may translate in a direction normal to the web also at the same half-wavelength as the flange and web buckling deformations.

2.2 Sections with deep lip stiffeners

When large lips are used for channel and Z-sections in flexure, of the order of 20 mm or more, an additional buckling mode may form shown at Point B in Figure 3.

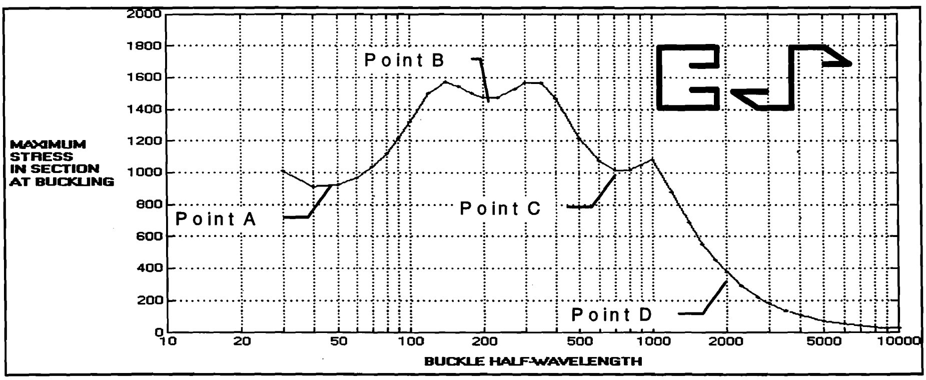


Figure 3 Buckling stress vs Half-wavelength for sections with deep lip stiffeners

Points A, C and D correspond to local, flange-distortional and flexural-torsional buckling modes as in Fig. 2. The mode at Point B is a new distortional mode which involves a distortional buckle of the lips as shown in Fig. 4. It has been called flange-lip distortional buckling in this paper.

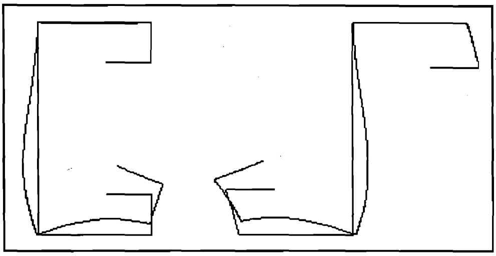


Figure 4 Flange-lip distortional buckling mode

The web undergoes flexure as before, and there is distortion in the compression flange. The compression lips rotate about the flange-lip junction. This mode was found in channel and Z-sections under flexure, with webs of 100 mm, flanges of either 50 mm or 75 mm, and with lips and return lips of 15 mm or 20 mm.

For practical purposes, this mode of distortional buckling is not likely to be critical, since very large lip depth to web depth ratios would be required in order to bring down the buckling stress of this mode to that of the local and flange-distortional modes.

For the purpose of this paper, this mode is recognised, but since it is not a critical mode of buckling no attempt has been made to derive an explicit expression for it. Where sections have been investigated that contain this mode, the distortional buckling stress for the section was taken as that for the flange-distortional buckling mode corresponding to Point C in Fig. 3.

3. DEVELOPMENT OF THE FLANGE-DISTORTIONAL BUCKLING EQUATIONS

3.1 Sections in pure compression

The paper by Lau and Hancock[1] derives distortional buckling formulae for channel columns based on a simple flange buckling model where the flange is treated as a thin-walled compression member as shown in Fig. 5 undergoing flexural-torsional buckling, and assuming that the flanges are undistorted. The rotational spring stiffness k_ϕ represents the flexural restraint provided by the web which is in pure compression, and the translational spring stiffness k_x represents the resistance to translational movement of the section in the buckling mode.

