Experimental Study on Interaction Between Local and Distortional Buckling of High Strength Cold-formed Lipped Channel Columns

L. Jiang

B. K. He

Y. Q. Li

Twenty-First International Specialty Conference on Cold-Formed Steel Structures
St. Louis, Missouri, USA, October 24 & 25, 2012

Experimental Study on Interaction between Local and Distortional Buckling of High Strength Cold-formed Lipped Channel Columns

L. Jiang[1], B. K. He[2] , Y. Q. Li[3]

Abstract

The distortional buckling behavior of 550MPa high strength cold-formed lipped channel columns under axial compression loads have been studied. The test results of 16 specimens show that local buckling may appear before distortional buckling and it makes the distortional buckling occur in advance. This interaction of local and distortional buckling has an adverse effect on bearing capacity of columns. But the design methods for distortional buckling in Specification AS/NZS 4600 and Direct Strength Method (DSM) haven't considered such interaction. Based on the test results, a method revised from DSM which could account for the adverse interaction has been suggested. The results calculated by the proposed method matched well with the test results.
Keyword: experimental study; high strength cold-formed steel columns; distortional buckling; interaction

---

[1]Baosteel Construction System Integration Co., LTD, Shanghai, China
[2]Xi'an University of Architecture and Technology, Xi'an, China
[3]Tongji University, Shanghai, China

Introduction

Distortional buckling occurs mostly in edge-stiffened sections such as lipped channel columns in Fig. 1. It can be seen from Fig. 1 that distortional buckling usually involves rotation of flange and lip about the flange-web junction in opposite direction. In the last decade years, distortional buckling has received lots of researches especially by G. Hancock (2001), B. Schafer and T. Pekoz. Their effective work has shown that distortional buckling is quite different from local and overall buckling. So it has been given a separate check in Australian Specifications of AS/NZS4600 and Direct Strength Method (B. Schafer and T. Pekoz). But in both of them, the interaction of local and distortional buckling is neglected. No design rules for distortional buckling exist in Chinese Specification GB50018-2002. Therefore an experimental study on distortional buckling as well as its interaction with other buckling modes of high strength cold-formed lipped channel columns was carried out recently and will be analyzed in this paper.

Summary of tests

As shown in Fig. 2, a lipped channel section which has a V shaped stiffener in flange as well as in the web was selected as specimens' section. The cross-section dimensions and lengths of specimens are shown in Table 1. The coupon test results (Zhou Tianhua, 2005) show that the material yield strength f_y is 695MPa and 710MPa for thickness of 0.48mm and 0.60mm respectively. And the elastic modulus E is 2.16×10^5 MPa for both of thicknesses.

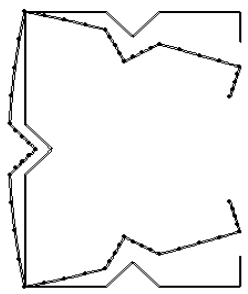


Fig. 1 Distortional buckling

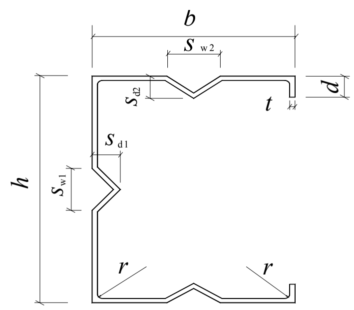


Fig. 2 Specimens' section

The test machine was YE-200A. Specimens were placed between the end plates which is thick and flat enough to ensure fixed end boundary conditions. Axial loads were subjected onto specimens by increments after geometric and physical alignment completed. The ultimate test strength P_t and relative failure mode of each specimen are shown in Table 1.All specimens failed by distortional buckling. The detailed failure characters are summarized as following:

(1) For shorter specimens of length 500mm, local buckling appeared first in the lip and then in the web, and a little distortion of flanges occurred nearly before the failure of specimens.

(2) For specimens of intermediate lengths 1000mm and 1500mm, the phenomenon shows that local buckling and distortional buckling existed simultaneously as shown in Fig. 3.

(3) For longer specimens of length 2000mm, the distortion of flanges appeared as soon as specimens were subjected to load. With the load increasing, the distortional deformation of flanges get so significant that two flanges contact together as shown in Fig. 4.

