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Improved Effective Width Method Considering Distortional Buckling for Cold-formed Thin-walled Steel Members with Lipped Channel Section

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Abstract

The local buckling, distortional buckling, and overall buckling would occur for cold-formed thin-walled steel members with lipped channel section. The effective width method is used to considering the effect of local and distortional buckling on load-carrying capacity of member in Chinese code. Especially, a very conservative stability coefficient of partially stiffened elements used to considering the local buckling and distortional buckling of flange of lipped channel sections. In this paper, the half-wave length, the elastic buckling stress of distortional-buckling of cold-formed thin-walled steel members with lipped channel section and the corresponding stability coefficient of partially stiffened elements were developed based on the energy method. With comparison among the calculated results of elastic buckling stress and half-wave length using the improved method and the Finite Strip Method, suitability and precision of the improved method were illuminated. Then, a uniform formula for the stability coefficient of partially stiffened elements considering both local and distortional buckling effect was established based on the proposed method. Finally, with comparison on lipped channel sections in the appendix of Chinese code and existing test results conducted by many researchers and the proposed method, it is shown that the proposed uniform formula had higher precision to calculate the stability coefficient of partially stiffened elements and the ultimate load-carrying capacity of cold-formed thin-walled steel members with lipped channel section.

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Introduction

Cold-formed lipped channel sections have been widely used in light gauge steel construction. These channel members may buckle in one and some of several modes including local buckling, distortional buckling, and flexural-torsional buckling based on different boundary conditions, sections, and effective length. The distortional buckling is more complication and the half-wave length of that is between local buckling and overall buckling. The design method for local buckling and overall buckling is more perfect but have no provision to consider distortional buckling in Chinese code "*technical code of cold-formed thin-walled steel structures*" (GB50018-2002). the North American(AISI-S100-2007) and the Australia Specification (AS/NZS4600:2005) for cold-formed steel structural members have provision to design distortional buckling strength based on several study references (Lau and Hancock 1987, Schafer and Pekez 1999, Schafer 2002) and Chinese researchers (Chen 2002, Li, Wang, and Shen, et al. 2010, Li, Liu, and Shen, et al. 2010, Yao 2012, Yao and Teng 2008, Yao, Cheng, and Xing 2008, Zhou and Wang 2009) have provided some design method for distortional buckling too, but these design methods are more complication. The test and theoretical analysis show that distortional buckling can decide the load-carrying capacities, so a simple design method for distortional buckling based on effective width method in Chinese code should be conducted. In this paper, the half-wave length, elastic buckling stress of distortional-buckling of partially stiffened elements (Fig.1) for cold-formed thin-walled steel members with lipped channel section and the corresponding stability coefficient of partially stiffened elements were developed using the energy method. A uniform formula for the stability coefficient of partially stiffened elements considering both local and distortional buckling effect was established. Finally, with examples' analysis and test results, the precision of the proposed uniform formula had verified.

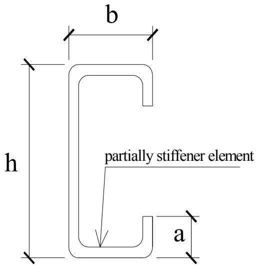

Fig.1 Members with lipped channel section

Elastic Distortional Buckling Analysis for Lipped Channel Sectional Members

The basic assumption (Zhou and Wang 2009) of distortional buckling analysis for partially stiffened element include that lips are as elastic bearing beam and have no restrained action for flange, shear stress around plate is zero, and the normal stress of no-bearing edge is zero.

The boundary conditions can obtain according to the basic assumption as shown in Eq. (1), (2), and (3).

$$w\Big|_{y=0} = 0 \tag{1}$$

$$\left.\frac{\partial^2 w}{\partial y^2}\right|_{y=0} = 0 \tag{2}$$

$$D\left[\frac{\partial^3 w}{\partial y^3} + (2-\upsilon)\frac{\partial^3 w}{\partial x^2 \partial y}\right]_{y=b} = EI\left.\frac{\partial^4 w}{\partial x^4}\right|_{y=b} \tag{3}$$

Where *D, E, t, w, I,* υ are flexural rigidity of unit plate, modulus of elasticity of steel, thickness of plate, the lateral deflected shape of plate, moment of inertia of the partially stiffened element and lip, and Poisson's ratio respectively.