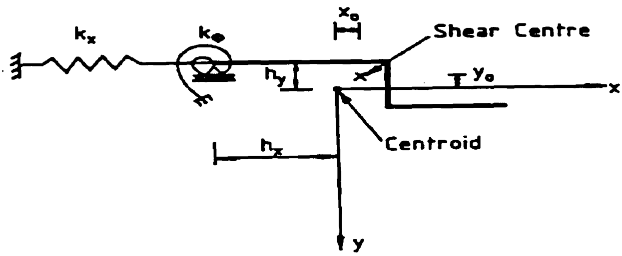


Figure 5 Flange-lip combination elastically restrained along flange-web junction

The combined torsional and flexural buckling equations of an undistorted section with continuous elastic supports formulated by Vlasov[6] and modified by Timoshenko and Gere[7] are solved in the Lau and Hancock paper to produce Eq. 1.

$$\left[\frac{\pi^2 EI_{xy}}{\lambda^2}(x_0 - h_x) + \frac{\lambda^2 k_x}{\pi^2}(y_0 - h_y) - Py_0\right]^2 -$$

$$\left(\frac{\pi^2 EI_y}{\lambda^2} + \frac{\lambda^2 k_x}{\pi^2} - P\right)\left[GJ + \frac{\pi^2}{\lambda^2}\left(EI_w + EI_x(x_0 - h_x)^2\right) - P\left(\frac{I_0}{A} - x_0^2 + h_x^2\right) + \frac{\lambda^2}{\pi^2}\left(k_x(y_0 - h_y)^2 + k_\phi\right)\right] = 0$$

.... **(1)**

where A = section area
I_x , I_y = principal second moments of area
I_{xy} = product second moment of area
I_w = warping constant
J = torsion constant of the flange-lip combination
I_0 = polar second moment of area about the shear centre

Eq. 1 can be used to determine the distortional buckling load P at a particular value of the half-wavelength λ, in terms of the section properties and k_ϕ and k_x. However this process involves iterations of λ values to find the value which corresponds to the minimum value of P, which for design purposes is impractical. Thus an approximation is used for the critical value of λ which is determined by assuming that k_x approaches infinity and k_ϕ is equal to the limiting value of $2D/b_w$ of the web. For this condition λ critical is given by Eq. 2.

$$\lambda_{critical} = \pi\left(\frac{EI_{wc} b_w}{2D}\right)^{0.25}$$

.... **(2)**

where D = plate flexural rigidity per unit width

$$= \frac{Et^3}{12(1 - \nu^2)}$$

b_w = web depth

$$I_{wc} = I_w + I_x(x_0 - h_x)^2 + I_y(y_0 - h_y)^2 - 2I_{xy}(x_0 - h_x)(y_0 - h_y)$$

Further simplification of Eq. 1 is achieved by using an approximate equation for k_ϕ and assuming $k_x = 0$. The equation for k_ϕ is derived by a similar approach to Bleich[8], who determined the coefficient of rotational restraint between adjacent plate elements in channel-, I- and Z-sections for local buckling by using the limiting value of $2D/b_w$ and a multiplying factor in order to take account of the compressive force on the web. An additional factor of 0.06λ added to b_w is an empirical factor to allow for effects of shear and flange distortion.

$$k_\phi = \frac{2D}{b_w + 0.06\lambda}\left(1 - \frac{P'}{A\sigma_w}\right) \quad \text{(3)}$$

where σ_w = local buckling stress of web plate in compression

Eq. 3 can be rewritten as:

$$k_\phi = \frac{Et^3}{5.46(b_w + 0.06\lambda)}\left[1 - \frac{1.11 f'_{od}}{Et^2}\left(\frac{b_w^{\,2}\lambda}{b_w^{\,2} + \lambda^2}\right)^2\right] \quad \text{(4)}$$

Eqs 2,3 and $k_x = 0$ are substituted into Eq. 1 to form the explicit equations for the elastic distortional buckling load. These equations are shown in Appx. D1 of AS/NZS 4600[3].

3.2 Sections under flexure

The Lau and Hancock formulae for sections in compression were modified by Hancock[2] to apply to distortional buckling in flexure.

If the web of a section in compression is treated as a simply supported beam in flexure, then the rotational stiffness at the end would be 2EI/L. If the web of a section in flexure is treated as a beam simply supported at one end and built in at the other, then the rotational stiffness would be 4EI/L. Hence it can be concluded that the change in end restraint from the compression case to the flexure case will approximately double the torsional restraint stiffness k_ϕ. Further, the web element is under a stress gradient caused by flexure of the member. The plate buckling coefficient k of a web element under pure in-plane bending varies as a function of the aspect ratio. The term in the brackets in Eq. 3 can be modified to account for the different k values for the web in bending. Consequently Eqs 2 and 4 have been modified to Eqs 5 and 6.

