Web crippling Design of Cold-formed Ferritic Stainless Steel Unlipped Channels with Web Holes and with Fastened Flanges under End-two-Flange Loading Condition - Part II: Parametric Study and Design Equations

Amir M. Yousefi, James B.P. Lim and G. Charles Clifton

Department of Civil and Environmental Engineering, The University of Auckland, New Zealand

Abstract

An extensive parametric study of cold-formed ferritic stainless steel unlipped channels with fastened flanges subjected to web crippling under end-two-flange (ETF) loading condition is undertaken, using quasi-static finite element analysis, to investigate the effects of web holes and cross-sections sizes. Both cases of unlipped channels with and without web holes are considered. The web holes are located either centred or offset to the load and reaction plates. It is noted that no cold-formed stainless steel standard provides capacity reduction factors for unlipped channels with fastened flanges subject to end-two-flange loading condition. The strengths obtained from reduction factor equations are first compared to strengths calculated from equations recently proposed for cold-formed stainless steel lipped channels. It is demonstrated that the strength reduction factor equations previously proposed for cold-formed stainless steel lipped channels can be unconservative for cold-formed ferritic stainless steel unlipped channels by up to 10%. The laboratory investigation shows that, for the case of plain unlipped channels (i.e. without web holes), the European Standard (EN 1993-1-4) is too conservative by as much as 43 %. From both laboratory and finite element results, web crippling design equations are proposed for both sections, with and without web holes.

Keywords

Cold-formed ferritic stainless steel; Finite element analysis; Unlipped channels; Web crippling; Web holes.

1 Introduction

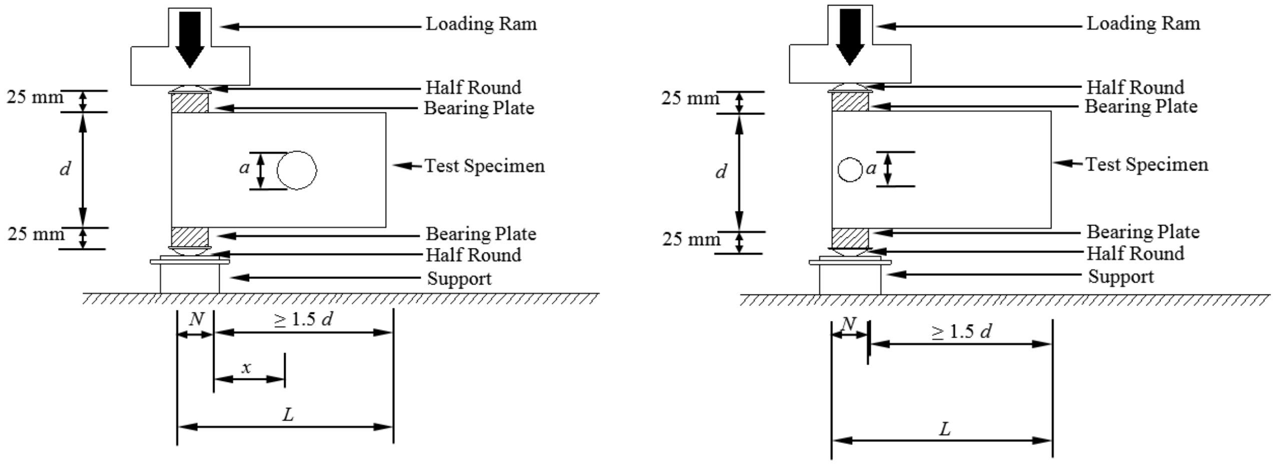
Design guidelines for cold-formed stainless steel structural members can be found in the American Society of Civil Engineers Specification (SEI/ASCE-8) [1], the Australian/New Zealand Standard (AS/NZS 4673) [2] and the European Standard (EN 1993-1-4) [3] (which refers to EN 1993-1-3 [4] for carbon steel). None of the aforementioned specifications, however, provide design guidance for cold-formed stainless steel channels with web holes; only the North American Specification (NAS) [5] for cold-formed carbon steel provides reduction factors for the web crippling strength of channels and only under one-flange loading. Furthermore, for the web crippling strength of cold-formed stainless steel channels, SEI/ASCE-8 [1], AS/NZS 4673 [2] and EN 1993-1-4 [3] make no distinction between lipped and unlipped flanges or the different stainless steel grades. Again, only NAS [5] for cold-formed carbon steel structural members, are separate equations provided for lipped and unlipped flanges.

Using the results of finite element static analyses, the Authors have recently proposed unified strength reduction factor equations for the web crippling strength of cold-formed stainless steel lipped channels with holes under the one and two flange loading condition covering three different stainless steel grades: duplex grade EN 1.4462; austenitic grade EN 1.4404 and ferritic grade EN 1.4003 [6-10]. Unlipped channels, however, were not considered, and no experimental tests were conducted. This paper both addresses these issues.

For stainless steel lipped channels, Krovink and van den Berg [11] and Krovink et al. [12] have considered lipped cold-formed stainless steel channels subject to one-flange loading. Zhou and Young [13-16] considered the web crippling strength of cold-formed stainless steel tubular sections, again without holes. Research by Lawson et al. [17], while concerned with web holes, focussed on the shear and bending capacity of the stainless steel lipped channels and not on the web crippling strength under concentrated loads. The Authors have also recently conducted experimental and numerical studies on cold-formed stainless steel unlipped channels subject to two-flange loading [18-20].

In terms of cold-formed carbon steel, Uzzaman et al. [21-24] have considered the web crippling strength of lipped channels under the two-flange loading condition. For web crippling without web holes, Poologanathan et al. [25] and Poologanathan and Mahendran [26] considered the web crippling strength of hollow flange channel beams, without holes in web. Lavan et al. [27] and Gunalan and Mahendran [28] have considered a Direct Strength Method approach in regard to the web crippling strength of lipped channels, again all without web holes.

Experimental and numerical investigations have been discussed in the companion paper [29]. In this study, non-linear quasi-static finite element analysis (FEA) is used to conduct parametric studies to determine the web crippling strength of cold-formed unlipped channels with and without web holes. As shown in Fig. 1, these web holes are either centred or offset to the load and reaction plates. The case of flanges fastened to the load and reaction plates is considered. The general purpose finite element program ABAQUS [30] is used for the numerical investigation. Based on the test data found in the companion paper [29], and the numerical results obtained from this study, an extensive statistics analysis is performed. For cold-formed ferritic stainless steel unlipped channels, web crippling design equations are proposed for both sections, with and without web holes that are conservative to both the experimental and finite element results.