The distortional buckling analytical model for partially stiffened element of lipped channel members is shown in Fig.2 and the equation (4) is the deflected shape function of distortional buckling.

$$w = fy\cos\left(\pi x / \lambda\right) \tag{4}$$

where f is parameter， λ is the half-wave length.

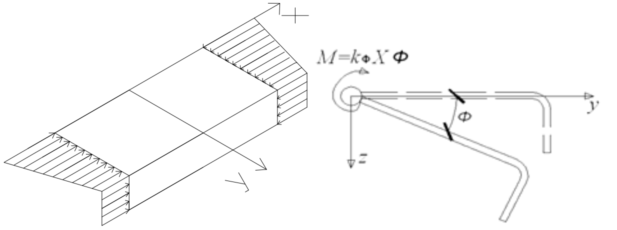

Fig.2 Distortional buckling analytical model for partially stiffened elements

The bending strain energy of the partially stiffened element is

$$U_f = \frac{D}{2}\int_{-\lambda/2}^{\lambda/2}\int_0^b \left\{\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2}\right)^2 - 2(1-\upsilon)\left[\frac{\partial^2 w}{\partial x^2}\times\frac{\partial^2 w}{\partial y^2} - \left(\frac{\partial^2 w}{\partial x \partial y}\right)^2\right]\right\} dydx \tag{5a}$$

The equation (5b) can be obtained by the substitution of deflected shape function for equation (5a).

$$U_f = \frac{Db\lambda f^2}{4}\left(\frac{\pi}{\lambda}\right)^2\left[\left(\frac{\pi}{\lambda}\right)^2 b^2/3+2(1-\nu)\right] \quad (5b)$$

The bending strain energy of lip is

$$U_{lip} = \frac{EI}{2}\int_{-\lambda/2}^{\lambda/2}\left(\frac{\partial^2 w}{\partial x^2}\right)^2_{y=b} dx \quad (6a)$$

The equation (6b) can be obtained by the substitution of deflected shape function for equation (6a).

$$U_{lip} = \frac{EI}{4} f^2 b^2 \left(\frac{\pi}{\lambda}\right)^4 \lambda \quad (6b)$$

The torsion strain energy of web is

$$U_w = \frac{k_\phi}{2}\int_{-\lambda/2}^{\lambda/2}\left(\frac{\partial w}{\partial x}\right)^2_{y=0} dx \quad (7a)$$

The equation (7b) can be obtained by the substitution of deflected shape function for equation (7a).

$$U_w = \frac{k_\phi}{4} f^2 \lambda \quad (7b)$$

When the maximum stress act at the stiffened edge, the potential energy of partially stiffened element is:

$$\begin{aligned} V_f &= -\frac{1}{2}\int_{-\lambda/2}^{\lambda/2}\int_0^b \sigma_x \left(\frac{\partial w}{\partial x}\right)^2 t\,dy\,dx \\ &= -\frac{1}{2}\int_{-\lambda/2}^{\lambda/2}\int_0^b \sigma_w (1-\alpha y/b)\left(\frac{\partial w}{\partial x}\right)^2 t\,dy\,dx \end{aligned} \quad (8a)$$

The equation (8b) can be obtained by the substitution of deflected shape function for equation (8a).

$$V_f = -\frac{1}{4} f^2 b^3 t\lambda \left(\frac{\pi}{\lambda}\right)^2 \sigma_{lip}\left(1/3-\alpha/4\right) \quad (8b)$$