$$\lambda_{critical} = \pi\left(\frac{EI_{wc} b_w}{4D}\right)^{0.25} \quad \text{(5)}$$

$$k_\phi = \frac{2Et^3}{5.46(b_w + 0.06\lambda)}\left[1 - \frac{1.11 f'_{od}}{Et^2}\left(\frac{b_w^{\,4}\lambda^2}{12.56\lambda^4 + 2.192 b_w^{\,4} + 13.39\lambda^2 b_w^{\,2}}\right)\right] \quad \text{(6)}$$

3.3 Development of the equations for the section properties

In order to calculate the distortional buckling stress from the equations given in Appendix D of AS/NZS 4600[3], the section properties of the flange-lip combination as shown in Fig. 5 are required. Explicit equations for these properties have been derived, and are given in Appendix A for the general case of a section with inclined and return lips.

Shear Centre: For sections with simple lip stiffeners, the shear centre will be at the lip-flange junction thus no calculation is required. However for sections with return lips, the shear centre (x_0, y_0) is calculated by equating the moment produced by the shear stresses induced by a unit shear force about a point, to the moment produced about the same point by the unit shear force acting at the shear centre, as outlined by Trahair and Bradford[9]. In the general equations given in Appendix A, the moments are taken about the lip-return lip junction, and the co-ordinates of the shear centre relative to this point are u_1 and u_2.
Warping section constant: For sections with simple lip stiffeners, the warping section constant $I_w = 0$. For sections with return lips, the approximation for I_w given by Yu[10] was used to produce the general equations for I_w in Appendix A.

4. COMPARISON OF ELASTIC DISTORTIONAL BUCKLING EQUATIONS WITH THIN-WALL

Numerical calculations have been performed for a practical range of section geometries where distortional buckling may be critical. The Lau and Hancock formulae for sections in compression and in bending respectively have been used, and are compared with the results obtained from THIN-WALL[12] in Tables B1 - B4 in Appendix B. The values from THIN-WALL can be regarded as theoretically accurate and were computed assuming no lateral restraint to the section. For the sections in bending, the values from THIN-WALL were computed by modifying the input data such that a uniform stress existed in the flanges and lips, to conform to the assumptions made in the formulae.

Table 1 shows a summary of the statistical analysis of the comparisons. The following section geometries were excluded from the statistical analysis as they produce large inaccuracies and thus fall outside of the limitations of the formulae, as is discussed in Section 5 of this paper:
Channel sections with return lips in pure compression: 200 mm webs and 50 mm flanges
Channel sections with return lips in pure bending: 50 mm flanges and 20 mm simple lips

Section	C with return lips	C with return lips	Z with simple lip	Z with return lips
Load Case	Compression	Bending	Bending	Bending
Ave. accuracy	-2.0%	1.39%	-2.26%	-1.54%
Mean	1.020	1.00	1.019	1.02
Standard Dev.	0.072	0.047	0.037	0.051

Table 1 - Summary of statistical analysis of the comparisons

5. LIMITATIONS OF THE ELASTIC DISTORTIONAL BUCKLING EQUATIONS

5.1 Negative values for k_ϕ

Channel sections with return lips and with web depths of 200 mm and flange widths of 50 mm under pure compression, were found to fall outside the limitations of the distortional buckling formulae, as shown in the shaded regions of Table B1. For these sections, the values of k_ϕ were found to be negative or very small, in which case the flange buckles before the web plate and the assumption that the web is restraining the flange is no longer valid. To avoid this problem, it is proposed that for channel sections with return lips in compression, the web to flange ratio must be less than 3.

5.2 Flange to simple lip ratio

Inaccuracies of the order of 15% - 25% for channel sections with return lips in flexure with flanges of 50 mm and simple lips of 20 mm, are shown in the shaded regions of Table B2. Although the formulae were conservative for these sections, it is proposed that this level of inaccuracy is not acceptable, and thus it is proposed that a lower limit of flange to simple lip ratio of no less than 3.33 be applied to the formulae, for channel sections with return lips in flexure.