(4) Three types of distortional buckling modes namely I-I, O-O and I-O mode can be identified. I-I means two flanges both move inwards, O-O means two flanges both move outward and I-O means one flange inward and another outward. The pictures of three buckling modes are shown in Fig. 5.

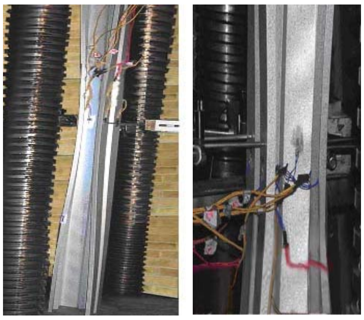


Fig. 3 Buckling modes of specimens LCC2a and LCC7a

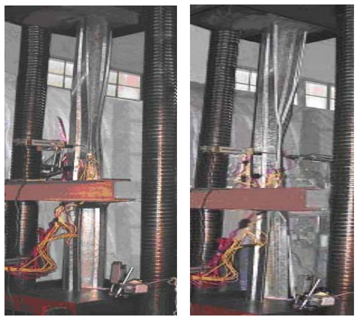


Fig. 4 Buckling modes of specimens LCC8a and LCC4a

（a) I-I mode (b) O-O mode (c) O-I mode

Fig. 5 Three types of flange distortional buckling modes

Table 1 Dimensions and experimental results of all specimens

Specimens	t/mm	h/mm	b/mm	S_{w1}/mm	S_{d1}/mm	S_{w2}/mm	S_{d2}/mm	d/mm	L/mm	P_t/kN	Buckling modes
LCC1a	0.48	109.0	80.0	18.6	8.8	20.1	10.1	12.0	499.8	40.6	O-I
LCC1b		108.8	80.0	18.4	9.2	20.5	9.9	11.9	500.0	37.8	I-I
LCC2a	0.48	109.5	80.0	19.6	9.4	20.2	10.1	11.6	999.8	23.6	I-I
LCC2b		108.9	80.0	19.4	9.5	20.3	9.6	11.8	1000.0	22.5	I-I
LCC3a	0.48	109.0	79.5	20.2	9.8	20.2	10.1	11.5	1501.0	20.8	O-I
LCC3b		109.0	79.5	20.4	9.8	20.0	9.4	11.7	1500.1	21.3	I-I
LCC4a	0.48	108.0	79.5	20.0	9.9	20.2	10.0	11.4	1999.1	18.4	I-I
LCC4b		108.5	80.0	20.2	9.2	20.2	9.4	11.3	1999.0	20.6	O-I
LCC5a	0.60	108.0	80.2	18.6	9.2	19.5	9.8	12.0	498.5	47.5	I-I
LCC5b		108.0	80.2	17.5	9.0	19.5	10.0	12.0	502.0	51.0	I-I
LCC6a	0.60	109.0	80.5	18.4	9.3	19.8	9.4	11.8	1000.1	46.4	O-O
LCC6b		109.5	80.0	19.3	9.2	20.3	9.4	11.8	1002.8	45.4	O-O
LCC7a	0.60	110.0	80.0	19.6	9.8	20.7	9.6	11.7	1499.0	33.2	I-I
LCC7b		109.8	79.8	19.6	9.2	19.7	9.9	11.7	1500.1	35.4	O-I
LCC8a	0.60	110.0	78.9	20.2	9.8	19.9	10.0	11.5	1999.1	32.6	I-I
LCC8b		109.8	79.5	20.3	9.3	20.5	10.4	11.4	1999.9	30.4	I-I

Comparisons and analysis

Elastic distortional buckling analysis

Following the intense work by Hancock et al, AS/NZS4600 is the first Specification to include rational design provisions to address distortional buckling. In the United States, Schafer and Pekoz have also devoted a great deal of work to the development of Direct Strength Method (DSM) which is able to account for the distortional buckling of columns. Both of these methods required the elastic distortional buckling stress f_d. Analytical formulas for f_d can be found in AS/NZS4600 and DSM, but it can only be used for simple sections without any intermediate stiffeners. Therefore finite element software ANSYS was used to perform an eigenvalue buckling analysis in order to get f_d of such complex shaped section as shown in Fig. 2. The element type is SHELL63. All ended degrees were restricted except Z direction at the loading end. The finite element model and the deformed shape after analysis are shown in Fig. 6. The analyzed results f_d are given in Table2.