The potential energy of lip is

$$\begin{aligned} V_{lip} &= -\frac{1}{2} at\int_{-\lambda/2}^{\lambda/2}\sigma_{lip}\left(\frac{\partial w}{\partial x}\right)^2_{y=b} dx \\ &= -\frac{1}{2} at\int_{-\lambda/2}^{\lambda/2}\sigma_w\left(1-\alpha\right)\left(\frac{\partial w}{\partial x}\right)^2_{y=b} dx \end{aligned} \quad (9a)$$

The equation (9b) can be obtained by the substitution of deflected shape function for equation (9a).

$$V_{lip} = -\frac{1}{4} atf^{2} b^{2} \lambda \left(\frac{\pi}{\lambda}\right)^{2} \sigma_{w} \left(1-\alpha\right) \tag{9b}$$

The entire buckling potential energy of partially stiffened element is

$$\prod = V_{lip} + V_{f} + U_{f} + U_{lip} + U_{w} \tag{10}$$

Substituting Eqs.(5b), (6b), (7b), (8b), and (9b) in Eq.(10) and assign $\partial\Pi / \partial f = 0$,the distortional buckling stress can be obtained as Eq. (11).

$$\sigma_{w} = \frac{k_{\phi} / \left(\pi / \lambda\right)^{2} + Db(\left(\pi b / \lambda\right)^{2} / 3 + 2(1-\upsilon)) + EI\left(\pi b / \lambda\right)^{2}}{tb^{3}(1/3 - \alpha/4) + atb^{2}\left(1-\alpha\right)} \tag{11}$$

The distortional buckling half-wave length can be determined using equation (12) if we ignore the impact of torsional stiffener of web on half-wave length and assign $\partial\sigma_{w} / \partial\lambda = 0$.

$$\lambda = \pi \sqrt[4]{\left(b^{3}D/3 + EIb^{2}\right)/k_{\phi}} \tag{12}$$

The elastic distortional buckling stress and half-wave length can be obtained using same the method when the maximum stress acts at partially stiffened edge.

$$\sigma_{lip} = \frac{k_{\phi} / \left(\pi / \lambda\right)^{2} + Db(\left(\pi b / \lambda\right)^{2} / 3 + 2(1-\upsilon)) + EI\left(\pi b / \lambda\right)^{2}}{tb^{3}(1/3 - \alpha/12) + atb^{2}} \tag{13}$$

$$\lambda = \pi \sqrt[4]{\left(b^{3}D/3 + EIb^{2}\right)/k_{\phi}} \tag{14}$$

The equation (12) and (14) calculated distortional buckling half-wave length have relate with rotational restraint. The value of k_{φ} asymptotes to a constant of $2D/h$ and $4D/h$ for axially-compressed members and bending members for long half-wavelength from the reference(Law and Hancock 1987, Yao and Teng 2008). The value of k_{φ} can use$(2+\alpha_{w})D/h$ for eccentrically-compressed members, where α_{w} is the factor of non-uniform stress distribution for web.

Distortional buckling half-wave length can be determined from equation (15) considering the factor of non-uniform stress distribution for web α_{w} and equation (14).

$$\lambda = \pi \sqrt[4]{\frac{b^{2}h}{6(1+0.5\alpha_{w})}\left(b + 3EI/D\right)} \tag{15}$$

Substituting Eq. (15) in Eq.(11)and (13)，the distortional buckling stress of lipped channel members can be obtained. Assigning rotational restraint kφ equals to 0 in Eqs. (11) and (13) and considering expression $\sigma = kE\pi^2 / \left(12\left(1-\nu^2\right)\right)\left(t/b\right)^2$, the distortional buckling stability coefficient of the partially stiffened element can be obtained ignore interaction of plates.