Offset web hole **(b) Centred web hole**

Fig. 1 Schematic front view of test set-up after Uzzaman et al. [21-24]

2 Experimental Investigation

Yousefi et al. [29] conducted a test programme on cold-formed ferritic stainless steel unlipped channels with and without web holes subjected to web crippling under ETF loading condition, as shown in Fig. 2. The case of flanges fastened to the load and reaction plates were considered. The specimens consisted of different web slenderness (h/t) values ranging from 154.25 to 251.75. The size of the web holes was varied in order to investigate the effect of the web holes on the web crippling strength. Web holes with nominal diameters (a) ranging from 68 mm to 99 mm were considered in the experimental investigation. The ratio of the diameter of the web holes to the depth of the flat portion of the webs (a/h) was kept constant 0.4. All test specimens were fabricated with web holes located at the mid-depth of the webs and centred to the load and reaction plates or with a horizontal clear distance to the near edge of the load and reaction plates (x), as shown in Fig. 1. The test data and material properties reported in the companion paper [29] are used in this paper for the development of web crippling strength design equations. Comparative hot-rolled mechanical properties can be found in Yousefi et al. [31] and Rezvani et al. [32].

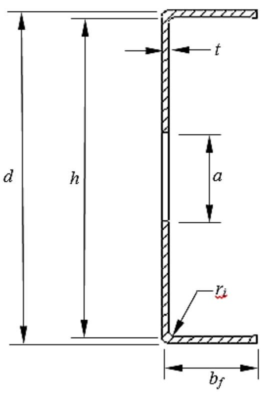


Fig. 2 Definition of symbols

3 Numerical Investigation

The non-linear general purpose finite element program ABAQUS [32] was used to simulate the web crippling behaviour of the unlipped channels with and without web holes subjected to web crippling. The load and reaction plates, the channels with web holes and the contact interfaces between the load and reaction plates and the unlipped channels were modelled. The details of the FEM are described in the companion paper [29]. In the finite element model, quasi-static analysis was used as it was found that the failure modes and post-buckling behaviour were in better agreement with the laboratory test results.

The measured cross-section dimensions and the material properties obtained from the tests were used. The channel sections of the model were based on the centreline dimensions of the cross-sections. ABAQUS [30] required the material stress-strain curve input as true stress-true curve. The stress-strain curves were directly obtained from the tensile tests and converted into true stress-strain curves as specified in the ABAQUS manual [30]. Finite element mesh sizes were 5 mm × 5 mm for the cold-formed stainless steel unlipped channels and 8 mm × 8 mm for the load and reaction plates.

The load and reaction plates, the unlipped channels with web holes and the interfaces between the load and the load plates have been modelled. Contact surfaces were defined between the load and reaction plates and the cold-formed stainless steel unlipped channels.

4 Parametric Study

The FE model developed closely predicted the experimental ultimate loads, failure modes and post-buckling behaviour of the unlipped channels with and without web holes and with fastened flanges subject to web crippling under ETF loading condition [29]. Using these models, parametric studies were carried out to study the effects of web holes and cross-section sizes on the web crippling strengths of unlipped channel subject to web crippling. The parameters comprise of different lengths of load and reaction plates. The unlipped channels cross-section sizes and the web holes locations were varied so to investigate the effect of load and reaction plates lengths ratio (N/h), web holes diameter ratio (a/h) and web holes location ratio (x/h) on the web crippling strength of unlipped channels under the ETF loading condition.

Table 1 Dimensions and web crippling strengths predicted from finite element analysis in parametric study of *a/h* for centred web hole

Specimen	Web	Flange	Thickness	Length	FEA load per web, P_{FEA}				
	d (mm)	b_f (mm)	t (mm)	L (mm)	A0 (kN)	A0.2 (kN)	A0.4 (kN)	A0.6 (kN)	A0.8 (kN)
175x60-t1.2-N50	178.35	60.14	1.10	314.83	2.33	2.02	1.70	1.36	1.01
175x60-t4.0-N50	178.35	60.14	4.00	314.83	38.45	34.03	29.19	22.44	13.08
175x60-t6.0-N50	178.35	60.14	6.00	314.83	78.52	70.37	59.84	42.79	28.24
175x60-t1.2-N75	178.56	60.06	1.15	339.50	2.96	2.61	2.23	1.81	1.36
175x60-t4.0-N75	178.56	60.06	4.00	339.50	46.10	39.97	34.56	28.19	15.48
175x60-t6.0-N75	178.56	60.06	6.00	339.50	95.86	83.86	72.21	53.76	34.13
175x60-t1.2-N100	178.12	60.25	1.09	364.50	3.02	2.69	2.24	1.85	1.39
175x60-t4.0-N100	178.12	60.25	4.00	364.50	54.84	47.26	40.73	33.87	18.86
175x60-t6.0-N100	178.12	60.25	6.00	364.50	114.02	99.02	86.25	66.17	40.67
200x75-t1.2-N50	203.55	74.97	1.16	349.33	2.41	2.11	1.77	1.39	1.04
200x75-t4.0-N50	203.55	74.97	4.00	349.33	37.98	33.85	29.21	23.44	12.46
200x75-t6.0-N50	203.55	74.97	6.00	349.33	78.46	71.17	60.95	43.64	26.98
200x75-t1.2-N75	203.51	75.08	1.10	374.50	2.45	2.15	1.82	1.43	1.08
200x75-t4.0-N75	203.51	75.08	4.00	374.50	44.75	39.04	34.06	28.23	14.74
200x75-t6.0-N75	203.51	75.08	6.00	374.50	94.77	83.09	72.30	53.70	32.33
200x75-t1.2-N100	203.56	75.04	1.09	379.50	2.65	2.31	1.95	1.55	1.16
200x75-t4.0-N100	203.56	75.04	4.00	379.50	52.57	45.24	39.10	32.96	17.71
200x75-t6.0-N100	203.56	75.04	6.00	379.50	111.73	96.84	84.61	65.31	38.29
250x100-t1.2-N50	253.86	100.03	1.17	424.83	2.09	1.81	1.46	1.14	0.83
250x100-t4.0-N50	253.86	100.03	4.00	424.83	37.08	32.95	28.38	23.21	10.64
250x100-t6.0-N50	253.86	100.03	6.00	424.83	77.80	71.54	61.27	44.54	23.36
250x100-t1.2-N75	253.57	99.96	1.16	450.00	2.28	2.00	1.62	1.27	0.93
250x100-t4.0-N75	253.57	99.96	4.00	450.00	42.51	37.15	31.94	26.51	12.53
250x100-t6.00-N75	253.57	99.96	6.00	450.00	92.01	81.09	70.28	52.78	26.96
250x100-t1.2-N100	253.47	100.00	1.13	474.50	2.34	2.04	1.67	1.34	1.01
250x100-t4.0-N100	253.47	100.00	4.00	474.50	47.94	41.32	35.82	29.83	14.76
250x100-t6.0-N100	253.47	100.00	6.00	474.50	106.47	92.13	79.42	61.90	31.21

