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Distortional Buckling of Cold-formed Stainless Steel Compression Members

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DISTORTIONAL BUCKLING OF COLD-FORMED STAINLESS STEEL COMPRESSION MEMBERS

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ABSTRACT: In this paper the critical local buckling strength of cold-formed stainless steel compression members , with special emphasis on the method developed by Lau and Hancock for distortional buckling is discussed. Cold-formed stainless steel channel and I-section members under axial compression in distortional buckling are analysed. A control experiment is carried out for comparing analytical methods with a finite element method and experimental values.

KEY WORDS: cold-formed stainless steel, distortional buckling , buckling stress, critical load, finite element method

Introduction

Stainless steel has established itself as a corrosion resistant construction material and has a fine exterior, with a wide usage in buildings. The applications of stainless steel as a kind of decorative material have been extended to structural members. The structural applications of cold-formed stainless steel structural members have been under consideration by researchers and engineers for a number of years with the introduction of stainless steel structural members. Based on experimental work the theory to calculate the strength of cold-formed stainless steel structural members when buckling occurs has been verified. The design equations to determine the effective width of elements are empirical equations based on the large deflection theory. The tangent modulus instead of the elastic modulus is used to determine the buckling strength in the inelastic stress range. [1]

The buckling modes of cold-formed stainless steel members such as local, flexural, torsional and torsional- flexural buckling are well known and they are well documented in design specifications. Distortional buckling is a special kind of buckling mode and is less well known. Experimental work has indicated that distortional buckling occurs frequently in middle slender columns in various kinds of cold-formed sections and that it should also be considered in design. Recently researchers paid more attention to this problem.

Lau and Hancock advanced an analytical model to calculate the elastic distortional buckling stress of cold-formed steel channels [2]. Their theory is adopted in the Australian/New Zealand Standard (AS/NZS)[3]. Distortional buckling is also a buckling mode that should be considered when designing stainless steel structural members and it is necessary to investigate its behaviour when distortional buckling occurs.

Research work on the distortional buckling of cold-formed stainless steel structural members is being conducted by the Chromium Steels Research Group at the Rand Afrikaans University in South Africa.[4] In this paper the distortional buckling of cold-formed stainless steel columns under axial compression is investigated. The strength of a number of channels and I-section stainless steel columns are analysed by using the design specifications (CAN/CSA-S136-M94 [5], SABS [6], AISI [7] and ASCE [8]), Lau and Hancock's method (AS/NZS)[3], and the finite element method [9]. In order to find the correct method for calculating the distortional buckling of cold-formed stainless steel structural members experimental work was carried out to make a comparison between the theoretical and numerical predictions and experimental values respectively. The effectiveness and application limit of the analysis methods are discussed.

Buckling Modes and Design Equations

Axially loaded cold-formed stainless steel compression members may buckle in several modes. These various forms of buckling of cold-formed stainless steel compression members are described in Figure 1.

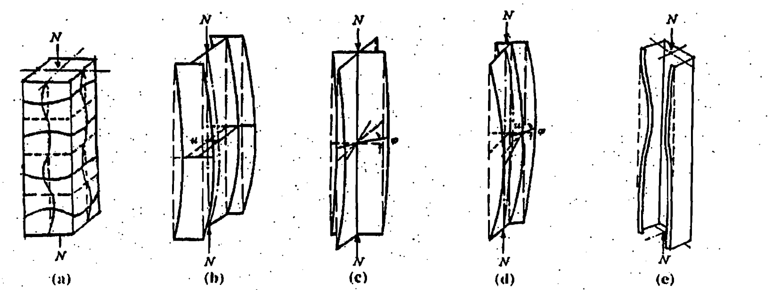

Figure 1. Buckling modes of axially loaded compression members
(a) Local Buckling **(b)** Flexural Buckling **(c)** Torsional Buckling
(d) Flexural-Torsional Buckling **(e)** Distortional Buckling

Buckling is a criterion to judge if a member has failed. When the overall buckling strength of a cold-formed stainless steel structural member is calculated the effects of local buckling should be considered in the calculation. In the stainless steel design specifications the design equations to calculate the overall buckling strength of axially loaded compression members are given as follows: [10][11]