When maximum stress act at the stiffened edge

$$k = \frac{b\left[\left(b/\lambda\right)^2/3 + 2\left(1-\nu\right)/\pi^2\right] + 12(1-\nu^2)I\left(b/\lambda\right)^2/t^3}{b\left(1/3-\alpha/12\right)+a} \tag{16a}$$

When maximum stress act at the patially stiffened edge

$$k = \frac{b\left[\left(b/\lambda\right)^2/3 + 2\left(1-\nu\right)/\pi^2\right] + 12(1-\nu^2)I\left(b/\lambda\right)^2/t^3}{b\left(1/3-\alpha/4\right)+a\left(1\text{-}\alpha\right)} \tag{16b}$$

The selected sectional dimension of partially stiffened element is that the width of flange is 60mm, thickness is 1mm, the width ratio for lip to flange is 0, 0.05, 0.1, 0.15, 0.2, 0.25, 0.3, 0.35 and 0.4, the width ratio for web and flange is 1, 2, 3, 4, and 5. The comparison on distortional buckling stress estimation using proposed method and the finite strip method CUFSM is shown in Table 1.

Table 1 Comparison on distortional buckling stress between the proposed method and the Finite Strip Method

	h	*a*=0	*a*=3	*a*=6	*a*=9	*a*=12	*a*=15	*a*=18	*a*=21	*a*=24
Proposed model	60	34.84	45.48	75.50	107.77	138.92	168.06	195.03	219.90	242.85
	90	32.49	40.65	64.76	90.78	115.95	139.53	161.37	181.52	200.12
	120	31.08	37.77	58.35	80.65	102.26	122.52	141.30	158.64	174.65
	150	30.13	35.80	53.98	73.74	92.92	110.92	127.61	143.03	157.27
	180	29.42	34.35	50.75	68.64	86.02	102.35	117.50	131.50	144.44
	210	28.87	33.22	48.24	64.67	80.66	95.69	109.64	122.54	134.46
	240	28.43	32.31	46.22	61.48	76.34	90.32	103.31	115.32	126.43
	270	28.06	31.56	44.54	58.83	72.76	85.87	98.06	109.34	119.77
	300	27.75	30.92	43.13	56.59	69.73	82.11	93.62	104.28	114.14
CUFSM	60	32.16	42.72	72.50	106.42	139.71	171.31	200.81	228.04	252.94
	90	30.64	38.64	62.75	90.46	117.57	143.29	167.28	189.38	209.59
	120	29.72	36.17	56.87	80.80	104.21	126.41	147.09	166.16	183.57
	150	29.11	34.48	52.81	74.14	95.02	114.81	133.24	150.23	165.75
	180	28.64	33.22	49.80	69.21	88.20	106.20	122.98	138.43	152.55
	210	28.29	32.24	47.44	65.35	82.88	99.49	114.98	129.25	142.22
	240	28.01	31.45	45.53	62.23	78.58	94.08	108.53	121.84	133.98
	270	27.76	30.79	43.96	59.64	75.01	89.59	103.17	115.68	127.10
	300	27.57	30.24	42.62	57.45	71.99	85.78	98.63	110.47	121.29
proposed model/ CUFSM	60	1.08	1.06	1.04	1.01	0.99	0.98	0.97	0.96	0.96
	90	1.06	1.05	1.03	1.00	0.99	0.97	0.96	0.96	0.95
	120	1.05	1.04	1.03	1.00	0.98	0.97	0.96	0.95	0.95
	150	1.04	1.04	1.02	0.99	0.98	0.97	0.96	0.95	0.95
	180	1.03	1.03	1.02	0.99	0.98	0.96	0.96	0.95	0.95
	210	1.02	1.03	1.02	0.99	0.97	0.96	0.95	0.95	0.95
	240	1.02	1.03	1.02	0.99	0.97	0.96	0.95	0.95	0.94
	270	1.01	1.02	1.01	0.99	0.97	0.96	0.95	0.95	0.94
	300	1.01	1.02	1.01	0.99	0.97	0.96	0.95	0.94	0.94

Table 1 show that the buckling stress using equation (11) and finite strip method CUFSM is very close and the maximum error is less than 8%. The calculated results for bending members, eccentrically-compressed members about strong and weak axis have the same accuracy (Yao 2012).