The models of unlipped channels had various depth sizes, with thicknesses (t) between 1.12 to 6.0 mm. Height to thickness (web slenderness) ratios (h/t) were between 148.92 to 232.63. The a/h ratios were 0.2, 0.4, 0.6 and 0.8. The x/h ratios were 0.2, 0.4 and 0.6. The length of load and reaction plates (N) were considered to be 50, 75 and 100 mm. The web crippling strengths of the unlipped channels with no holes in web were also obtained for each series of models. Hence, the capacity reduction factor (R), which is the ratio of the web crippling strengths for unlipped channels with holes in web over the web crippling strengths of unlipped channels with no holes in web, was used as a degrading ratio to quantify the effect of holes on the web crippling strengths of unlipped channels. The models have been coded so that the nominal model dimension, the length of the load or reaction plates and web holes ratio (A) can be identified in Tables 1 to 3.

Table 2 Dimensions and web crippling strengths predicted from finite element analysis in parametric study of *a/h* for offset web hole

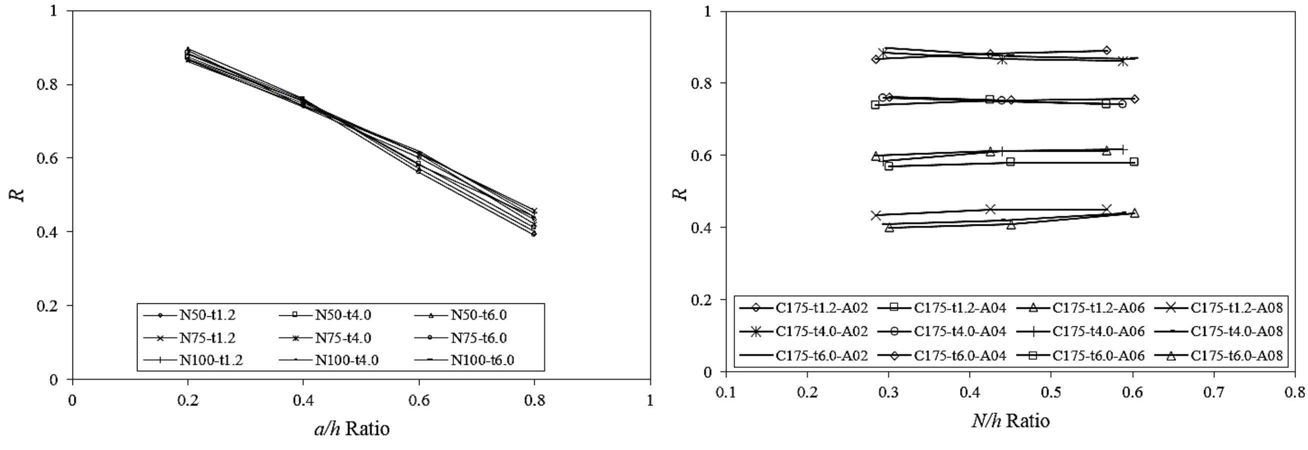
Specimen	Web	Flange	Thickness	Length	FEA load per web, P_{FEA}				
	d (mm)	b_f (mm)	t (mm)	L (mm)	A0 (kN)	A0.2 (kN)	A0.4 (kN)	A0.6 (kN)	A0.8 (kN)
175x60-t1.2-N50	178.35	60.14	1.10	314.83	2.33	2.21	2.15	2.01	1.91
175x60-t4.0-N50	178.35	60.14	4.00	314.83	38.45	38.11	37.15	34.42	31.59
175x60-t6.0-N50	178.35	60.14	6.00	314.83	78.52	78.10	76.93	73.19	71.26
175x60-t1.2-N75	178.56	60.06	1.15	339.50	2.96	2.83	2.65	2.43	2.21
175x60-t4.0-N75	178.56	60.06	4.00	339.50	46.10	45.86	44.95	42.78	40.32
175x60-t6.0-N75	178.56	60.06	6.00	339.50	95.86	95.19	93.49	88.66	84.54
175x60-t1.2-N100	178.12	60.25	1.09	364.50	3.02	2.86	2.69	2.47	2.26
175x60-t4.0-N100	178.12	60.25	4.00	364.50	54.84	54.11	52.69	49.36	46.18
175x60-t6.0-N100	178.12	60.25	6.00	364.50	114.02	113.15	109.20	101.91	98.12
200x75-t1.2-N50	203.55	74.97	1.16	349.33	2.41	2.35	2.22	2.05	1.96
200x75-t4.0-N50	203.55	74.97	4.00	349.33	37.98	37.12	36.70	33.65	30.15
200x75-t6.0-N50	203.55	74.97	6.00	349.33	78.46	78.02	77.09	73.67	69.79
200x75-t1.2-N75	203.51	75.08	1.10	374.50	2.45	2.37	2.25	2.1	2.03
200x75-t4.0-N75	203.51	75.08	4.00	374.50	44.75	44.03	43.52	41.58	37.56
200x75-t6.0-N75	203.51	75.08	6.00	374.50	94.77	94.01	92.72	88.22	84.27
200x75-t1.2-N100	203.56	75.04	1.09	379.50	2.65	2.57	2.45	2.30	2.12
200x75-t4.0-N100	203.56	75.04	4.00	379.50	52.57	52.01	50.26	46.54	41.84
200x75-t6.0-N100	203.56	75.04	6.00	379.50	111.73	110.21	106.16	98.44	93.25
250x100-t1.2-N50	253.86	100.03	1.17	424.83	2.09	2.04	1.92	1.77	1.52
250x100-t4.0-N50	253.86	100.03	4.00	424.83	37.08	36.62	35.14	32.24	29.32
250x100-t6.0-N50	253.86	100.03	6.00	424.83	77.80	77.09	75.90	72.84	69.14
250x100-t1.2-N75	253.57	99.96	1.16	450.00	2.28	2.26	2.13	1.98	1.78
250x100-t4.0-N75	253.57	99.96	4.00	450.00	42.51	41.97	40.12	38.46	35.12
250x100-t6.00-N75	253.57	99.96	6.00	450.00	92.01	91.29	89.40	85.37	81.67
250x100-t1.2-N100	253.47	100.00	1.03	474.50	2.34	2.29	2.20	2.05	1.97
250x100-t4.0-N100	253.47	100.00	4.00	474.50	47.94	47.60	46.44	44.05	41.49
250x100-t6.0-N100	253.47	100.00	6.00	474.50	106.47	105.78	102.91	95.86	90.26