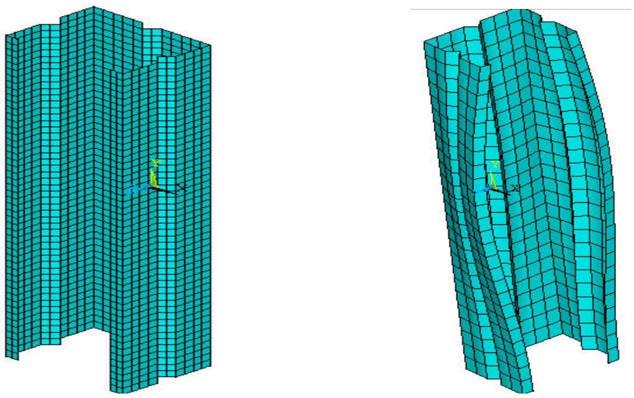


Fig. 6 Analyzed model and deformed shape after analysis

Table 2 Elastic distortional buckling stress f_d

Specimens	LCC1	LCC2	LCC3	LCC4
f_d/MPa	114	106	88	81
specimens	LCC5	LCC6	LCC7	LCC8
f_d/MPa	179	161	146	101

Calculated by AS/NZS4600

The following Esq. (1a) and (1b) in AS/NZS4600 are able to predict distortional buckling strength P_c of columns.

$$\text{For } f_d > f_y/2 \qquad P_c = A f_y [1 - f_y/(4f_d)] \qquad (1a)$$

$$\text{For } f_y/13 \le f_d \le f_y/2 \qquad P_c = A f_y [0.055((f_y/f_d)^{1/2} - 3.6)^2 + 0.237] \qquad (1b)$$

where f_d=elastic distortional buckling stress, using the analyzed results in Table 2.

The calculated results P_c and its comparisons with test results P_t are shown in Table 3 and Fig. 7. As can be seen, P_c is higher than P_t for intermediate length specimens such as LCC2, LCC3 and LCC7. This result indicates that the adverse interaction of local and distortional buckling hasn't been accounted in AS/NZS4600.

Calculated by direct strength method

Two types of DSM formulas were used for calculating columns' strength. One is for columns subjected to interaction of local-overall buckling (L+E); the other is for columns subjected to interaction of distortional-overall buckling (D+E).

Esq. (2a) and (2b) are used to predict axial strength P_{nl} considering interaction of local and overall buckling (L+E).

$$\text{For } \lambda_d \leq 0.776 \; P_{nl} = P_{ne} \tag{2a}$$

$$\text{For } \lambda_d > 0.776 \; P_{nl} = P_{ne}\,[1\text{-}0.25(\mathrm{P_{crl}} / \mathrm{P_{ne}})^{0.4}](\mathrm{P_{crl}} / \mathrm{P_{ne}})^{0.4} \tag{2b}$$

Where $\lambda_d = (P_{ne} \,/\, P_{crl})^{1/2}$; P_{ne} =overall compression member strength not considering the effect of local buckling, P_{ne}=$\psi\ A\ f_v$, ψ can be attained from Specification GB50018-2002 by slenderness ratio $\lambda_c = \lambda_w\ (f_y/235)^{1/2}$, λ_w = the slenderness ratio of columns subjected to torsion-flexural buckling; P_{crl}=f_{ol}×A, f_{ol}=elastic local buckling stress, using the analyzed results of finite strip software CUFSM (B. W. Schafer).