Stability coefficient of partially stiffened element

Substituting v and π in Eq. (16) and considering local buckling stability coefficient, the stability coefficient of partially stiffened element can be obtained.

When maximum stress acts on the stiffened edge:

$$k=\min\left(2\alpha^3+2\alpha+4,\frac{b\left[(b/\lambda)^2/3+0.142\right]+10.92I(b/\lambda)^2/t^3}{b(1/3-\alpha/12)+a}\right) \tag{17a}$$

When maximum stress acts on the partially stiffened edge:

$$k=\begin{cases}\min\left(2\alpha^3+2\alpha+4,\dfrac{b\left[(b/\lambda)^2/3+0.142\right]+10.92I(b/\lambda)^2/t^3}{b(1/3-\alpha/4)+a(1\text{-}\alpha)}\right) & \alpha<\dfrac{b/3+a}{b/4+a}\\ 2\alpha^3+2\alpha+4 & \alpha\geq\dfrac{b/3+a}{b/4+a}\end{cases} \tag{17b}$$

The half-wavelength is the minimum of distortional buckling half-wavelength and length of member in equation (15).

Distortional buckling load-carrying capacities of lipped channel members

The load-carrying capacities of lipped channel members can be determined using Chinese code if the stability coefficient of the partially stiffened element can be calculated using Eq.(17) and the effective width of plates using Chinese code GB50018-2002. The load-carrying capacities of lipped channel members are the minimum of overall stability strength considering local buckling and distortional buckling strength in North America code, which is very accurate. So the North America Code can be used to verify the accuracy of the proposed method in this paper.

Sections in the appendix of Chinese code

The sections in the appendix of Chinese code (GB50018-2002) are the common sections used in china. These sections are used to verify the proposed method. The lengths of members are 5, 10, and 15 time width of web. The scope of slenderness is from 30 to 150. Comparison on load-carrying capacities of axially-compressed members with sections in the appendix of Chinese code using Chinese code, proposed method and North

America code is shown in table 2. Where P_{c1}、P_{c2} are load-carrying capacities using Chinese code considering interaction of plates or not, P_{cr1}、$P_{cr2}$are load-carrying capacities using the proposed method considering interaction of plates or not, P_A is the load-carrying capacities using North America code.

Table 2 Comparison on load-carrying capacities of axially-compressed members with sections in the appendix of Chinese code

