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Biaxial bending of cold-formed steel storage rack uprights - Part II: Direct Strength Method

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Abstract

This paper uses the results from the parametric studies reported in the companion paper to verify the accuracy of different forms of published direct strength method (DSM) equations. They consist of the classical DSM equations and considering the inelastic reserve capacity into these equations, with and without an extended range of the cross-sectional slenderness. The verifications are made for local and distortional buckling modes. Results show that for all investigated buckling modes, the DSM results in better predictions when the inelastic reserve capacity is considered. The appropriate form of the DSM to predict the biaxial capacity of unperforated cold-formed steel storage rack uprights is discussed.

Introduction

In the companion paper (Talebian et al. 2018b), a Finite Element (FE) model was developed and validated against the local and distortional buckling biaxial bending experimental results reported in Talebian et al. (2018a) and performed on two types of cold-formed steel storage rack uprights. Parametric studies were then conducted to expand the available experimental results over a wider range of upright cross-sectional slenderness ratios. Only local and distortional buckling failure modes were considered in the companion paper. The numerical results were then compared to the linear interaction equation in cold-formed steel structures design specifications (North American Specification AISI-S100 (AISI 2016), Australian and New Zealand Standard AS/NZS 4600:2005 (AS/NZS 2005) and Eurocode 3 EN1993-1-3 (CEN 2006)). The results of the parametric studies showed that the linear biaxial bending interaction equation is conservative and underestimates the biaxial bending capacity by up to 39% and 46% for local and distortional buckling modes, respectively.

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The focus of the present paper is to assess the accuracy of different forms of the Direct Strength Method (DSM) (Schafer, 2008) in predicting the biaxial bending capacity of cold-formed steel storage rack uprights. The results from the parametric studies performed in the companion paper are used for this purpose. Three different DSM approaches are investigated in this study, namely (i) by using the classical DSM equations given in the AS/NZS 4600:2005 (AS/NZS, 2005), with the nominal member moment capacity equal to the yield moment for compact cross-sections, (ii) through exploiting the inelastic reserve capacity for compact cross-sections, as permitted in the new AISI-S100 (2016) and (iii) by adopting an extended range of the cross-sectional slenderness for the inelastic reserve capacity, as proposed by Pham and Hancock (2013).

Investigated upright sections and tested configurations

In the companion paper, the parametric studies have been performed on slender, semi-compact and compact unperforated storage rack upright cross-sections for local and distortional buckling failure modes. In total, ten and four upright sections were considered for local and distortional buckling modes, respectively. Figure 1 shows the different cross-sectional shapes considered in the companion paper and their main cross-sectional dimensions and properties are summarised in Table 1.

Table 1. Nominal cross-sectional dimensions and properties of investigated uprights

	Thick. (mm)	Depth (mm)	Width (mm)	Second moment of area I_{Major} / I_{Minor}	Used for local buckling	Used for distortional buckling
Type C	2	140	100	2.53	Yes	No
Type D	1.2	90	72	1.58	Yes	Yes
Type E	1.2	90	72	2.06	Yes	No
Type F	1.5	125	100	1.79	Yes	Yes
Type G	1.5	100	110	0.94	Yes	No
Type H	1.5	100	90	1.41	Yes	No
Type I	1.5	100	80	2.13	Yes	No
Type J	0.6	140	100	2.53	Yes	No
Type K	0.8	90	72	1.57	Yes	No
Type L	0.8	90	72	2.03	Yes	No
Type M	1.8	80	60	2.17	No	Yes
Type N	1.5	80	90	1.17	No	Yes

Nine biaxial bending configurations per upright type and buckling mode were investigated and detailed in the companion paper (Talebian et al. 2018b).