Flexural buckling strength
$$f_x = \frac{\pi^2 E_t}{(L_x / r_x)^2} \qquad (1)$$

$$f_y = \frac{\pi^2 E_t}{(L_y / r_y)^2} \tag{2}$$

Torsional buckling strength $$f_t = \frac{1}{A r_0^2}\left[\frac{\pi^2 E_t C_w}{L_t^2} + G_t J\right] \tag{3}$$

Flexural-torsional buckling strength $$f_{tf} = \frac{1}{2\beta}\left[(f_x + f_t) - \sqrt{(f_x + f_t)^2 - 4\beta f_x f_t}\right] \tag{4}$$

The local buckling effects is determined at the lowest value of the above overall buckling strengths. The empirical effective width equation derived by Winter is used to take into account the post local buckling strength of an element.

$$b_e = B \cdot t \tag{5}$$

where

b_e — effective width
t — base steel thickness
B — effective width ratio

When the width to thickness ratio of an element, W, is larger than the limiting ratio, $W_{\lim}$, Equation 6 is used to calculate the effective width ratio of that element.

$$B = 0.95\sqrt{\frac{kE}{f}}\left[1 - \frac{0.208}{W}\sqrt{\frac{kE}{f}}\right] \tag{6}$$

where $$W_{\lim} = 0.644\sqrt{\frac{kE}{f}} \tag{7}$$

W — width to thickness ratio
k — buckling coefficient for compressive elements
E — elastic modulus
f — design strength

The critical load for a column can be determined by using Equation 8

$$P = A_e f_n \tag{8}$$

where A_e — effective cross sectional area
f_n — critical buckling stress (taken as the smaller value in Equations 1 to 4.)

A separate design equation for distortional buckling is not used in the above design specifications except the AS/NZS [3] specification.

Model for Distortional Buckling

Distortional buckling of compression members usually involves rotation of each flange and lip about the flange-web junction in opposite directions as shown in Figure 1(e) and Figure 2. Distortional buckling in channel section columns has been investigated in detail by Hancock [2,12] and his research group at the University of Sydney in Australia. Lau and Hancock[2] advanced an analytical model to calculate the elastic distortional buckling strength as shown in Figure 3 [12]. In this model, the rotational spring, k_ϕ, represents the flexural restraint provided by the web which is in pure compression, and the translational spring, k_x, represents the resistance to translational movement of the section in the buckling mode. The flexural restraint decreases as the compressive stress in the web increases. Lau and Hancock assume that the value of translational spring stiffness, k_x, is zero so that the flange is free to translate in the x-direction in the buckling mode.

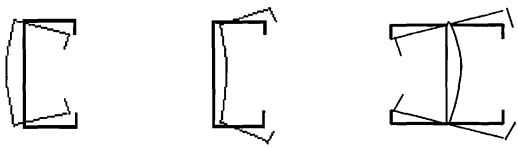

Figure 2 Distortional buckling modes

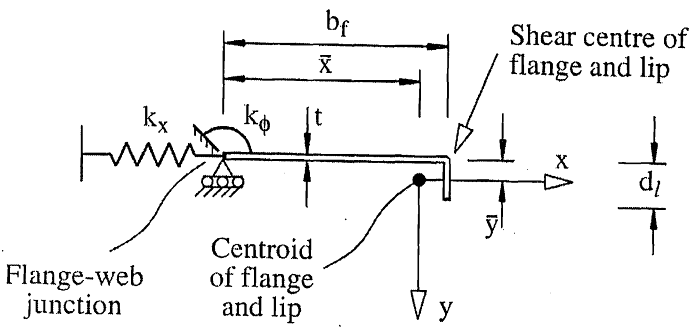

Figure 3 Analytical model for distortional buckling

The equation for the rotational spring stiffness, k_ϕ, is given by

$$k_\phi = \frac{Et^3}{5.46(b_w + 0.06\lambda)}\left[1 - \frac{1.11 f'_{od}}{Et^2}\left(\frac{b_w{}^2\lambda}{b_w{}^2 + \lambda^2}\right)^2\right] \tag{9}$$

where

$$\lambda = 4.80\left(\frac{I_x b_f{}^2 b_w}{t^3}\right)^{0.25} \tag{10}$$

λ = the half-wavelength of the distortional buckle
b_w = the web depth
b_f = the flange width
t = the thickness of a sheet
I_x = the second moment of area of the flange and lip about the x-axis
E = elastic modulus
f'_{od} = buckling stress of flange with $k_x = 0$ and $k_\phi = 0$