L/mm	h/mm	b/mm	a/mm	t/mm	P_{c1}/kN	P_{c2}/kN	P_{cr1}/kN	P_{cr2}/kN	P_A/kN	P_{c1}/P_A	P_{c2}/P_A	P_{cr1}/P_A	P_{cr2}/P_A
400	80	40	15	2	103.02	103.64	108.24	108.88	111.32	0.93	0.93	0.97	0.98
500	100	50	15	2.5	155.67	155.66	163.10	163.77	168.40	0.92	0.92	0.97	0.97
600	120	50	20	2.5	163.48	166.76	172.41	174.36	177.92	0.92	0.94	0.97	0.98
600	120	60	20	3	227.61	228.18	242.06	239.91	247.60	0.92	0.92	0.98	0.97
700	140	50	20	2	115.40	121.56	124.72	133.55	132.23	0.87	0.92	0.94	1.01
700	140	50	20	2.2	133.71	140.04	142.98	150.27	149.66	0.89	0.94	0.96	1.00
700	140	50	20	2.5	162.75	168.27	171.71	175.17	176.73	0.92	0.95	0.97	0.99
700	140	60	20	3	228.85	231.58	240.86	242.54	248.80	0.92	0.93	0.97	0.97
800	160	60	20	2	118.34	126.01	132.70	140.70	145.20	0.82	0.87	0.91	0.97
800	160	60	20	2.2	141.25	147.23	153.30	164.04	165.71	0.85	0.89	0.93	0.99
800	160	60	20	2.5	172.14	179.43	184.45	195.89	195.58	0.88	0.92	0.94	1.00
800	160	70	20	3	241.07	245.14	256.29	267.67	270.11	0.89	0.91	0.95	0.99
900	180	70	20	2	118.51	129.31	134.34	146.67	141.72	0.84	0.91	0.95	1.03
900	180	70	20	2.2	142.40	151.77	161.17	171.00	165.53	0.86	0.92	0.97	1.03
900	180	70	20	2.5	180.97	187.32	195.78	210.36	203.75	0.89	0.92	0.96	1.03
1000	200	70	20	2	114.84	127.70	130.22	143.62	140.44	0.82	0.91	0.93	1.02
1000	200	70	20	2.2	137.99	149.63	156.27	167.49	164.85	0.84	0.91	0.95	1.02
1000	200	70	20	2.5	176.54	184.71	195.05	206.09	202.22	0.87	0.91	0.96	1.02
1100	220	75	20	2	113.60	127.25	128.80	145.13	141.69	0.80	0.90	0.91	1.02
1100	220	75	20	2.2	136.51	150.90	154.60	169.26	162.53	0.84	0.93	0.95	1.04
1100	220	75	20	2.5	174.69	186.29	197.51	208.28	204.28	0.86	0.91	0.97	1.02
800	80	40	15	2	94.00	94.01	98.20	97.28	97.72	0.96	0.96	1.00	1.00
1000	100	50	15	2.5	140.66	140.66	147.39	145.56	146.78	0.96	0.96	1.00	0.99
1200	120	50	20	2.5	142.96	144.88	149.80	148.36	147.96	0.97	0.98	1.01	1.00
1200	120	60	20	3	206.58	206.58	219.17	213.78	216.46	0.95	0.95	1.01	0.99
1400	140	50	20	2	95.43	99.60	101.75	106.09	103.17	0.92	0.97	0.99	1.03
1400	140	50	20	2.2	110.27	113.99	116.40	118.68	116.60	0.95	0.98	1.00	1.02