In terms of web holes located in between the load and reaction plates (centred holes), 108 sections were considered to determine the effect of web holes diameter ratio (a/h) as well as load and reaction plates lengths ratio (N/h). Table 1 presents the web crippling strengths (PFEA) per single web predicted from the FE analyses as well as cross-section dimensions. Fig. 3 demonstrates the effects of the web holes diameter ratio (a/h) and load and reaction plates lengths ratio (N/h) on the web crippling strength reduction factors of the C175 section. As can be seen from Fig. 3(a), the reduction factor decreases as the web holes diameter ratio (a/h) increases from the ratio of 0.2 to the ratio of 0.8. Also, it is clear from Fig. 3(b) that the reduction factor is not sensitive to the load and reaction plates length ratio (N/h).

Table 3 Dimensions and web crippling strengths predicted from finite element analysis in parametric study of x/h for offset web hole

Specimen	Web		Flange	Thickness	Length	FEA load per web, P_{FEA}		
	d (mm)	b_f (mm)	t (mm)	L (mm)	X0 (kN)	X0.2 (kN)	X0.4 (kN)	X0.6 (kN)
175x60-t1.2-N50-A0	178.35	60.14	1.10	314.83	2.33	2.33	2.33	2.33
175x60-t1.2-N50-A0.2	178.35	60.14	1.10	314.83	2.14	2.21	2.26	2.30
175x60-t1.2-N50-A0.4	178.35	60.14	1.10	314.83	2.04	2.14	2.17	2.20
175x60-t1.2-N50-A0.6	178.35	60.14	1.10	314.83	1.98	2.05	2.09	2.15
175x60-t1.2-N50-A0.8	178.35	60.14	1.10	314.83	1.89	1.97	2.03	2.08
175x60-t1.2-N75-A0	178.56	60.06	1.15	339.50	2.96	2.96	2.96	2.96
175x60-t1.2-N75-A0.2	178.56	60.06	1.15	339.50	2.88	2.90	2.92	2.94
175x60-t1.2-N75-A0.4	178.56	60.06	1.15	339.50	2.79	2.82	2.85	2.89
175x60-t1.2-N75-A0.6	178.56	60.06	1.15	339.50	2.65	2.69	2.73	2.80
175x60-t1.2-N75-A0.8	178.56	60.06	1.15	339.50	2.54	2.58	2.61	2.73
175x60-t1.2-N100-A0	178.12	60.25	1.09	364.50	3.02	3.02	3.02	3.02
175x60-t1.2-N100-A0.2	178.12	60.25	1.09	364.50	2.92	2.95	2.97	2.99
175x60-t1.2-N100-A0.4	178.12	60.25	1.09	364.50	2.85	2.87	2.89	2.94
175x60-t1.2-N100-A0.6	178.12	60.25	1.09	364.50	2.80	2.82	2.84	2.87
175x60-t1.2-N100-A0.8	178.12	60.25	1.09	364.50	2.74	2.78	2.81	2.85
200x75-t1.2-N50-A0	203.55	74.97	1.16	349.33	2.41	2.41	2.41	2.41
200x75-t1.2-N50-A0.2	203.55	74.97	1.16	349.33	2.21	2.27	2.33	2.36
200x75-t1.2-N50-A0.4	203.55	74.97	1.16	349.33	1.98	2.11	2.21	2.27
200x75-t1.2-N50-A0.6	203.55	74.97	1.16	349.33	1.76	1.95	2.11	2.22
200x75-t1.2-N50-A0.8	203.55	74.97	1.16	349.33	1.51	1.78	1.98	2.14
200x75-t1.2-N75-A0	203.51	75.08	1.10	374.50	2.45	2.45	2.45	2.45
200x75-t1.2-N75-A0.2	203.51	75.08	1.10	374.50	2.28	2.32	2.36	2.38
200x75-t1.2-N75-A0.4	203.51	75.08	1.10	374.50	2.07	2.18	2.26	2.32
200x75-t1.2-N75-A0.6	203.51	75.08	1.10	374.50	1.90	2.06	2.17	2.26
200x75-t1.2-N75-A0.8	203.51	75.08	1.10	374.50	1.74	1.95	2.09	2.19
200x75-t1.2-N100-A0	203.56	75.04	1.09	379.50	2.65	2.65	2.65	2.65
200x75-t1.2-N100-A0.2	203.56	75.04	1.09	379.50	2.51	2.55	2.58	2.60
200x75-t1.2-N100-A0.4	203.56	75.04	1.09	379.50	2.33	2.43	2.49	2.54

Specimen	Web	Flange	Thickness	Length	FEA load per web, P_{FEA}			
	d (mm)	b_f (mm)	t (mm)	L (mm)	X0 (kN)	X0.2 (kN)	X0.4 (kN)	X0.6 (kN)
200x75-t1.2-N100-A0.6	203.56	75.04	1.09	379.50	2.19	2.33	2.42	2.50
200x75-t1.2-N100-A0.8	203.56	75.04	1.09	379.50	2.06	2.23	2.36	2.45
250x100-t1.2-N50-A0	253.86	100.03	1.17	424.83	2.09	2.09	2.09	2.09
250x100-t1.2-N50-A0.2	253.86	100.03	1.17	424.83	1.91	1.97	2.01	2.04
250x100-t1.2-N50-A0.4	253.86	100.03	1.17	424.83	1.66	1.79	1.89	1.96
250x100-t1.2-N50-A0.6	253.86	100.03	1.17	424.83	1.45	1.65	1.80	1.90
250x100-t1.2-N50-A0.8	253.86	100.03	1.17	424.83	1.23	1.50	1.68	1.83
250x100-t1.2-N75-A0	253.57	99.96	1.16	450.00	2.28	2.28	2.28	2.28
250x100-t1.2-N75-A0.2	253.57	99.96	1.16	450.00	2.14	2.20	2.24	2.26
250x100-t1.2-N75-A0.4	253.57	99.96	1.16	450.00	1.92	2.03	2.13	2.19
250x100-t1.2-N75-A0.6	253.57	99.96	1.16	450.00	1.72	1.90	2.04	2.13
250x100-t1.2-N75-A0.8	253.57	99.96	1.16	450.00	1.54	1.77	1.94	2.07
250x100-t1.2-N100-A0	253.47	100.00	1.13	474.50	2.34	2.34	2.34	2.34
250x100-t1.2-N100-A0.2	253.47	100.00	1.13	474.50	2.18	2.23	2.27	2.29
250x100-t1.2-N100-A0.4	253.47	100.00	1.13	474.50	2.05	2.08	2.11	2.17
250x100-t1.2-N100-A0.6	253.47	100.00	1.13	474.50	1.85	1.94	2.07	2.16
250x100-t1.2-N100-A0.8	253.47	100.00	1.13	474.50	1.74	1.80	1.98	2.10