Esq. (3a) and (3b) are used to predict axial strength P_{nd} considering interaction of distortional-overall buckling (D+E).

$$\text{For } \lambda_d \leq 0.561 \; P_{nd} = P_{ne} \tag{3a}$$

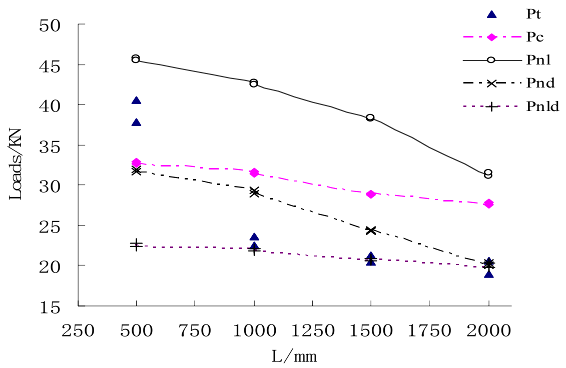
$$\text{For } \lambda_d > 0.561 \; P_{nd} = P_{ne}\,[1\text{-}0.25(\mathrm{P_{crd}} / \mathrm{P_{ne}})^{0.6}](\mathrm{P_{crd}} / \mathrm{P_{ne}})^{0.6} \tag{3b}$$

Where $\lambda_d = (P_{ne} \,/\, P_{nd})^{1/2}$; P_{ne} =overall compression member strength not considering the effect of local buckling; P_{crd}=A×f_d, f_d =elastic distortional buckling stress using the analyzed results in Table 2.

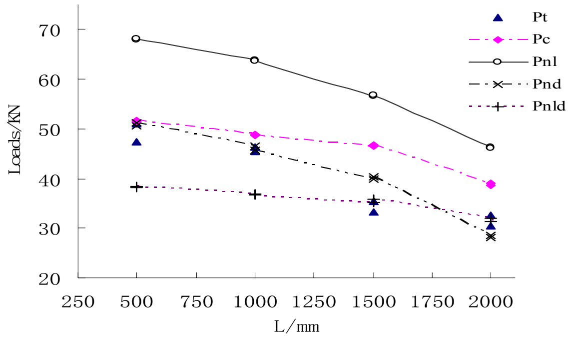
The calculated results P_{nl} and P_{nd} are shown in Table 3 and Fig. 7. As can be seen, the calculated results $\mathrm{P_{nl}}$ are much higher than test results P_t for all specimens. This result indicates that the behavior of distortional buckling is different from local buckling. The calculated results P_{nd} are close to test results P_t for shorter and longer columns but higher than test results P_t for intermediate length columns. This result indicates that Esq. (3a) and (3b) are unsafe for intermediate length columns which failed from the interaction of local and distortional buckling.

Table 3 Comparisons of test results and calculated results

Specimens	P_t/kN	P_c/kN	P_t/ P_c	P_{nl}/kN	P_t/ P_{nl}	P_{nd}/kN	P_t/ P_{nd}	P_{nld}/kN	(P_t-P_{nld})/ P_t
LCC1a	40.6	32.9	1.23	45.8	0.89	31.9	1.27	22.8	44%
LCC1b	37.8	32.6	1.16	45.5	0.83	31.7	1.19	22.4	41%
LCC2a	23.6	31.7	0.74	42.8	0.55	29.3	0.81	22.1	6%
LCC2b	22.5	31.4	0.72	42.5	0.53	29.0	0.78	21.8	3%
LCC3a	20.8	28.8	0.72	38.2	0.54	24.3	0.86	20.6	1%
LCC3b	21.3	29.0	0.73	38.4	0.55	24.5	0.87	20.9	2%
LCC4a	18.4	27.6	0.67	31.2	0.59	20.0	0.92	19.8	-8%
LCC4b	20.6	27.8	0.74	31.5	0.65	20.3	1.01	20.3	-1%
LCC5a	47.5	51.5	0.92	67.9	0.70	50.7	0.94	38.1	20%
LCC5b	51.0	51.6	0.99	68.1	0.75	51.2	0.99	38.5	25%
LCC6a	46.4	48.8	0.95	63.8	0.73	46.5	0.99	36.9	20%
LCC6b	45.4	48.6	0.93	63.7	0.71	45.6	0.99	36.7	19%
LCC7a	33.2	46.5	0.71	56.7	0.59	40.0	0.83	35.2	-6%
LCC7b	35.4	46.8	0.76	56.9	0.62	40.3	0.88	35.8	-1%
LCC8a	32.6	39.0	0.84	46.3	0.70	28.6	1.14	32.0	2%
LCC8b	30.4	38.6	0.79	46.1	0.66	28.2	1.08	31.3	-3%



(a) Specimens of sectional thickness 0.48mm



(b) Specimens of sectional thickness 0.60mm

Fig. 7 Comparisons of test results and calculated results

Calculated by the suggested method

From the comparisons of test and calculated results by the methods above, the conclusion can be drawn that design methods for distortional buckling in AS/NZS4600 and DSM are somewhat unsafe. The reason is that both AS/NZS4600 and DSM neglect the adverse effect of the interaction of local and distortional buckling.