5.3 Constant stress block over the lips

It was noted in Section 4 that when THIN-WALL was used for sections in bending, the data files were edited such that the sections had a constant stress block over the lips, in order to correspond with the assumption of such in the distortional buckling formulae. However to accurately predict the distortional buckling stress of a section in bending using the formulae, these formulae must take into account the stress gradient that will exist over the depth of the lip, and the reduced stress in the return lip. It is proposed that the distortional buckling stress derived from these formulae be multiplied by an adjustment factor of $b_w / (b_w - 2\,\bar{y})$, derived by assuming that the average stress in the lips is the stress at the centroid of the flange-lip component of the section ($\bar{y}$). Analyses were done using THIN-WALL without editing the stress in the section to obtain the 'real' distortional buckling stress of the section. These are compared in Table B5, with the formulae with the adjustment factor for channel sections with return lips in flexure, for a representative group of sections. The average accuracy of this method is 3%.

5.4 Depth of lip

It is proposed that a limitation be applied to the length of the lip stiffeners in accordance with Lau and Hancocks[1] finding that if the lip stiffeners are very small, the primary and secondary local minima will merge into one local minima at a short half-wavelength, with the flange-web junction remaining straight as in a pure local mode. Consequently the formulae will be very conservative, since they assume that the flange-web junctions are allowed to bend laterally. It is proposed that the lip stiffeners must comply to the AISI[12] (1980) depth requirements of edge stiffeners of:

$$d_{\min} = 2.8t\left(\frac{b^2}{t^2} - \frac{27600}{f_y}\right)^{\frac{1}{6}}$$

but not less than 4.8t

where f_y = the yield stress of the steel (MPa)
b/t = flat-width ratio of the sub-element.

6. CONCLUSIONS

The explicit formulae for the determination of the elastic distortional buckling stress for Channel- and Z-sections with lip stiffeners and return lips have been tested and compared with accurate solutions for sections in compression and flexure. It is suggested that the following limitations be applied to these formulae:

For sections in compression:

- web to flange ratio must be less than 3
- the depth of lip stiffeners must comply to AISI[12]

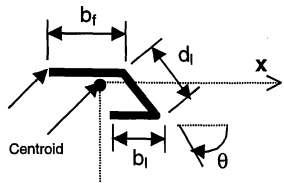
For sections in flexure:

- a factor of $b_w /(b_w -2\ \bar{y})$ must be applied to the calculated stress
- for channel sections with return lips, flange to simple lip ratio must be greater than 3.33
- the depth of lip stiffeners must comply to AISI[12]

With the limitations applied, the formulae will provide designers with a relatively simple method of determining the elastic distortional buckling stress of thin-walled sections with complex geometry, to a high degree of accuracy.

7. APPENDIX A – SECTION PROPERTIES OF A FLANGE-LIP COMBINATION FOR THE GENERAL CASE OF INCLINED AND RETURN LIPS

Section properties of a compression flange with a simple lip and return lip (with slope = θ) are as follows:



Centreline dimensions

$$A = (b_f + d_l + b_l)t$$

$$\bar{x} = \frac{b_f^{\,2} + d_l(2b_f + d_l\cos\theta) + b_l(2b_f + 2d_l\cos\theta - b_l)}{2(b_f + d_l + b_l)}$$

$$\bar{y} = \frac{1}{2}d_l\sin\theta\frac{d_l + 2b_l}{b_f + d_l + b_l}$$

$$J = t^3\frac{b_f + d_l + b_l}{3}$$

$$I_x = b_f t\bar{y}^2 + d_l t\left(\bar{y} - d_l\frac{\sin\theta}{2}\right)^2 + \frac{d_l^{\,3}t\sin^2\theta}{12} + b_l t(d_l\sin\theta - \bar{y})^2$$

$$I_y = b_f t\left(\frac{b_f}{2} - \bar{x}\right)^2 + \frac{b_f^{\,3}t}{12} + d_l t\left(\bar{x} - b_f - d_l\frac{\cos\theta}{2}\right)^2 + \frac{d_l^{\,3}t\cos^2\theta}{12} + b_l t\left(b_f + d_l\cos\theta - \frac{b_l}{2} - \bar{x}\right)^2 + \frac{b_l^{\,3}t}{12}$$

$$I_{xy} = d_l t\left(b_f + d_l\frac{\cos\theta}{2} - \bar{x}\right)\left(d_l\frac{\sin\theta}{2} - \bar{y}\right) - \bar{y}b_f t\left(\frac{b_f}{2} - \bar{x}\right) + \frac{d_l^{\,3}t\sin\theta\cos\theta}{12} + b_l t\left(b_f + d_l\cos\theta - \frac{b_l}{2} - \bar{x}\right)(d_l\sin\theta - \bar{y})$$