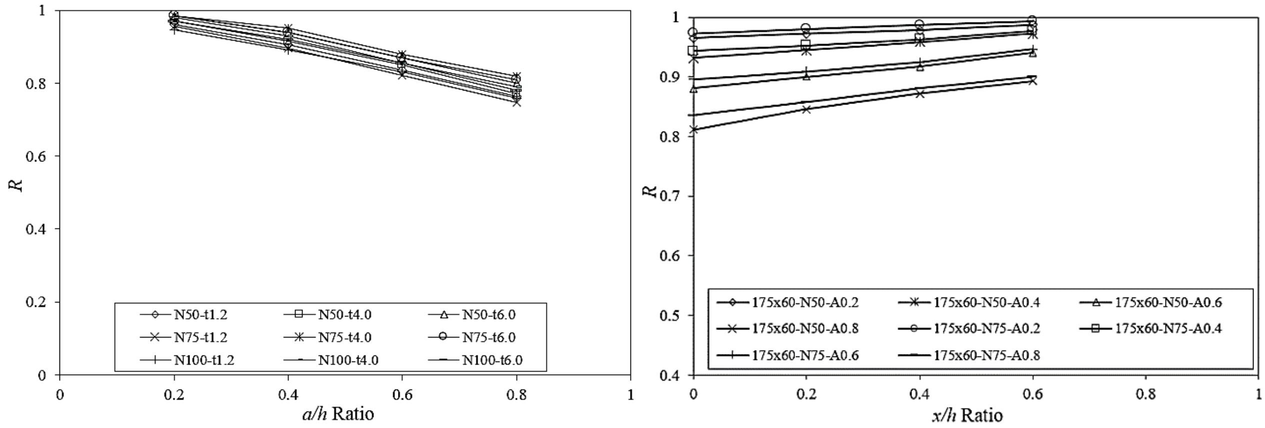


(a) With *a/h* for centered web hole

(b) With *N/h* for centered web hole

Fig. 3 Variation in reduction factors for C175 section

In terms of circular web holes located in mid-length of the unlipped channels (offset holes), 252 sections were modelled and analysed to determine the effects of web holes diameter ratio (a/h) and web holes location ratio (x/h). The web crippling strengths (PFEA) per single web predicted from the FE analyses as well as cross-section dimensions are presented in Tables 2 and 3. Fig. 4 demonstrates the effects of the web holes diameter ratio (a/h) and web holes location ratio (x/h) on the web crippling strength reduction factors of the C175 section. It can be deduced, from Fig. 4(a), that the strength reduction factor decreases as the web holes diameter ratio (a/h) increases from the ratio of 0.2 to the ratio of 0.8. Also, it is evident from Fig. 4(b) that the reduction factor is more sensitive to the location of the holes in the web and the web holes location ratio (x/h).



(a) With *a/h* for offset web hole (b) With *N/h* for offset web hole

Fig. 4 Variation in reduction factors for C175 section

5 Reliability Analysis

New design equations are evaluated in terms of a reliability analysis. Reliability analyses on cold-formed steel structural components are carried out based on the NAS [5]. According to this, the reliability index (β) with a lower limit of 2.5 is considered as a relative evaluation of the reliable design. The design equations are reliable in cases where the reliability index (β) is equal to or more than 2.5. In the reliability analysis, the 1.2D + 1.6L as load combination for design of structural components was used, as specified in the SEI/ASCE-7 Standard [33], where D and L indicate dead and live load, respectively.

For web crippling strength, the parameters for statistical analysis are as per Table F1 of the NAS [5], where Fm = 1.00, Mm = 1.10, VF = 0.05, VM = 0.10 are the coefficients of variation and mean values for fabrication factors and material properties. The statistical parameters of VP and Pm are the coefficient of variation of load results. The mean values are presented in Tables 9 and 10. For computing the reliability index (β), the resistance factor of 0.85 (β =0.85) as well as the correction factor (Cp) from the NAS were used in the reliability analysis. Further details on reliability analysis are described in the NAS [5]. As can be seen in Tables 4 to 7, the determined reliability indexes (β) are more than the lower limit of 2.5.

6 Design Strength Comparison for Cold-formed Ferritic Stainless Steel Unlipped Channels without Web Holes

As noted previously, the existing cold-formed stainless steel design specifications [1-3] do not address the web crippling design recommendations for cold-formed stainless steel unlipped channels with web holes and with fastened flanges under ETF loading condition, where the web hole is located either centred or offset to the load and reaction plates. However, the web crippling strengths for sections without web holes, from experimental and numerical results, can be compared with the web crippling strengths obtained from design guidelines.

Table 4 shows the comparison of web crippling strength with design strength for the ETF loading condition. In the EN 1993-1-4 comparison, the mean value of the ratio is 1.43 with the corresponding coefficients of variation (COV) of 0.13. In the SEI/ASCE-8 and AS/NZS 4673 comparison, the mean values of the ratios are 1.28 and 1.29 with the corresponding coefficients of variation (COV) of 0.13 and 0.12, respectively. The identical mean values for the SEI/ASCE 8-02 and AS/NZS 4673 is due to the fact that design rules in the AS/NZS 4673 Standard has been adopted from SEI/ASCE-8 Specification.