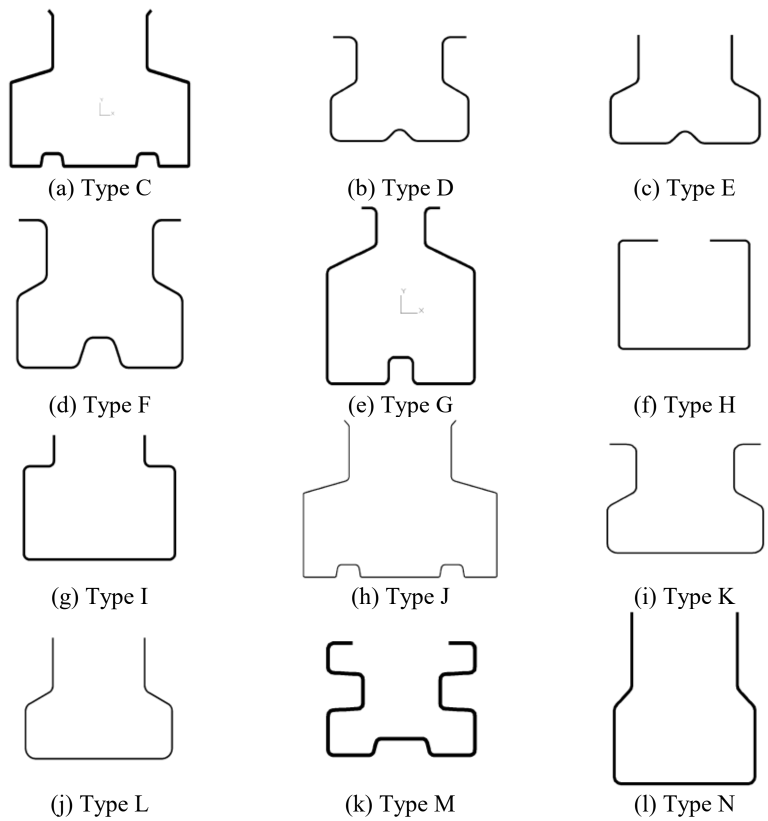

Figure 1. Upright cross-sections considered

Direct Strength Method equations to predict bending capacity

Local Buckling

The DSM nominal member moment capacity M_{bl} for local buckling, ignoring inelastic reserve capacity, is defined as (AISI-S100, 2016, AS/NZS, 2005, Schafer, 2008):

$$M_{bl} = M_y \quad \text{if} \quad \lambda_l \leq 0.776 \tag{1}$$

$$M_{bl} = \left[1 - 0.15\left(\frac{M_{ol}}{M_y}\right)^{0.4}\right]\left(\frac{M_{ol}}{M_y}\right)^{0.4} M_y \quad \text{if} \quad \lambda_l > 0.776 \tag{2}$$

where M_{ol} and M_y are the elastic local buckling moment and yield moment respectively, and λ_l is a non-dimensional slenderness ratio defined as:

$$\lambda_l = \sqrt{\frac{M_y}{M_{ol}}} \tag{3}$$

The recent AISI-S100 (2016) now allows the nominal member moment capacity to range between M_y and the plastic moment M_p for compact cross-sections if $\lambda_l \leq 0.776$ (local inelastic reserve capacity). When the first yield is in compression:

$$M_{bl} = M_y + (1 - 1/C_{yl}^2)(M_p - M_y) \tag{4}$$

where

$$C_{yl} = \sqrt{0.776/\lambda_l} \leq 3 \tag{5}$$

and when the first yield is in tension:

$$M_{bl} = M_{yc} + (1 - 1/C_{yl}^2)(M_p - M_y) \leq M_{yt3} \tag{6}$$

where

$$M_{yt3} = M_y + 8/9(M_p - M_y) \tag{7}$$

and M_{yc} is the moment at which yielding initiates in compression (after yielding in tension). M_{yc} has been conservatively taken as M_y in the following sections (AISI-S100, 2016, Torabian, et al., 2014).

Pham and Hancock (2013) proposed an extended range of the cross-sectional slenderness for which the inelastic strength can be applied. For local buckling, the inelastic reserve capacity can be applied when $\lambda_l \leq 1.55$ and C_{yl} in Eq. (5) becomes:

$$C_{yln} = \sqrt{1.55/\lambda_l} \leq 3 \tag{8}$$

and the inelastic local strength is calculated as:

$$M_{nyl} = M_y + (1 - 1/C_{yln}^2)(M_p - M_y) \tag{9}$$

M_{nyl} is then used in the classical DSM (Eqs. (1-2)) instead of M_y, and λ_{ln} defined as:

$$\lambda_{ln} = \sqrt{\frac{M_{nyl}}{M_{ol}}} \tag{10}$$

is used instead of λ_l to obtain the new nominal member capacity with extended range M_{bln}.