Principal section properties of a compression flange with a simple lip and return lip (with slope = θ) are as follows:

$$I_c = \frac{1}{2}(I_x + I_y)$$

$$Rad = \sqrt{I_{xy}^{\,2} + (I_y - I_c)^2}$$

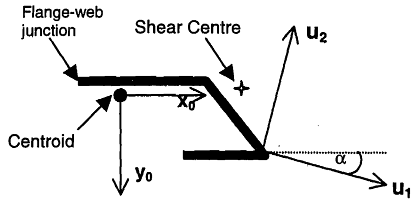
$$I_{px} = I_c - Rad$$

$$I_{py} = I_c + Rad$$

$$\alpha = -\frac{1}{2}\tan^{-1}\left(\frac{2I_{xy}}{I_x - I_y}\right)$$

Shear centre co-ordinates of a compression flange with a simple lip and return lip (with slope = θ) are as follows:

$$u_1 = \frac{-td_l b_f^{\,2} \sin\theta \sin\alpha}{6I_{px}}\left(3\bar{x} - 3\bar{y}\cot\alpha - b_f\right)$$



$$u_2 = \frac{-td_l b_f^{\,2} \sin\theta \cos\alpha}{6I_{py}}\left(b_f - 3\bar{x} - 3\bar{y}\tan\alpha\right)$$

$$x_0 = u_1 \cos\alpha + u_2 \sin\alpha + b_f + d_l \cos\theta - \bar{x}$$

$$y_0 = u_1 \sin\alpha - u_2 \cos\alpha + d_l \sin\theta - \bar{y}$$

Warping section constant of a compression flange with a simple lip and return lip (with slope = θ) is as follows:

$$a_1 = -\left(\bar{y} + y_0\right) b_f$$

$$a_2 = a_1 - \frac{y_0 d_l}{\cos\theta}$$

$$a_3 = a_2 - \left(d_l \sin\theta - \bar{y} - y_0\right) b_l$$

$$C = \frac{1}{2A}\left(a_1 t b_f + \left(a_1 + a_2\right) t d_l + \left(a_2 + a_3\right) t b_l\right)$$

$$b_0 = C$$

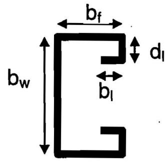
$$b_1 = C - a_1$$

$$b_2 = C - a_2$$

$$b_3 = C - a_3$$

$$I_w = \frac{1}{3}\left[\left(b_0^{\,2} + b_0 b_1 + b_1^{\,2}\right) t b_f + \left(b_1^{\,2} + b_1 b_2 + b_2^{\,2}\right) t d_l + \left(b_2^{\,2} + b_2 b_3 + b_3^{\,2}\right) t b_l\right]$$