The SEI/ASCE-8 and AS/NZS 4673 provide conservative web crippling strengths predictions. A comparison of the obtained values from these standards with the corresponding experimental and numerical values shows that although the SEI/ASCE-8 and AS/NZS 4673 values are higher, they are about 29% higher than the experimental and numerical failure loads. It is noted that SEI/ASCE-8 and AS/NZS 4673 are conservative for the web crippling strengths of cold-formed ferritic stainless steel unlipped channels without web holes. For the Australian/New Zealand Standard comparison, the mean values of ratio are 1.29 with the corresponding coefficients of variation (COV) of 0.12. It is also noted that design equations are too conservative for the cold-formed ferritic stainless steel unlipped channels, without web holes, under the end-two-flange (ETF) loading condition.

Table 4 Comparison of experimental and numerical results with design strength

Specimen	Web slenderness	Bearing length ratio	Bearing length ratio	Inside bend radius ratio	Failure load	Web crippling strength per web predicted from current design codes				Comparison			
	h/t	N/t	N/h	ri/t	P (kN)	PASCE (kN)	PAS/NZS (kN)	P Euro (kN)	Proposed (kN)	P/PASCE	P/PAS/NZS	P/PEuro	P/PP
175x60-t1.2-N50-A0	160.14	45.45	0.28	1.09	2.33	2.10	2.07	1.87	2.33	1.11	1.13	1.25	1.00
175x60-t4.0-N50-A0	42.59	12.50	0.29	0.30	38.45	31.26	31.10	27.98	41.87	1.23	1.24	1.37	0.92
175x60-t6.0-N50-A0	27.73	8.33	0.30	0.20	78.52	70.34	70.05	62.98	95.00	1.12	1.12	1.25	0.83
175x60-t1.2-N75-A0	153.27	65.22	0.43	1.04	2.96	2.69	2.65	2.39	2.99	1.10	1.12	1.24	0.99
175x60-t4.0-N75-A0	42.64	18.75	0.44	0.30	46.10	32.99	32.83	29.53	46.45	1.40	1.40	1.56	0.99
175x60-t6.0-N75-A0	27.76	12.50	0.45	0.20	95.86	73.04	72.73	65.40	104.33	1.31	1.32	1.47	0.92
175x60-t1.2-N100-A0	161.41	91.74	0.57	1.10	3.02	2.70	2.66	2.40	2.89	1.12	1.14	1.26	1.05
175x60-t4.0-N100-A0	42.53	25.00	0.59	0.30	54.84	34.74	34.57	31.09	50.36	1.58	1.59	1.76	1.09
175x60-t6.0-N100-A0	27.69	16.67	0.60	0.20	114.02	75.76	75.44	67.83	112.27	1.51	1.51	1.68	1.02
200x75-t1.2-N50-A0	173.47	43.10	0.25	1.03	2.41	2.20	2.16	1.95	2.38	1.10	1.11	1.23	1.01
200x75-t4.0-N50-A0	48.89	12.50	0.26	0.30	37.98	30.75	30.59	27.51	40.42	1.24	1.24	1.38	0.94
200x75-t6.0-N50-A0	31.93	8.33	0.26	0.20	78.46	69.60	69.30	62.31	92.52	1.13	1.13	1.26	0.85
200x75-t1.2-N75-A0	183.01	68.18	0.37	1.09	2.45	2.22	2.18	1.97	2.35	1.11	1.12	1.24	1.04
200x75-t4.0-N75-A0	48.88	18.75	0.38	0.30	44.75	32.46	32.29	29.04	44.86	1.38	1.39	1.54	1.00
200x75-t6.0-N75-A0	31.92	12.50	0.39	0.20	94.77	72.28	71.96	64.71	101.63	1.31	1.32	1.46	0.93
200x75-t1.2-N100-A0	184.75	91.74	0.50	1.10	2.65	2.46	2.42	2.19	2.54	1.08	1.10	1.21	1.04
200x75-t4.0-N100-A0	48.89	25.00	0.51	0.30	52.57	34.17	33.98	30.57	48.60	1.54	1.55	1.72	1.08
200x75-t6.0-N100-A0	31.93	16.67	0.52	0.20	111.73	74.96	74.63	67.11	109.31	1.49	1.50	1.66	1.02
250x100-t4.0-N50-A0	61.47	12.50	0.20	0.30	37.08	29.73	29.55	26.59	1.89	1.25	1.25	1.39	1.11
250x100-t6.0-N50-A0	40.31	8.33	0.21	0.20	77.80	68.13	67.80	60.98	37.79	1.14	1.15	1.28	0.98
250x100-t4.0-N75-A0	61.39	18.75	0.31	0.30	42.51	31.39	31.20	28.07	88.02	1.35	1.36	1.51	0.88
250x100-t6.0-N75-A0	40.26	12.50	0.31	0.20	92.01	70.76	70.42	63.33	2.10	1.30	1.31	1.45	1.08
250x100-t4.0-N100-A0	61.37	25.00	0.41	0.30	47.94	33.04	32.84	29.55	41.95	1.45	1.46	1.62	1.01
250x100-t6.0-N100-A0	40.25	16.67	0.41	0.20	106.47	73.38	73.03	65.68	96.71	1.45	1.46	1.62	0.95
Mean, Pm										1.28	1.29	1.43	1.00
Coefficient of variation, Vp										0.13	0.12	0.13	0.07
Reliability index, β										3.20	3.25	3.62	2.69
Resistance factor, ϕ										0.85	0.85	0.85	0.85

7 Reduction Factor Comparison with Yousefi *et al.* [8] for Lipped Cold-formed Stainless Steel Section with Web Holes

As mentioned earlier, Yousefi *et al.* [10] provides strength reduction factor equations for circular web holes located at the mid-depth of the webs and centred to the load and reaction plates or with a horizontal clear distance to the near edge of the load and reaction plates. The web crippling strength predicted from test and numerical results were compared with the web crippling strength obtained from Yousefi *et al.* [10].

The equations proposed by Yousefi *et al.* [10] are summarised below:

$$\mathit{Centred\ web\ hole} \qquad R_p = 0.97 - 0.62\left(\frac{a}{h}\right) + 0.04\left(\frac{N}{h}\right) \leq 1 \tag{1}$$

$$\mathit{Offset\ web\ hole} \qquad R_p = 0.94 - 0.03\left(\frac{a}{h}\right) + 0.04\left(\frac{x}{h}\right) \leq 1 \tag{2}$$

Where the limits for the reduction factor in equations (1), and (2) are $h/t \leq 157.68$, $N/t \leq 120.97$, $N/h \leq 1.15$, $a/h \leq 0.8$, and $\theta = 90°$.