Distortional Buckling

Similarly, the DSM nominal member moment capacity M_{bd} for distortional buckling, ignoring inelastic reserve capacity, is as follows (AISI-S100, 2016, AS/NZS, 2005, Schafer, 2008):

$$M_{bd} = M_y \quad \text{if} \quad \lambda_d \leq 0.673 \tag{11}$$

$$M_{bd} = \left[1 - 0.22\left(\frac{M_{od}}{M_y}\right)^{0.5}\right]\left(\frac{M_{od}}{M_y}\right)^{0.5} M_y \quad \text{if} \quad \lambda_d > 0.673 \tag{12}$$

where M_{od} is the elastic buckling moment for distortional buckling and λ_d is a non-dimensional slenderness ratio defined as:

$$\lambda_d = \sqrt{\frac{M_y}{M_{od}}} \tag{13}$$

According to AISI-S100 (2016), distortional inelastic reserve capacity is permitted to be taken into account if $\lambda_d \leq 0.673$. The same equations as for local buckling (Eqs (4-7)) are used with C_{yl} in Eqs (4, 6) replaced by:

$$C_{yd} = \sqrt{0.673 / \lambda_d} \leq 3 \tag{14}$$

For distortional buckling, the inelastic strength with extended range proposed by Pham and Hancock (2013) can be applied when $\lambda_d \leq 1.45$ and C_{yd} in Eq. (14) becomes:

$$C_{ydn} = \sqrt{1.45 / \lambda_d} \leq 3 \tag{15}$$

and the inelastic distortional strength is calculated as:

$$M_{nyd} = M_y + (1 - 1/C_{ydn}^2)(M_p - M_y) \tag{16}$$

The M_{nyd} is then used in the classical DSM (Eqs. (11-12)) instead of M_y and λ_{dn} defined as:

$$\lambda_{dn} = \sqrt{\frac{M_{nyd}}{M_{od}}} \tag{17}$$

is used instead of λ_d to obtain the new nominal member capacity with extended range M_{bdn}.

Elastic Buckling, Yield and Plastic Moments

Elastic buckling moments (M_{ol} and M_{od}) for each tested configuration were calculated and input in the DSM expressions running linear buckling analyses (LBA) in Abaqus (2015). A similar model to the one described in the companion paper was used. Concentrated bending moments about major and minor axes were applied at the pinned boundary conditions.

For each of tested configurations, the yield moment M_y and plastic moment M_p were calculated about the axis about which the biaxial bending moment was applied using a yield stress equal to 450 MPa, as used in parametric studies.

Comparison of direct strength method design with parametric results

Local Buckling

Table 2 provides the elastic local slenderness ratio λ_l (Eq. (3)) and the FEA biaxial failure moment (M_{FEA}) to the DSM predicted moment (M_{DSM}) ratio for the three different DSM approaches and local buckling.

Figure 2 also graphically compares the DSM local buckling curve to the normalised FEA predicted capacities. As shown in Table 2, the DSM without the inelastic reserve capacity typically conservatively estimates the bending capacity of the studied uprights, with the FEA to DSM capacity ratios ranging between 0.99 and 2.05, both values for Type J upright in Configurations 1 and 8, respectively. On average, the DSM without the inelastic reserve capacity conservatively estimates the bending capacity by 44% with a Coefficient of Variation (COV) for all tested uprights and configuration of 17%. The classical DSM is generally more accurate in predicting the moment capacity when bending solely occurs about the major axis than about any other axis.

The use of the DSM with inelastic reserve capacity, as in the AISI-S100 (2016), results in a 10% improvement of the predictions, when compared to the classical DSM. For all configurations, considering the AISI-S100 (2016) inelastic reserve capacity overestimates the biaxial bending capacity by 34% on average, with a COV of 14%. Note, that when compared to the classical DSM, considering the inelastic reserve capacity only influences the prediction when λ_l is less than 0.776.