8. APPENDIX B – TABLES OF ELASTIC DISTORTIONAL BUCKLING STRESSES



Overall dimensions

b_f (F)	b_w (w)	d_l (L)	b_l (R)	t (t)	Lau & Hancock Method	Finite Strip - No Lateral Restraint	Accuracy (%)	Lau & Han / Finite Strip
50	100	10	10	1.5	340	340	0%	1.00
50	100	10	15	1.5	369	358	-3%	1.03
50	100	10	20	1.5	402	385	-4%	1.04
50	100	15	10	1.5	413	406	-2%	1.02
50	100	15	15	1.5	433	426	-2%	1.02
50	100	15	20	1.5	454	441	-3%	1.03
50	100	20	10	1.5	422	430	2%	0.98
50	100	20	15	1.5	421	433	3%	0.97
50	100	20	20	1.5	419	428	2%	0.98
75	100	10	10	1.5	194	202	4%	0.96
75	100	10	15	1.5	207	216	4%	0.96
75	100	10	20	1.5	219	227	4%	0.96
75	100	15	10	1.5	256	271	6%	0.94
75	100	15	15	1.5	270	286	5%	0.95
75	100	15	20	1.5	284	301	6%	0.94
75	100	20	10	1.5	296	317	7%	0.93
75	100	20	15	1.5	308	332	7%	0.93
75	100	20	20	1.5	320	346	8%	0.92
50	200	10	10	1.5	78	95	18%	0.82
50	200	10	15	1.5	101	109	8%	0.92
50	200	10	20	1.5	119	123	3%	0.97
50	200	15	10	1.5	144	130	-11%	1.11
50	200	15	15	1.5	172	149	-15%	1.15
50	200	15	20	1.5	196	162	-21%	1.21
50	200	20	10	1.5	197	160	-24%	1.24
50	200	20	15	1.5	219	164	-33%	1.33
50	200	20	20	1.5	236	174	-35%	1.35
75	200	10	10	1.5	113	105	-7%	1.07
75	200	10	15	1.5	124	114	-8%	1.08
75	200	10	20	1.5	133	121	-10%	1.10
75	200	15	10	1.5	156	142	-10%	1.10
75	200	15	15	1.5	169	151	-12%	1.12
75	200	15	20	1.5	181	161	-12%	1.12
75	200	20	10	1.5	189	168	-12%	1.12
75	200	20	15	1.5	201	178	-13%	1.13
75	200	20	20	1.5	211	187	-13%	1.13

Table B1 Elastic distortional buckling stresses - Channel section with return lips under pure compression

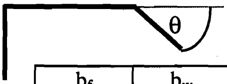
Sections with negative $k\phi$ values

Sections with unacceptable errors

b_f (F)	b_w (w)	d_l (L)	b_l (R)	t (t)	Lau & Hancock Flexural Method	Finite Strip - No Lateral Restraint	Accuracy (%)	Lau & Hancock / Finite Strip
50	100	10	10	1.5	513	505	-2%	1.02
50	100	10	15	1.5	555	553	0%	1.00
50	100	10	20	1.5	602	586	-3%	1.03
50	100	15	10	1.5	617	652	5%	0.95
50	100	15	15	1.5	643	698	8%	0.92
50	100	15	20	1.5	670	748	10%	0.90
50	100	20	10	1.5	622	733	15%	0.85
50	100	20	15	1.5	615	775	21%	0.79
50	100	20	20	1.5	608	823	26%	0.74
75	100	10	10	1.5	278	260	-7%	1.07
75	100	10	15	1.5	293	276	-6%	1.06
75	100	10	20	1.5	315	292	-8%	1.08
75	100	15	10	1.5	370	353	-5%	1.05
75	100	15	15	1.5	392	375	-4%	1.04
75	100	15	20	1.5	412	394	-5%	1.05
75	100	20	10	1.5	430	423	-2%	1.02
75	100	20	15	1.5	448	445	-1%	1.01
75	100	20	20	1.5	465	459	-1%	1.01
50	200	10	10	1.5	348	342	-2%	1.02
50	200	10	15	1.5	379	364	-4%	1.04
50	200	10	20	1.5	413	393	-5%	1.05
50	200	15	10	1.5	428	423	-1%	1.01
50	200	15	15	1.5	450	454	1%	0.99
50	200	15	20	1.5	471	481	2%	0.98
50	200	20	10	1.5	441	469	6%	0.94
50	200	20	15	1.5	438	491	11%	0.89
50	200	20	20	1.5	433	512	15%	0.85
75	200	10	10	1.5	204	201	-1%	1.01
75	200	10	15	1.5	218	216	-1%	1.01
75	200	10	20	1.5	232	227	-2%	1.02
75	200	15	10	1.5	273	273	0%	1.00
75	200	15	15	1.5	290	290	0%	1.00
75	200	15	20	1.5	305	308	1%	0.99
75	200	20	10	1.5	319	327	2%	0.98
75	200	20	15	1.5	334	348	4%	0.96
75	200	20	20	1.5	347	367	5%	0.95

Table B2 Elastic distortional buckling stresses - Channel section with return lips under pure bending