1400	140	50	20	2.5	132.72	136.53	139.33	137.94	137.26	0.97	0.99	1.02	1.00
1400	140	60	20	3	199.71	201.77	209.88	206.87	207.31	0.96	0.97	1.01	1.00
1600	160	60	20	2	102.41	106.99	110.95	119.23	116.04	0.88	0.92	0.96	1.03
1600	160	60	20	2.2	118.51	123.62	127.17	135.32	131.16	0.90	0.94	0.97	1.03
1600	160	60	20	2.5	143.97	148.45	152.62	157.33	154.55	0.93	0.96	0.99	1.02
1600	160	70	20	3	212.27	214.40	224.17	228.97	227.80	0.93	0.94	0.98	1.01
1800	180	70	20	2	104.95	111.32	118.12	125.47	124.68	0.84	0.89	0.95	1.01
1800	180	70	20	2.2	125.68	130.09	136.42	146.27	143.92	0.87	0.90	0.95	1.02
1800	180	70	20	2.5	153.11	158.66	164.05	175.68	170.66	0.90	0.93	0.96	1.03
2000	200	70	20	2	97.46	104.05	110.42	116.42	119.11	0.82	0.87	0.93	0.98
2000	200	70	20	2.2	116.93	121.54	127.79	135.67	134.89	0.87	0.90	0.95	1.01
2000	200	70	20	2.5	143.68	149.69	153.51	163.29	159.16	0.90	0.94	0.96	1.03
2200	220	75	20	2	94.54	102.35	107.10	114.72	117.05	0.81	0.87	0.91	0.98
2200	220	75	20	2.2	113.44	119.58	127.44	133.70	134.92	0.84	0.89	0.94	0.99
2200	220	75	20	2.5	143.05	147.47	153.22	163.14	161.12	0.89	0.92	0.95	1.01
1200	80	40	15	2	77.47	77.46	78.49	77.83	78.50	0.99	0.99	1.00	0.99
1500	100	50	15	2.5	114.05	114.05	114.68	114.15	116.10	0.98	0.98	0.99	0.98
1800	120	50	20	2.5	103.39	102.44	105.04	102.44	108.56	0.95	0.94	0.97	0.94
1800	120	60	20	3	168.80	168.80	170.37	169.25	172.26	0.98	0.98	0.99	0.98
2100	140	50	20	2	62.76	64.53	65.93	64.57	68.33	0.92	0.94	0.96	0.95
2100	140	50	20	2.2	71.62	72.12	75.23	72.12	76.91	0.93	0.94	0.98	0.94
2100	140	50	20	2.5	85.41	83.61	86.42	83.61	89.81	0.95	0.93	0.96	0.93
2100	140	60	20	3	145.25	143.63	146.39	143.63	152.53	0.95	0.94	0.96	0.94
2400	160	60	20	2	69.76	71.72	73.81	75.43	78.90	0.88	0.91	0.94	0.96
2400	160	60	20	2.2	80.08	82.04	84.40	84.28	89.00	0.90	0.92	0.95	0.95
2400	160	60	20	2.5	95.79	97.78	100.93	97.78	104.40	0.92	0.94	0.97	0.94
2400	160	70	20	3	156.41	157.54	164.73	160.11	169.10	0.92	0.93	0.97	0.95
2700	180	70	20	2	75.30	77.87	80.60	85.72	88.59	0.85	0.88	0.91	0.97
2700	180	70	20	2.2	86.95	89.22	92.31	95.79	100.00	0.87	0.89	0.92	0.96
2700	180	70	20	2.5	104.79	107.00	110.65	111.16	117.53	0.89	0.91	0.94	0.95
3000	200	70	20	2	66.05	68.43	70.25	73.39	75.03	0.88	0.91	0.94	0.98
3000	200	70	20	2.2	76.07	78.41	80.47	82.10	84.75	0.90	0.93	0.95	0.97
3000	200	70	20	2.5	91.22	94.05	96.46	95.41	99.71	0.91	0.94	0.97	0.96
3300	220	75	20	2	64.76	67.27	69.01	72.85	73.46	0.88	0.92	0.94	0.99
					Mean					0.8990	0.9283	0.9616	0.9908

Variance	0.0469	0.0292	0.0262	0.0294
Coefficient of variation	0.0521	0.0314	0.0272	0.0297

The comparison on load-carrying capacities for bending members and eccentrically-compressed members are in reference (Yao 2012) and the corresponding statistical results are shown in Table 3 and 4.where M_{c1} and P_{c1}, $M_{c2}$and P_{c2} are load-carrying capacities using Chinese code considering interaction of plates or not, where $M_{cr1}$and P_{cr1}, $M_{cr2}$and P_{cr2} are load-carrying capacities using the proposed method considering interaction of plates or not, M_A and P_A is the load-carrying capacity calculated using North American specification.

Table 3 Comparison on load-carrying capacities of bending members with sections in the appendix of Chinese code

	M_{c1}/M_A	M_{c2}/M_A	M_{cr1}/M_A	M_{cr2}/M_A
Mean	0.9443	0.9386	0.9945	0.9940
Variance	0.0312	0.0174	0.0102	0.0103
Coefficient of variation	0.0331	0.0186	0.0102	0.0104

Table 4 Comparison on load-carrying capacities of eccentrically -compressed members with sections in the appendix of Chinese code

	P_{c1}/P_A	P_{c2}/P_A	P_{cr1}/P_A	P_{cr2}/P_A
Mean	1.0816	1.1661	1.0188	1.1094
Variance	0.0591	0.0502	0.0389	0.0526
Coefficient of variation	0.0547	0.0431	0.0382	0.0474

As shown in Table 2, the load-carrying capacities calculated using the proposed method is close to that calculated using North America code because these two methods all considering distortional buckling. The load-carrying capacities calculated using Chinese code is very conservative because the Chinese code using the very low stability coefficient.

As shown in Table 3 and 4, the bending members and eccentrically-compressed member have the same law with axially-compressed members.