Through the computation process which is iterative due to the incorporation of f'_{od} in Equation 9, a solution can be obtained. The elastic distortional buckling stress, f_{od}, can be written as Equation 11.

$$f_{od} = \frac{E}{2A}\left[(\alpha_1 + \alpha_2) - \sqrt{(\alpha_1 + \alpha_2)^2 - 4\alpha_3}\right] \tag{11}$$

where α_1, α_2, and α_3 are characteristic values of complexity which are related to k_ϕ, λ and the geometry and dimensions of the flange and the lip.

Distortional Buckling Analysis

Distortional buckling occurs frequently in cold-formed stainless steel channel and I-section columns. In this study a comparison is made between the theoretical predictions using the American [7][8], Canadian and South African design specifications [5][6], the Australian/New Zealand design specification [3] and a finite element [13] prediction. Axially loaded Type 3CR12 corrosion resisting steel channel and I-sections are used.

The lengths of the thirty-six channel columns are 0.3 m, 0.8 m, 1.2 m and 1.8 m respectively. The web height is 100 mm, the flange widths vary between 30 mm and 80 mm in increments of 10 mm, and the lip heights vary between 5 mm and 20 mm. The length of the twenty I-section columns is 1 m. The flange widths vary between 40 mm and 80 mm in increments of 10 mm. The lip heights vary between 5 mm and 20 mm.

The results are given in Table1 and Table 2 with respect to these two groups. Some of the buckling models in Table 1 obtained by ABAQUS are shown in Figure 4. The results of the channel columns with flange width 60 mm for the three methods as mentioned before are compared and illustrated by the curves in Figure 5.

Twenty Type 3CR12 I-section short columns (L=300 mm) under axial compression were tested experimentally. The test set-up and a specimen in the distortional buckling mode are shown in

Figure 6. A comparison between the theoretical analyses (using design specifications), numerical method (using a FEM program-ABAQUS) and experimental values has been made. The results are reported in Table 3. The experimental results and theoretical prediction for the ultimate capacities of the columns are given in Figure 7.

Table 1 Results of channel columns

Name	w (mm)	d_i (mm)	L (mm)	P_t (kN)	P_h (kN)	P_a (kN)	Buckling Mode
3005-80	30	5	800	42.84	56.72	40.39	D
3010-80	30	10	800	49.67	70.44	47.2	D
3015-80	30	15	800	55.09	78.24	56.51	D
3020-80	30	20	800	59.6	81.95	61.97	D
4005-80	40	5	800	53.32	61.01	52.73	D
4010-80	40	10	800	64.15	76.38	64.76	D
4015-80	40	15	800	69.42	85.13	72.2	D
4020-80	40	20	800	74.4	90.46	79.51	D
5005-80	50	5	800	57.33	58.36	54.69	D
5010-80	50	10	800	71.33	78.45	69.86	D
5015-80	50	15	800	81.54	89.4	81.4	D, L
5020-80	50	20	800	87.7	96.35	87.95	D
6005-80	60	5	800	60.22	54.83	57.03	D
6010-80	60	10	800	71.08	77.34	71.99	D
6015-80	60	15	800	82.22	91.37	86.9	D
6020-80	60	20	800	96.48	100.16	93.73	L
7005-80	70	5	800	63.88	54.84	57.82	D
7010-80	70	10	800	77.91	72.97	71.5	D
7015-80	70	15	800	87.77	91.05	90.48	D
7020-80	70	20	800	98.35	102.04	96.47	L
8005-80	80	5	800	65.05	54.4	58.29	D
8010-80	80	10	800	79.03	68.34	70.27	D
8015-80	80	15	800	89.13	88.29	90.22	D
8020-80	80	20	800	100.48	102	95.05	L
6005-30	60	5	300	69.1	59.8	54.8	D
6010-30	60	10	300	83	80.9	77.3	D
6015-30	60	15	300	91.6	92.3	91.4	L
6020-30	60	20	300	102	97.2	100	L
6005-120	60	5	1200	54.8	55.8	54.8	F
6010-120	60	10	1200	66.1	60.3	77.3	D
6015-120	60	15	1200	77.2	84.1	91.4	D
6020-120	60	20	1200	90	88.9	100	D
6005-180	60	5	1800	45.7	48.8	54.8	F
6010-180	60	10	1800	58.2	65.1	77.3	F
6015-180	60	15	1800	67.9	83.8	91.4	F
6020-180	60	20	1800	75.6	89	100	F