Sections with unacceptable errors



b_f (F)	b_w (w)	d_l (L)	θ (angle)	t (t)	Finite Strip - No Lateral Restraint	Lau & Hancock Flexural Method	Accuracy %	Lau & Han / Finite Strip
50	100	10	45	1.5	287	288	-1%	1.01
50	100	10	60	1.5	342	349	-2%	1.02
50	100	10	75	1.5	380	398	-5%	1.05
50	100	15	45	1.5	348	353	-1%	1.01
50	100	15	60	1.5	433	446	-3%	1.03
50	100	15	75	1.5	499	520	-4%	1.04
50	100	20	45	1.5	378	380	-1%	1.01
50	100	20	60	1.5	489	501	-2%	1.02
50	100	20	75	1.5	576	597	-4%	1.04
75	100	10	45	1.5	149	157	-6%	1.06
75	100	10	60	1.5	174	187	-7%	1.07
75	100	10	75	1.5	190	212	-11%	1.11
75	100	15	45	1.5	197	210	-7%	1.07
75	100	15	60	1.5	240	258	-7%	1.07
75	100	15	75	1.5	274	295	-8%	1.08
75	100	20	45	1.5	238	246	-4%	1.04
75	100	20	60	1.5	294	310	-5%	1.05
75	100	20	75	1.5	343	359	-5%	1.05
50	200	10	45	1.5	210	198	6%	0.94
50	200	10	60	1.5	242	233	4%	0.96
50	200	10	75	1.5	262	266	-1%	1.01
50	200	15	45	1.5	247	246	1%	0.99
50	200	15	60	1.5	296	332	-12%	1.12
50	200	15	75	1.5	339	354	-4%	1.04
50	200	20	45	1.5	273	271	1%	0.99
50	200	20	60	1.5	330	332	-1%	1.01
50	200	20	75	1.5	414	416	-1%	1.01
75	200	10	45	1.5	120	116	4%	0.96
75	200	10	60	1.5	140	136	3%	0.97
75	200	10	75	1.5	153	154	-1%	1.01
75	200	15	45	1.5	156	155	1%	0.99
75	200	15	60	1.5	187	187	0%	1.00
75	200	15	75	1.5	210	215	-3%	1.03
75	200	20	45	1.5	183	183	0%	1.00
75	200	20	60	1.5	233	187	20%	0.80
75	200	20	75	1.5	259	265	-2%	1.02

Table B3 Elastic distortional buckling stresses – Z-section with simple lips under pure bending

b_f (F)	b_w (w)	d_l (L)	b_l (R)	t (t)	θ (angle)	Finite Strip No Lateral Restr.	Lau & Han. Flexural Method	Accuracy (%)	Lau & Han. / Finite Strip
50	100	10	10	1.5	75	489	507	-4%	1.04
50	100	10	15	1.5	75	536	549	-2%	1.02
50	100	10	20	1.5	75	569	596	-5%	1.05
50	100	15	10	1.5	75	591	614	-4%	1.04
50	100	15	15	1.5	75	689	653	5%	0.95
50	100	15	20	1.5	75	681	688	-1%	1.01
50	100	20	10	1.5	75	635	660	-4%	1.04
50	100	20	15	1.5	75	676	677	0%	1.00
50	100	20	20	1.5	75	715	674	6%	0.94
75	100	10	10	1.5	75	262	281	-7%	1.07
75	100	10	15	1.5	75	279	300	-8%	1.08
75	100	10	20	1.5	75	296	317	-7%	1.07
75	100	15	10	1.5	75	343	360	-5%	1.05
75	100	15	15	1.5	75	368	382	-4%	1.04
75	100	15	20	1.5	75	389	402	-3%	1.03
75	100	20	10	1.5	75	405	415	-2%	1.02
75	100	20	15	1.5	75	432	436	-1%	1.01
75	100	20	20	1.5	75	455	456	0%	1.00
50	200	10	10	1.5	75	330	351	-7%	1.07
50	200	10	15	1.5	75	350	384	-10%	1.10
50	200	10	20	1.5	75	379	419	-11%	1.11
50	200	15	10	1.5	75	389	431	-11%	1.11
50	200	15	15	1.5	75	413	463	-12%	1.12
50	200	15	20	1.5	75	436	490	-12%	1.12
50	200	20	10	1.5	75	451	472	-5%	1.05
50	200	20	15	1.5	75	436	488	-12%	1.12
50	200	20	20	1.5	75	451	486	-8%	1.08
75	200	10	10	1.5	75	200	207	-3%	1.03
75	200	10	15	1.5	75	214	222	-3%	1.03
75	200	10	20	1.5	75	225	235	-5%	1.05
75	200	15	10	1.5	75	259	267	-3%	1.03
75	200	15	15	1.5	75	274	284	-4%	1.04
75	200	15	20	1.5	75	289	301	-4%	1.04
75	200	20	10	1.5	75	300	314	-5%	1.05
75	200	20	15	1.5	75	317	328	-3%	1.03
75	200	20	20	1.5	75	332	344	-4%	1.04