In order to account for above adverse effect, a method which calculates the strength P_{nld} of columns subjected to interaction between local and distortional buckling by replacing P_{ne} in Esq.(2a) and (2b) of DSM (L+E) with P_c from Esq.(1a) and (1b) is proposed. Its calculated formulation is given as following Esq. (4a) and (4b).

$$\text{For } \lambda_d \leq 0.776 \quad P_{nld} = P_c \tag{4a}$$

$$\text{For } \lambda_d > 0.776 \quad P_{nld} = P_c\,[1-0.25(P_{crl} / P_c)^{0.4}](P_{crl} / P_c)^{0.4} \tag{4b}$$

Obviously, the above proposed method regards the distortional buckling mode as overall buckling because the denominator in Esq. (4b) is P_C. At the same time, the Esq. (4b) considers the effect of local buckling mode for its molecular is P_{crl}.

The calculated results P_{nld} of suggested method for intermediate length specimens are shown in Table 3 and Fig. 7. As can be seen, the calculated results P_{nld} matched well with the test results P_t and the negative difference between them are within 8%. So the suggested method is able to account for the adverse interaction of local and distortional buckling in intermediate length columns.

Conclusions

The distortional buckling behavior of 16 high strength cold-formed thin-wall lipped channel specimens under axial compression loads has been studied in this paper. According to the comparisons of test and calculated results based on AS/NZS4600 and DSM, the following conclusions can be drawn.

(1) The behaviors of distortional buckling are much different from that of local and overall buckling. So the procedure in design for local and overall buckling isn't fit for distortional buckling and a separate check should be performed on it.

(2) High strength cold-formed steel columns of intermediate length may local buckles before distortional buckling occurs. Appropriate attention should be paid on the adverse effect of the interaction of local and distortional buckling.

(3) The design formulas for distortional buckling in AS/NZS4600 and DSM should be revised because they are somewhat unconservative for columns subjected to the interaction of local and distortional buckling.

(4) The suggested method can be used to accounts for the adverse interaction of local and distortional buckling of intermediate length columns and may be served as a reference to design.

Acknowledgements

The authors are grateful to the financial support by the National Nature Science Foundation of China (No. 51078288)

References

AS/NZS4600:1996, Australian/New Zealand Standard Cold-Formed Steel Structures.
Demao Yang, Gregory J. Hancock. (12/12/2004). "Compression tests of high strength steel channel columns with interaction between local and distortional buckling", Journal of Structural Engineering, 130(2):1954-1963.
GB50018(27/9/2002), "Technical code of cold-formed thin-wall steel structures", GB50018-2002 Chinese Standard, Beijing, China. (in Chinese)

Hancock G.J., et al. (27/7/2001) . "Cold-formed steel structures to the AISI Specification". Marcel Dekker, New York.
Schafer, B. W. "Elastic buckling analysis of thin-walled members by finite strip analysis ", CUFSM v2.6.
Zhou Tianhua, Zhou xuhong, He Baokang. (30/6/2005). "Application and materialproperties of grade 550 high strength steel thin- plate", Journal of Architecture and Civil Engineering, 22(2): 43-46. (in Chinese)

Appendix. - Notation

f_y: Material yield strength
E: Elastic modulus
P_t: Ultimate test strength
f_d: Elastic distortional buckling stress
P_c: Distortional buckling strength
P_{nl}: Axial strength considering interaction of local and overall buckling (L+E)
P_{ne}: Overall compression member strength not considering the effect of local buckling
f_{ol}: Elastic local buckling stress
λ_w: Slenderness ratio of columns subjected to torsion-flexural buckling
P_{nd}: Axial strength considering interaction of distortional-overall buckling (D+E)