P_t — Theoretical buckling load by using the design specifications [5, 6, 7, 8]
P_a — The buckling load by using the finite element method program—ABAQUS
P_h — The buckling load by using Lau and Hancock model (AS/NZS) [3]
L — The length of columns
w — The flange width
di — The lip hight
L — Local buckling
D — Distortional buckling
F — Flexural buckling

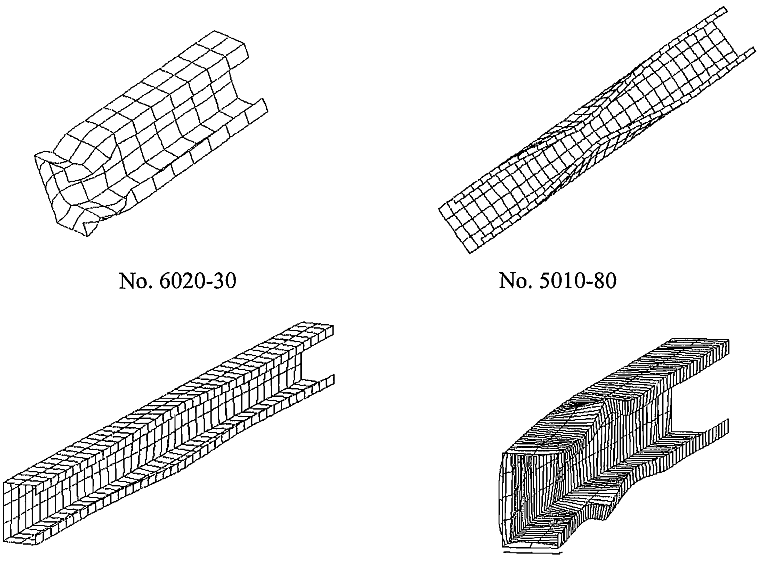

Figure 4. Finite element buckling modes of channel columns

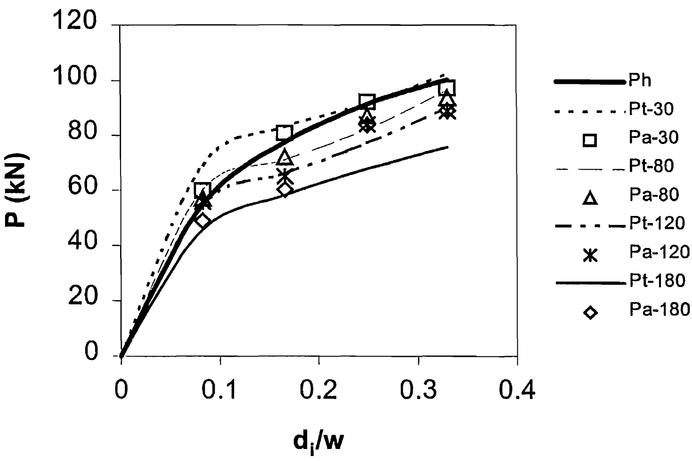

Figure 5 Results of channel section columns

Table 2 Results of I-section columns

Name	w (mm)	d (mm)	$\frac{d}{w}$	P_t (kN)	P_h (kN)	P_a (kN)	$\frac{P_a}{P_t}$	$\frac{P_a}{P_h}$	Buckling mode
I4005-100	40	5	0.125	107	122	125.1	1.17	1.03	d.b
I4010-100	40	10	0.25	130	152.8	145.9	1.12	0.96	d.b
I4015-100	40	15	0375	142	170.3	159.4	1.12	0.94	d.b
I4020-100	40	20	0.5	153	180.9	169.8	1.11	0.94	d.b
I5005-100	50	5	0.1	116	116.7	135.5	1.17	1.16	d.b
I5010-100	50	10	0.2	144	157	151.1	1.05	0.96	d.b
I5015-100	50	15	0.3	165	178.8	167.7	1.02	0.94	d.b
I5020-100	50	20	0.4	180	192.7	186.2	1.03	0.96	d.b
I6005-100	60	5	0.083	122	109.7	138.8	1.14	1.27	d.b
I6010-100	60	10	0.166	144	154.7	152.1	1.06	0.98	d.b
I6015-100	60	15	0.25	166	182.7	168.6	1.02	0.92	d.b
I6020-100	60	20	0.33	195	200.3	190.2	0.98	0.95	d.b
I7005-100	70	5	0.0714	130	109.6	140.2	1.08	1.28	d.b
I7010-100	70	10	0.143	159	145.9	153.2	0.96	1.05	d.b
I7015-100	70	15	0.214	179	182.1	176.9	0.99	0.97	d.b
I7020-100	70	20	0.285	201	204.1	191.4	0.95	0.94	d.b
I8005-100	80	5	0.0625	134	108.8	138.4	1.03	1.27	d.b
I8010-100	80	10	0.125	163	136.7	155.2	0.95	1.14	d.b
I8015-100	80	15	0.1875	185	176.6	174.1	0.94	0.99	d.b
I8020-100	80	20	0.25	207	204	190.5	0.92	0.93	d.b