Table 5 compares of the web crippling strength with that of Yousefi *et al.* [10] for sections with web holes located centred and offset to the load and reaction plates, for case of flanges fastened to the load and reaction plates. As can be seen, the equations are unconservative especially for the case of the centred web holes with flanges fastened to the load and reaction plates. The value of P_m is 0.90 with a corresponding COV of 1.14; the design strengths obtained from Yousefi *et al.* [10] for cold-formed stainless steel lipped channels are unconservative for cold-formed ferritic stainless steel unlipped channels by up to 10%. However, as noted previously, the equations proposed by Yousefi *et al.* [10] were for cold-formed stainless steel lipped channels with different grades of stainless steels.

8 Proposed Strength Reduction Factors

Comparing the failure loads of the unlipped channels having web holes with that of sections without web holes, as shown in Tables 1 to 3, it can be see that, as expected, the failure load decreases as the size of the web holes increases. It can also be seen that the failure load increases slightly as the length of the load and reaction plates increases and the distance of the web holes increases.

Evaluation of the experimental and the numerical results shows that the ratios *a/h*, *N/h* and *x/h* are the primary parameters influencing the web crippling behaviour of the sections with web holes. Therefore, based on both the experimental and the numerical results obtained from this study, four strength reduction factor equations (R_p) are proposed using bivariate linear regression analysis for the end-two-flange loading condition for the centred web holes and offset web holes, respectively.

Table 5 Comparison of web crippling strength reduction factor with reduction factors equations proposed by Yousefi et al.[10]

Specimen	Failure load without web holes $P_{(A0)}$ (kN)	Failure load with web holes $P_{(Web\ hole)}$ Centred	Offset	Reduction factor $R=P_{(Web\ hole)}/P_{(A0)}$ Centred	Offset	Factored resistance *(Eq. 1)* Centred	Factored resistance *(Eq. 2)* Offset	Comparison with factor resistance from Yousefi *et al.* R/R_{Lipped} Centred	Offset
175x60-t1.2-N50-A0.2	2.33	2.02	2.21	0.87	0.95	0.91	0.97	0.95	0.98
175x60-t1.2-N50-A0.4	2.33	1.70	2.15	0.73	0.92	0.77	0.94	0.95	0.99
175x60-t1.2-N50-A0.6	2.33	1.36	2.01	0.58	0.86	0.62	0.90	0.94	0.96
175x60-t1.2-N50-A0.8	2.33	1.01	1.91	0.43	0.82	0.48	0.87	0.91	0.94
200x75-t4.0-N75-A0.2	44.75	39.04	44.03	0.87	0.98	0.92	0.97	0.95	1.01
200x75-t4.0-N75-A0.4	44.75	34.06	43.52	0.76	0.97	0.77	0.94	0.98	1.04
200x75-t4.0-N75-A0.6	44.75	28.23	41.58	0.63	0.93	0.63	0.90	1.00	1.03
200x75-t4.0-N75-A0.8	44.75	14.74	37.56	0.33	0.84	0.48	0.87	0.68	0.97
250x100-t6.0-N100-A0.2	106.47	92.13	105.78	0.87	0.99	0.92	0.97	0.94	1.02
250x100-t6.0-N100-A0.4	106.47	79.42	102.91	0.75	0.97	0.78	0.94	0.96	1.03
250x100-t6.0-N100-A0.6	106.47	61.90	95.86	0.58	0.90	0.63	0.90	0.92	1.00
250x100-t6.0-N100-A0.8	106.47	31.21	90.26	0.29	0.85	0.48	0.87	0.60	0.98
Mean, Pm								0.90	0.98
Coefficient of variation, Vp								0.14	0.04
Reliability index, β								1.83	2.59
Resistance factor, ϕ								0.85	0.85

The equations proposed are as follows:

Centred web hole

$$R_p = 0.97 - 0.76\left(\frac{a}{h}\right) + 0.06\left(\frac{N}{h}\right) \leq 1 \tag{3}$$

Offset web hole

$$R_p = 0.96 - 0.41\left(\frac{a}{h}\right) + 0.25\left(\frac{x}{h}\right) \leq 1 \tag{4}$$

Where the limits for the reduction factor in equations (5), (6), (7) and (8) are $h/t \leq 200$, $N/t \leq 90.09$, $N/h \leq 0.61$, $a/h \leq 0.8$, and $\theta = 90^o$.

9 Comparison of Experimental and Numerical Results with the Proposed Reduction Factor

The calculated strength reduction factor (R_p) values from the proposed Equations (3) and (4), are compared to the obtained strength reduction factor (R) values from the numerical and the experimental results, as depicted versus the ratios a/h and h/t in Figs. 5 and 6. Tables 6 and 7 summarize a statistical analysis to define the reliability and accuracy of the proposed reduction factor equations. It is demonstrated that the proposed reduction factor equations are generally conservative and agree well with the numerical and experimental results for sections with centred and offset web holes.