Regarding the DSM predictions using the extended range of the inelastic reserve capacity, Table 2 and Figure 2 show that the proposed method in Pham and Hancock (2013) provides better strength predictions when compared to the other two DSM approaches. On average, for all configurations and upright types, this method overestimates the FEA capacity by 21%, with a COV of 17%. As can be seen in Figure 2, the proposed method in Pham and Hancock (2013) is mainly conservative for slenderness ratio greater than about 1.15.

Distortional Buckling

Table 3 provides the elastic distortional slenderness λ_d and the M_{FEA}/M_{DSM} ratios, with and without the inelastic reserve capacity, for all analyses failing in distortional buckling. Figure 3 compares the DSM distortional buckling curve to normalised FEA results.

Table 3 shows that the DSM without considering the inelastic reserve capacity usually conservatively estimates the bending capacity of the investigated uprights, with a FEA to DSM biaxial moment capacity ratio up to 1.91 (Type M and Configuration 7). For all configurations and upright types, the classical DSM overestimates on average the FEA capacity by 24%, with a COV of 21%. Similar to local buckling, the classical DSM typically better predicts the bending capacity for bending about major axis only.

The use of the DSM with inelastic reserve capacity, as in the AISI-S100 (2016), leads to an average underestimation of the bending capacity of 16%, with COV of 13%.

Similar to local buckling, the DSM predictions using the extended range of the inelastic reserve capacity proposed by Pham and Hancock (2013) provides better strength predictions when compared to the other two DSM approaches investigated herein. On average, this method overestimates the capacity about 1% with a COV of 14%.

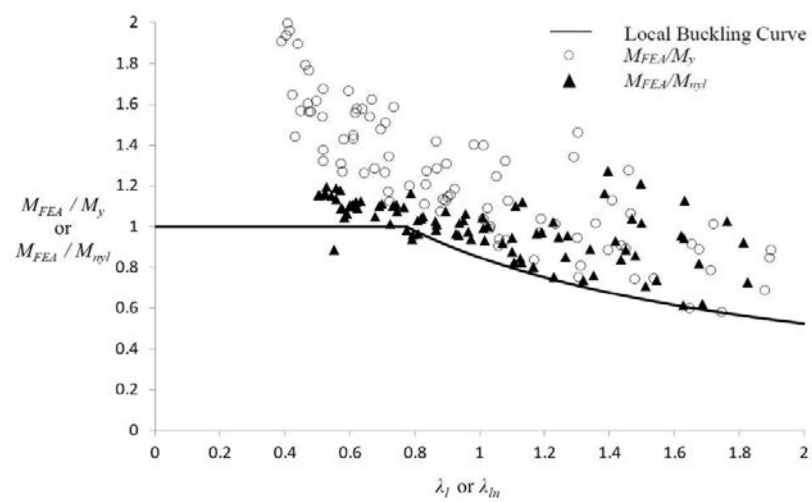

Figure 2. Comparison of the DSM curve to parametric studies data for local buckling