						Mean	1.04	1.03	
						COV	7.56	12.01	

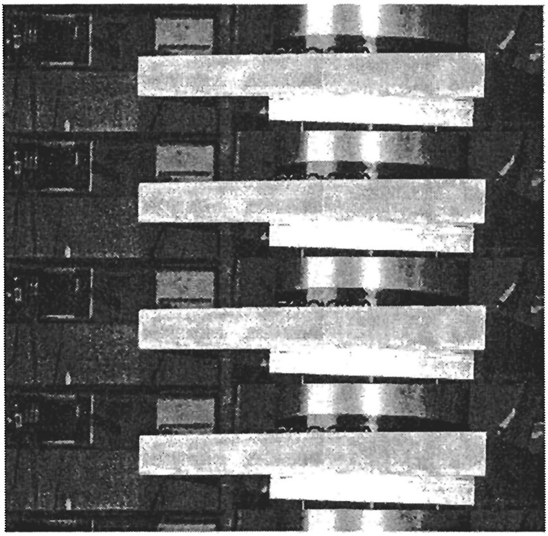

Figure 6 Test set-up

From Tables 1 to 3, it can be seen that the theoretical results for the critical loads compare well with the finite element predictions, and experiment results. It is concluded that the equations in the stainless steel design specification [8] to calculate the buckling load of compression members give satisfactory results.

From Figure 4, Figure 5 and Table 1 it is seen that the channel columns with middle length under compression almost buckled in the distortional mode. When increasing the length of a member, the buckling mode may change from local buckling to overall buckling. It can be seen that distortional buckling is a buckling mode in the interim. By using Lau and Hancock's method to predict the distortional buckling mode, a good result was obtained. It can be concluded that Lau and Hancock's model is suitable for calculating the distortional buckling stress of the middle slender cold-formed stainless steel channel section columns.

Although some experimental results are not satisfactory due to testing errors it can be concluded from Table 2, Table 3 and Figure 7 that Lau and Hancock's method may be suitable for calculating the distortional buckling stress for middle slender cold-formed stainless steel I-section columns. Lau and Hancock's distorsional buckling model for predicting the buckling strength of short I-section columns may be too conservative in many cases. Lau and Hancock's distortional buckling model has limitations, especially for short I-section columns with smaller ratios of the lip height to the flange width, d_l/w.