Comparison on test results

The test results conducted by researchers (Yao 2012) are used to verify the accuracy of proposed method. The statistical results of load-carrying capacities calculated using Chinese code, proposed method, and North America code for axially-compressed members, bending members, and eccentrically-compressed members are shown in Table 5, 6, and 7.

Table 5 Comparison on load-carrying capacities of axially- compressed members between the tested and calculated results

	P_{c1}/P_t	P_{c2}/P_t	P_{cr1}/P_t	P_{cr2}/P_t	P_A/P_t
Mean	1.1416	1.0739	1.0877	1.0257	0.9751
Variance	0.1963	0.1907	0.1084	0.0987	0.1100
Coefficient of variation	0.1719	0.1776	0.0997	0.0962	0.1128

Table 6 Comparison on load-carrying capacities of bending members between the tested and calculated results

	P_{c1}/P_t	P_{c2}/P_t	P_{cr1}/P_t	P_{cr2}/P_t	P_A/P_t
Mean	1.0500	1.0487	1.0040	0.9856	1.0037
Variance	0.1291	0.1318	0.1124	0.1182	0.0974
Coefficient of variation	0.1230	0.1256	0.1119	0.1200	0.0970

Table 7 Comparison on load-carrying capacities of eccentrically -compressed members between the tested and calculated results

	P_{c1}/P_t	P_{c2}/P_t	P_{cr1}/P_t	P_{cr2}/P_t	P_A/P_t
Mean	1.1934	1.1184	1.1139	1.0547	1.1370
Variance	0.2342	0.2067	0.2001	0.1823	0.1720
Coefficient of variation	0.1963	0.1848	0.1797	0.1729	0.1513

As shown in Table 5, 6, and 7, the proposed method can calculated the load-carrying capacities of lipped channel members very well because of the revise of stability coefficient of the partially stiffened element which can consider the interaction with local buckling, distortional buckling, and overall buckling.

Conclusion

The following conclusion can be obtained according to the distortional buckling research of cold-formed thin-walled lipped channel members based on the energy method.

The energy method is feasible and has very high precision for researching the distortional buckling of cold-formed thin-walled lipped channel members.

The half-wave length, elastic buckling stress of distortional-buckling of cold-formed thin-walled steel members with lipped channel section and the corresponding stability coefficient of partially stiffened elements were developed based on the energy method. With comparison among the calculated results of elastic buckling stress using the proposed method and the Finite Strip Method, suitability and good precision of the developed method were illuminated.

The effective width method in Chinese code for calculating the local buckling strength can be used to calculate the distortional buckling strength of lipped channel members through revising the stability coefficient of the partially stiffened element.

The proposed method have high precision to calculated the load-carrying capacities of lipped channel members through comparison on load-carrying capacities calculated by the proposed method, the North American code, and test results.

Notation

The following symbols are used in this paper:

D = flexural rigidity of unit plate;
E = modulus of elasticity of steel;
t = thickness of plate;
w = the lateral deflected shape of plate;
I = moment of inertia of the partially stiffened element and lip;
υ = Poisson's ratio;
λ = the half-wave length;
α_w = the factor of non-uniform stress distribution for web;
P_{c1} = load-carrying capacities using Chinese code considering interaction of plates;
P_{c2} = load-carrying capacities using Chinese code not considering interaction of plates;
P_{cr1} = load-carrying capacities using the proposed method considering interaction of plates;
P_{cr2} = load-carrying capacities using the proposed method not considering interaction of plates;
P_{A} = the load-carrying capacities using North America code;
M_{c1} = load-carrying capacities using Chinese code considering interaction of plates;
M_{c2} = load-carrying capacities using Chinese code not considering interaction of plates;
M_{cr1} = load-carrying capacities using the proposed method considering interaction of plates;
M_{cr2} = load-carrying capacities using the proposed method not considering interaction of plates;
M_{A} = load-carrying capacity calculated using North American specification.

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