Table 2. Comparison of parametric results with DSM for local buckling uprights

Up-right	Conf	λ_l	M_{FEA}/M_{DSM} (No reserve)(1)	M_{FEA}/M_{DSM} (With reserve)(2)	M_{FEA}/M_{DSM} (Pham and Hancock(3)	Up-right	Conf	λ_l	M_{FEA}/M_{DSM} (No reserve)(1)	M_{FEA}/M_{DSM} (With reserve)(2)	M_{FEA}/M_{DSM} (Pham and Hancock(3)
Type C	0	0.57	1.31	1.22	1.12	Type H	0	1.30	1.06	1.06	1.05
	1	0.78	1.21	1.21	1.06		1	1.17	1.09	1.09	1.02
	2	0.83	1.26	1.26	1.08		2	1.08	1.16	1.16	1.05
	3	0.74	1.59	1.52	1.18		3	1.03	1.20	1.20	1.08
	4	0.71	1.51	1.40	1.08		4	1.06	1.10	1.10	1.04
	5	0.52	1.38	1.20	1.07		5	1.06	1.15	1.15	1.05
	6	0.43	1.44	1.04	0.89		6	1.01	1.23	1.23	1.10
	7	0.40	1.94	1.36	1.16		7	1.09	1.40	1.40	1.27
	8	0.41	2.00	1.40	1.20		8	1.23	1.37	1.37	1.32
Type D	0	0.58	1.27	1.19	1.09	Type I	0	0.83	1.16	1.16	1.10
	1	0.61	1.43	1.25	1.02		1	0.72	1.13	1.10	0.95
	2	0.62	1.56	1.36	1.08		2	0.72	1.17	1.14	0.98
	3	0.60	1.67	1.40	1.10		3	0.64	1.58	1.39	1.10
	4	0.61	1.45	1.31	1.11		4	0.62	1.58	1.39	1.11
	5	0.47	1.60	1.27	1.09		5	0.90	1.23	1.23	1.12
	6	0.46	1.79	1.38	1.18		6	1.02	1.30	1.30	1.19
	7	0.44	1.90	1.40	1.19		7	0.98	1.63	1.63	1.39
	8	0.45	1.57	1.30	1.16		8	1.01	1.66	1.66	1.43
Type E	0	0.90	1.26	1.26	1.18	Type J	0	1.88	1.25	1.25	1.30
	1	1.19	1.37	1.37	1.30		1	1.65	0.99	0.99	1.01
	2	1.30	1.33	1.33	1.28		2	1.74	1.01	1.01	1.05
	3	1.08	1.64	1.64	1.38		3	1.54	1.18	1.18	1.17
	4	1.05	1.52	1.52	1.29		4	1.48	1.14	1.14	1.11
	5	0.52	1.32	1.17	1.05		5	1.71	1.34	1.34	1.38
	6	0.48	1.57	1.26	1.09		6	1.39	1.31	1.31	1.26
	7	0.42	1.96	1.36	1.15		7	1.29	1.87	1.87	1.71
	8	0.39	1.91	1.33	1.16		8	1.30	2.05	2.05	1.88
Type F	0	0.64	1.26	1.21	1.10	Type K	0	0.88	1.16	1.16	1.08
	1	0.71	1.27	1.21	0.99		1	0.91	1.28	1.28	1.11
	2	0.69	1.48	1.37	1.09		2	0.90	1.44	1.44	1.20
	3	0.66	1.54	1.37	1.06		3	0.87	1.52	1.52	1.24
	4	0.68	1.29	1.20	0.99		4	0.89	1.23	1.23	1.09
	5	0.58	1.43	1.25	1.05		5	1.18	1.28	1.28	1.18
	6	0.52	1.68	1.35	1.13		6	1.36	1.47	1.47	1.39
	7	0.47	1.77	1.33	1.11		7	1.47	1.62	1.62	1.58
	8	0.47	1.56	1.29	1.14		8	1.65	1.52	1.52	1.55
Type G	0	1.03	1.19	1.19	1.13	Type L	0	1.43	1.37	1.37	1.35
	1	0.87	1.38	1.38	1.21		1	1.89	1.55	1.55	1.64
	2	0.72	1.34	1.29	1.08		2	1.90	1.63	1.63	1.79
	3	0.50	1.62	1.30	1.10		3	1.72	1.73	1.73	1.86
	4	0.42	1.65	1.30	1.16		4	1.68	1.50	1.50	1.57
	5	0.92	1.32	1.32	1.18		5	1.31	1.14	1.14	1.10
	6	0.84	1.33	1.33	1.15		6	1.45	1.35	1.35	1.32
	7	0.67	1.62	1.48	1.18		7	1.41	1.68	1.68	1.59
	8	0.52	1.54	1.29	1.11		8	1.46	1.94	1.94	1.88
								Average (all uprights)	1.44	1.34	1.21
								COV (%)	17.00	15.00	18.00

(1) No inelastic reserve capacity; (2) Inelastic reserve capacity as in AISI-S100 (2016); (3) Extended reserve strength in Pham and Hancock (2013)

Table 3. Comparison of parametric results with DSM for distortional buckling uprights