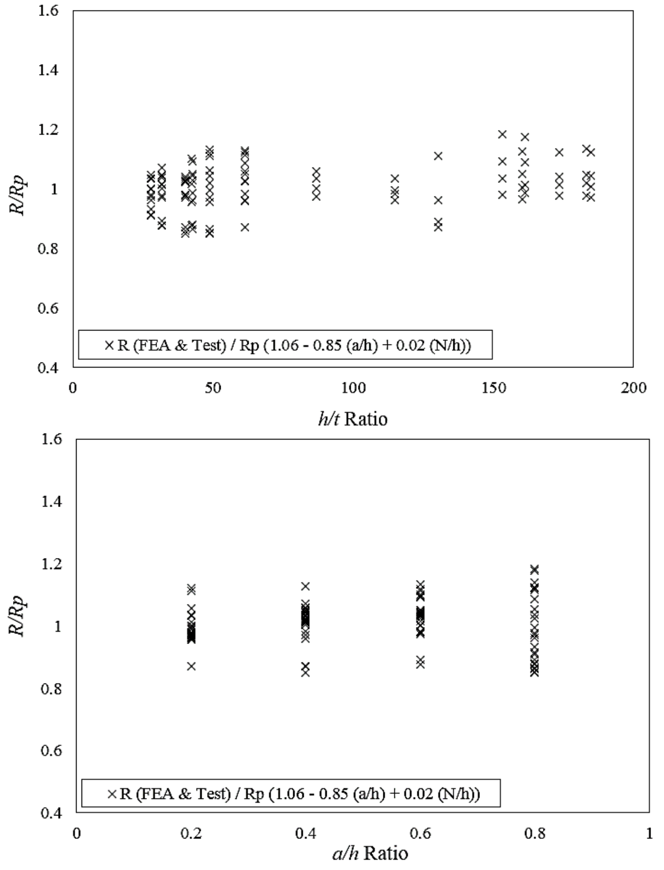


Fig. 5 Comparison of strength reduction factor for centred web hole

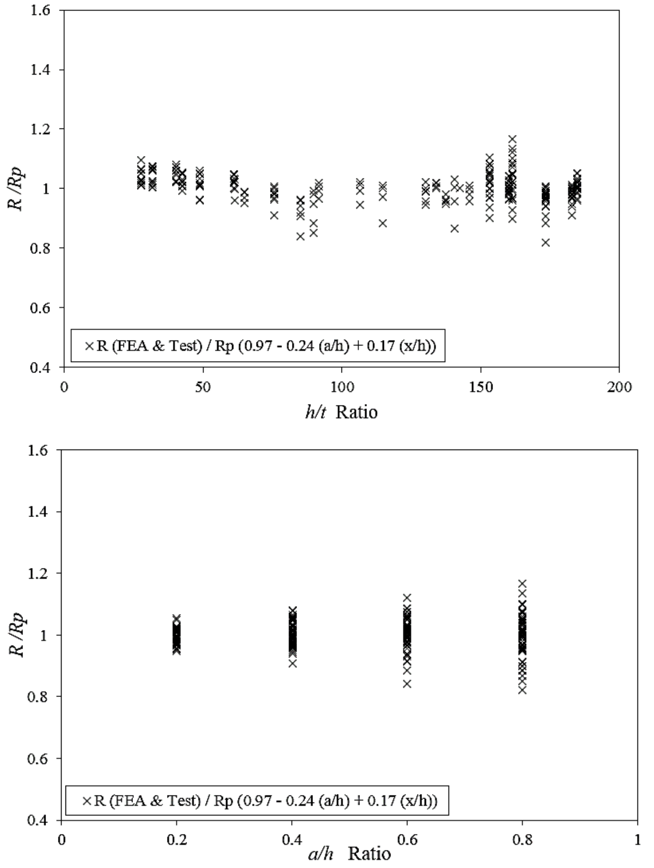


Fig. 6 Comparison of strength reduction factor for offset web hole

For the centred web hole, the mean value of the web crippling reduction factor ratio is 1.00. The corresponding values of COV of 0.08 and the reliability index values (β) is of 2.66. For the offset web hole, the mean value of the web crippling strength reduction factor ratio is 1.00. The corresponding values of COV of 0.05 and the reliability index values (β) is of 2.80, respectively. Therefore, the proposed reduction factor equations are able to predict the effect of the web holes on the web crippling strengths of unlipped channels under the ETF loading condition.

Table 6 Statistical analysis for comparison of strength reduction factor for centred web hole

Statistical parameters	***R* (Test & FEA) / R_p (0.97-0.76 (*a/h*)+0.06 (*N/h*))**
Number of data	108
Mean, P_m	1.00
Coefficient of variation, V_p	0.08
Reliability index, β	2.66
Resistance factor, ϕ	0.85

Table 7 Statistical analysis for comparison of strength reduction factor for offset web hole

Statistical parameters	***R* (Test & FEA) / R_p (0.96-0.41(*a/h*)+0.25 (*x/h*))**
Number of data	252
Mean, P_m	1.00
Coefficient of variation, V_p	0.05
Reliability index, β	2.80
Resistance factor, ϕ	0.85

10 Proposed Design Equations and Comparison with Experimental and Numerical Results

As noted previously, stainless steel design specifications, particularly the SEI/ASCE-8 and AS/NZS 4673 provide too conservative predictions for the web crippling strength of cold-formed ferritic stainless steel unlipped channels. Thus, based on experimental and numerical results, the web crippling design equation for cold-formed ferritic stainless steel unlipped channels with fastened flanges and with no web holes, under the end-two-flange (ETF) loading condition is proposed. The proposed equations uses the similar techniques as the NAS Specification [5] with new coefficients. The proposed design equation is as follows:

$$P_p = 7.49t^2 f_y \sin\theta \left(1 - 0.12\sqrt{\frac{R}{t}}\right)\left(1 + 0.27\sqrt{\frac{B}{t}}\right)\left(1 - 0.05\sqrt{\frac{h}{t}}\right) \tag{5}$$

Where t is the thickness of the web, fy is the yield stress (σ0.2 proof stress), B is the length of the bearing, h is the depth of the plain part of the web and θ is the angle between the plane of the web and the plane of the bearing surface. The coefficients as well as the resistance factor ϕ of 0.85 are based on the experimental and the numerical results obtained in this study, as shown in Table 4. The limits for the design equation (5) is $h/t \leq 200$, $N/t \leq 90.09$ and $N/h \leq 0.61$.

As shown in Table 4, the experimental and numerical ultimate web crippling loads per web (PExp and PFEA) are compared with the unfactored design strengths (PP) predicted using the proposed equation (5). The proposed design strengths were calculated using the material properties and the measured cross-section dimensions. The proposed design strengths are generally conservative and reliable. The mean values of the web crippling load ratio is 1.00 with the corresponding COV of 0.07, and the reliability indices (β) of 2.69.

11 Conclusions

In this paper, an extensive parametric study of cold-formed ferritic stainless steel unlipped channels with fastened flanges subjected to web crippling under end-two-flange (ETF) loading condition was undertaken, using quasi-static finite element analysis, to investigate the effects of web holes and cross-sections sizes. Both cases of unlipped channels with and without web holes were considered. The web holes were located either centred or offset to the load and reaction plates. It is noted that no cold-formed stainless steel standard provides capacity reduction factors for unlipped channels with fastened flanges subject to end-two-flange loading condition.

The strengths obtained from reduction factor equations were first compared to strengths calculated from equations recently proposed for cold-formed stainless steel lipped channels. It is demonstrated that the strength reduction factor equations previously proposed for cold-formed stainless steel lipped channels can be unconservative for cold-formed ferritic stainless steel unlipped channels by up to 10%. The laboratory investigation showed that, for the case of plain unlipped channels (i.e. without web holes), the European Standard (EN 1993-1-4) was conservative by as much as 14%. From both laboratory and finite element results, web crippling design equations were proposed for both sections, with and without web holes.

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