Table 3 Experimental results of I-section Columns

Name	h (mm)	w (mm)	d_i (mm)	d_i/w	Area (mm^2)	P_e (kN)	P_t (kN)	P_h (kN)	P_a (kN)	$\frac{P_a}{P_e}$	$\frac{P_h}{P_e}$	$\frac{P_t}{P_e}$
I3007-30	94	30	7	0.233	496	122	138.9	134.7	139.6	1.14	1.1	1.14
I3010-30	101	30	10	0.33	538	143	147.9	149.8	150.4	1.05	1.05	1.03
I3015-30	101	30	14	0.466	563	168	158.5	163.8	163.3	0.97	0.98	0.94
I3020-30	101	30	20	0.66	601	fail	171	174	178.5	–	–	–
I4007-30	95	40	7	0.175	563	167	157.5	145	154.7	0.93	0.87	0.94
I4010-30	99	40	10	0.25	595	164	167.1	162	169.8	1.04	0.99	1.02
I4015-30	101	40	15	0.375	634	fail	185	181.2	187.1	–	–	–
I4020-30	101	40	20	0.5	665	199	196	192.4	199.9	1.01	0.97	0.99
I6007-30	95	60	7	0.116	691	175	151.1	138.9	165.7	0.95	0.79	0.86
I6010-30	102	60	10	0.166	733	203.5	166.8	167.2	189.4	0.93	0.82	0.82
I6015-30	100	60	15	0.25	759	206	190.1	195.3	207.4	1.01	0.95	0.92
I6020-30	100	60	20	0.33	791	175	219.6	213.3	216.2	1.24	1.22	1.26
I7007-30	95	70	7	0.1	755	fail	162.5	127.7	164.3	–	–	–
I7010-30	100	70	9	0.129	784	190	174.5	148.6	185.2	0.98	0.78	0.918
I7015-30	100	70	15	0.214	823	200	200.6	195.7	205.1	1.03	0.98	1
I7020-30	100	70	20	0.285	855	213.4	223.6	218.2	212.8	1.00	1.02	1.05
I8007-30	95	80	7	0.088	819	fail	163.2	128.1	163.6	–	–	–
I8010-30	100	80	10	0.125	855	179	180.4	146	189.6	1.06	0.82	1.01
I8015-30	100	80	15	0.188	886	201	202.4	191.3	206.1	1.03	0.95	1.01
I8020-30	100	80	20	0.25	919	202	226.8	219.2	209.5	1.04	1.09	1.12
									Mean	1.02	0.96	1.00
									COV	7.66	12.73	10.74

w — the flange width
d — the lip height
h — the web height
P_e — Experimental result
P_t — Theoretical buckling load by using the design specifications [5, 6, 7, 8]
P_h — Buckling load using Lau and Hancock model (AS/NZS) [3]
P_a — Buckling load using the finite element method program—ABAQUS