Up-right	Conf	λ_d	M_{FEA}/M_{DSM} (No reserve)[(1)]	M_{FEA}/M_{DSM} (With reserve)[(2)]	M_{FEA}/M_{DSM} (Pham and Hancock[(3)]	Up-right	Conf	λ_d	M_{FEA}/M_{DSM} (No reserve)[(1)]	M_{FEA}/M_{DSM} (With reserve)[(2)]	M_{FEA}/M_{DSM} (Pham and Hancock[(3)]
Type D	0	0.74	0.92	0.92	0.85	Type F	0	0.78	0.97	0.97	0.90
	1	0.76	1.01	1.01	0.83		1	0.83	0.94	0.94	0.81
	2	0.76	1.13	1.13	0.92		2	0.80	1.10	1.10	0.91
	3	0.72	1.17	1.17	0.92		3	0.75	1.18	1.18	0.94
	4	0.74	1.06	1.06	0.91		4	0.77	1.18	1.18	1.01
Type M	0	0.63	1.10	1.09	0.97	Type N	0	1.29	1.07	1.07	1.06
	1	0.66	1.19	1.18	0.97		1	1.39	1.26	1.26	1.24
	2	0.63	1.27	1.22	0.98		2	1.32	1.30	1.30	1.25
	3	0.57	1.55	1.40	1.08		3	1.26	1.27	1.27	1.18
	4	0.59	1.55	1.46	1.20		4	1.25	0.93	0.93	0.88
	5	0.36	1.37	1.08	0.96						
	6	0.31	1.62	1.20	1.07						
	7	0.30	1.91	1.35	1.19						
	8	0.33	1.64	1.32	1.20						
						Average (all uprights)			1.24	1.16	1.01
						COV (%)			21.00	13.00	14.00

[(1)] No inelastic reserve capacity; [(2)] Inelastic reserve capacity as in AISI-S100 (2016); [(3)] Extended reserve strength in Pham and Hancock (2013)

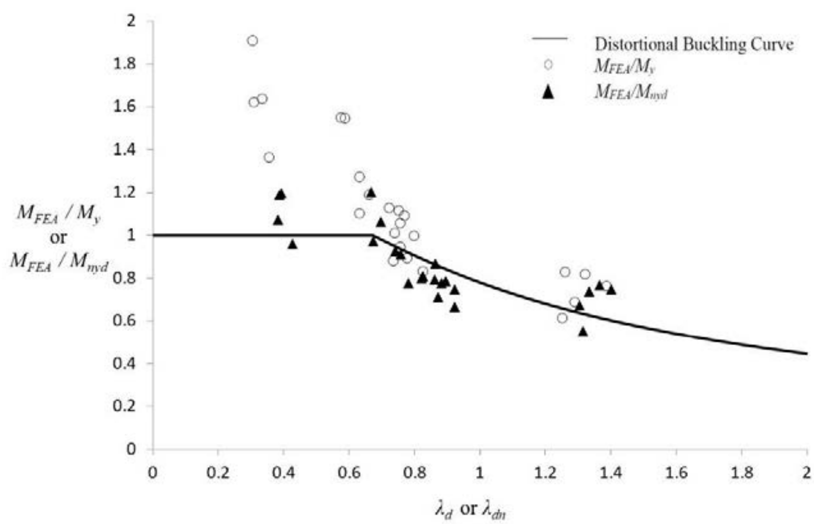

Figure 3. Comparison of the DSM curve to parametric studies data for distortional buckling

Conclusion

This paper presented the evaluation of different Direct Strength Method approaches to estimate the biaxial bending capacity of cold-formed steel storage rack uprights falling in local and distortional buckling. The DSM, as published in the AISI-S100 (2016), with or without considering the inelastic reserve capacity, was found to underestimate the biaxial bending capacity for the majority of the tested configurations. On average, the capacity to DSM prediction ratios were equal to 1.44 and 1.24 for local and distortional buckling, respectively, when the inelastic reserve capacity was ignored. When considering it, these ratios changed to 1.34 and 1.16 for local and distortional buckling, respectively. When using the extended inelastic reserve capacity range proposed by Pham and Hancock (2013), the DSM equations better predict the biaxial capacity, with an capacity to prediction equal to 1.21 and 1.01 for local and distortional buckling, respectively.

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