Table B4 Elastic distortional buckling stresses – Z-section with return lips under pure bending (continued on next page)

b_f (F)	b_w (w)	d_l (L)	b_l (R)	t (t)	M (angle)	Finite Strip No Lateral Restr.	Lau & Han. Flexural Method	Accuracy (%)	Lau & Han. / Finite Strip
50	100	10	10	1.5	60	431	433	0%	1.00
50	100	10	15	1.5	60	463	462	0%	1.00
50	100	10	20	1.5	60	499	499	0%	1.00
50	100	15	10	1.5	60	503	483	4%	0.96
50	100	15	15	1.5	60	538	503	7%	0.93
50	100	15	20	1.5	60	582	531	9%	0.91
50	100	20	10	1.5	60	533	483	9%	0.91
50	100	20	15	1.5	60	561	489	13%	0.87
50	100	20	20	1.5	60	606	504	17%	0.83
75	100	10	10	1.5	60	233	249	-7%	1.07
75	100	10	15	1.5	60	248	262	-6%	1.06
75	100	10	20	1.5	60	259	276	-6%	1.06
75	100	15	10	1.5	60	299	307	-3%	1.03
75	100	15	15	1.5	60	318	320	-1%	1.01
75	100	15	20	1.5	60	334	333	0%	1.00
75	100	20	10	1.5	60	348	339	3%	0.97
75	100	20	15	1.5	60	360	349	3%	0.97
75	100	20	20	1.5	60	382	360	6%	0.94
50	200	10	10	1.5	60	300	301	0%	1.00
50	200	10	15	1.5	60	318	323	-2%	1.02
50	200	10	20	1.5	60	333	350	-5%	1.05
50	200	15	10	1.5	60	345	344	0%	1.00
50	200	15	15	1.5	60	360	360	0%	1.00
50	200	15	20	1.5	60	390	381	2%	0.98
50	200	20	10	1.5	60	384	351	8%	0.92
50	200	20	15	1.5	60	376	357	5%	0.95
50	200	20	20	1.5	60	397	367	8%	0.92
75	200	10	10	1.5	60	181	184	-2%	1.02
75	200	10	15	1.5	60	190	194	-2%	1.02
75	200	10	20	1.5	60	198	205	-3%	1.03
75	200	15	10	1.5	60	225	228	-2%	1.02
75	200	15	15	1.5	60	243	239	2%	0.98
75	200	15	20	1.5	60	252	250	1%	0.99
75	200	20	10	1.5	60	262	255	3%	0.97
75	200	20	15	1.5	60	269	263	2%	0.98
75	200	20	20	1.5	60	289	272	6%	0.94

Table B4 Elastic distortional buckling stresses – Z-section with return lips under pure bending

b_f (F)	b_w (w)	d_l (L)	b_l (R)	t (t)	Lau & Hancock Flexural Method	Adjust-ment factor	Adjusted Lau & Hancock value	Finite Strip - No Lateral Restraint True stress block	Accuracy (%)
50	100	10	10	1.5	513	1.036	532	540	2%
50	100	15	15	1.5	643	1.082	696	797	13%
75	100	10	10	1.5	278	1.026	285	275	-4%
75	100	15	15	1.5	392	1.060	415	420	1%
75	100	20	20	1.5	465	1.106	514	548	6%
50	200	10	10	1.5	348	1.018	355	351	-1%
50	200	15	15	1.5	450	1.039	468	476	2%
75	200	10	10	1.5	204	1.013	206	206	0%
75	200	15	15	1.5	290	1.029	298	306	2%
75	200	20	20	1.5	347	1.050	364	397	8%
							Average accuracy		3%

Table B5 Comparison of adjusted distortional buckling stresses with THIN-WALL

9. APPENDIX C - REFERENCES

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