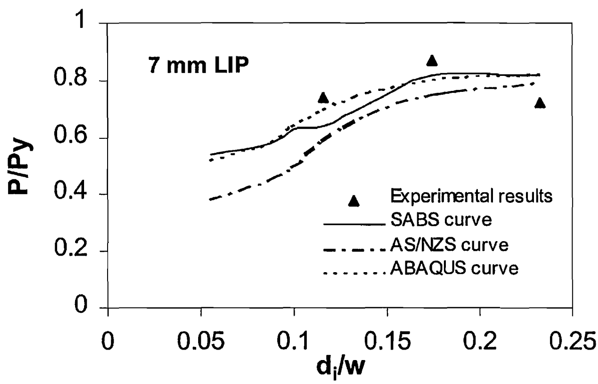

Figure 7a Ultimate strength of sections for 7 mm lip

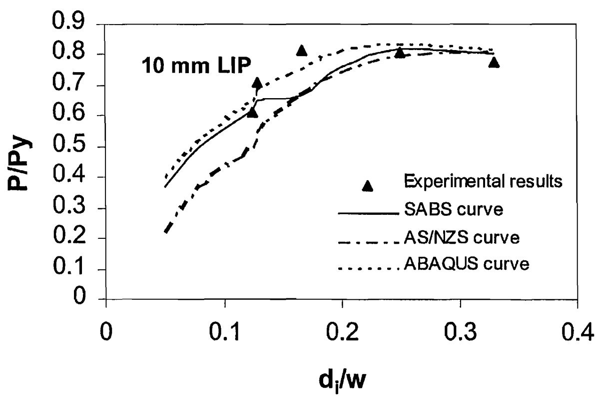

Figure 7b Ultimate strength of sections for 10 mm lip

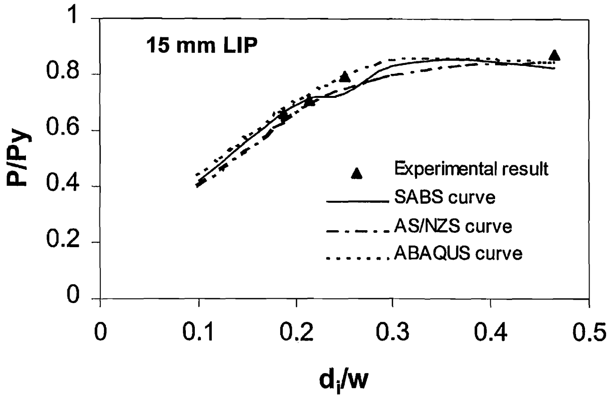

Figure 7c Ultimate strength of sections for 15 mm lip

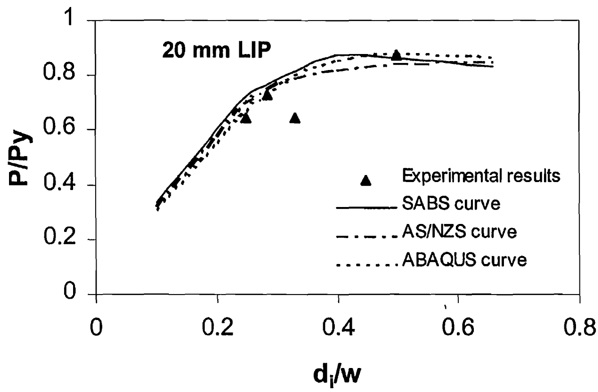

Figure 7d Ultimate strength of sections for 20 mm lip

5. Conclusion

With the utilisation of cold-formed stainless steels in building construction, a number of countries have published their specifications for the design of cold-formed stainless steel structural members. Because cold-formed stainless steel structural members is a new type of light steel material and its history of utilisation in structures is not long, many things about its structural applications and utilisation are not completely understood, and therefore, a number of issues should be addressed and studied further. A more thorough investigation and study is essential for cold-formed stainless steels.

Distortional buckling is a special kind of buckling mode in cold-formed stainless steel structural members. It is situated between local and overall buckling and is not well known. Lau and Hancock advanced an analytical model to calculate the elastic distortional buckling stress for cold-formed steel channel and Z-section members. According to the analytical and experimental results as well as the finite element method analysis for channel and I-section columns under axial compression, it can be concluded that Lau and Hancock's method may be suitable for calculating the distortional buckling stress for the middle slender cold-formed stainless steel channel and I- section columns. However, Lau and Hancock's distortional buckling model to predict the buckling strength of short I-section columns is also found to be too conservative in many cases. This limits the use of Lau and Hancock's distortional buckling model for predicting distortional buckling, especially for short I-section columns with smaller ratios of the lip height to the flange width, d_l/w.

There are two design methods suggested to calculate the distortional buckling strength for middle slender cold-formed stainless steel channel and I-section columns. The first one is to use the lower value of the methods in design specifications [5,6,7,8] and Lau and Hancock's method [2]. These two methods prove to be slightly conservative in some cases but ensure adequate safety in stainless steel structural members. The second method is to use the analytical formula in the design specifications to calculate the buckling load for stainless steel I-section columns because of its accuracy in this situation. There is no specialized formula for the distortional buckling mode for stainless steel structural members in the design specifications. The second method makes the calculations convenient for the designer with respect to the I-section columns.

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