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WEB CRIPPLING DESIGN OF COLD-FORMED DUPLEX STAINLESS STEEL LIPPED CHANNEL-SECTIONS WITH WEB OPENINGS UNDER END-ONE-FLANGE LOADING CONDITION

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Abstract. *Cold-formed stainless steel sections are becoming more widely used in the residential and commercial sectors due to their high corrosion resistance and high strength-to-weight ratio. However, their susceptibility to web crippling at points of concentrated loading is well-known to be an important design issue. In addition, web openings are also become popular, as they improve ease of installation of services. This paper presents the results of an investigation into the effect of web crippling on cold-formed duplex stainless steel lipped channel-sections, having such openings, under the end-one-flange (EOF) loading condition. 728 non-linear elasto-plastic finite element analyses are undertaken, with web openings located either centred above the bearing plate or offset to bearing plate. The effect of the size of the web opening, length of bearing plate and location of the web opening is considered. Strength reduction factor equations are proposed, that can be used to take into account such openings in design.*

1 INTRODUCTION

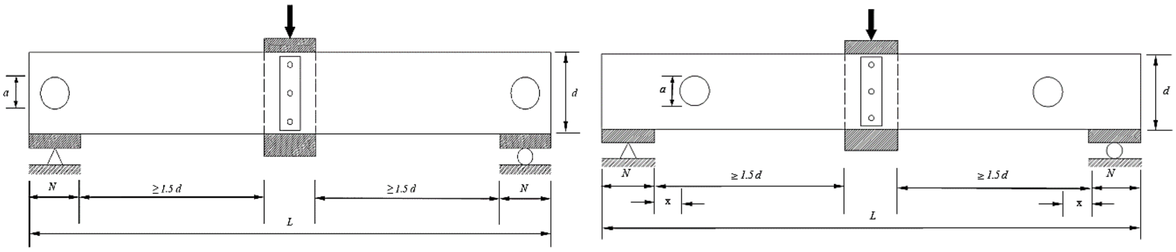
Cold-formed stainless steel sections increasingly are been used in the construction industry, for both architectural as well as structural applications (Nethercot *et al.* [1], Theofanous and Gardner [2], Kiymaz and Seckin [3]) and the use of web openings in such sections is becoming increasingly popular (Lawson *et. al.* [4]). Such openings, however, result in the sections being more susceptible to web crippling as a form of localized buckling, especially under concentrated loads applied to the bearing flange in the vicinity of the openings.

The authors have recently proposed strength reduction factor equations for the web crippling strength of cold-formed stainless steel lipped channel-sections with circular web openings under the one and two flange loadings (Yousefi *et al.* [5-9]**)**. The equations covered three stainless steel grades: duplex grade EN 1.4462; austenitic grade EN 1.4404 and ferritic grade EN 1.4003. Other than Yousefi *et al.* [5-9] no previous research has considered the web crippling strength of cold-formed stainless steel lipped channel-sections with circular web openings under either of the one or two-flange loading conditions. The work extended that of Lian *et al.* [10-11] considering cold-formed stainless steel instead of cold-formed carbon steel. Conducting a parametric study of 2,218 cold-formed stainless steel lipped channel-sections with various dimensions and thicknesses, the strength reduction factor equations proposed by Lian *et al.* [10-11] were shown to be conservative by 2% for the duplex grade and around 9% for the austenitic and ferritic grades.

For cold-formed carbon steel with circular web openings, Lian *et al.* [10-11] have considered the end-one-flange (EOF) loading condition (see Figure 1). The work of Lian *et al.* [10-11] was a continuation of the work of Uzzaman *et al.* [12-15] who considered the two-flange loading condition. For cold-formed stainless steel lipped channel-sections without openings, only Krovink *et al.* [16] has considered the web crippling strength. Zhou and Young [17-20] have considered the web crippling strength of cold-formed stainless steel tubular sections; Keerthan and Mahendran [21] and Keerthan *et al.* [22] considered the web crippling strength of hollow flange channel beams. Research by Lawson *et al.* [4], while concerned with circular web openings, focussed on the bending strength of the sections and not on the web crippling strength under concentrated loads.

This paper considers the web crippling strength of cold-formed stainless steel lipped channel-sections with web openings subjected to the end-one-flange (EOF) loading condition (see Figure 2) for the duplex EN 1.4462 grade, as part of the authors' works on one and two flange loadings (Yousefi *et al.* [5-9]**)**. Using the general purpose finite element program ABAQUS [23], 728 non-linear elasto-plastic finite element analyses are undertaken, with web openings located either centred above the bearing plate or offset to bearing plate. The effect of the size of the web opening, length of bearing plate and location of the web opening is considered. Strength reduction factor equations are proposed, that can be used to take into account such openings in design.

Figure 1: Experimental analysis of cold-formed steel channel sections under EOF loading condition



(a) (b)

Figure 2: End-one-flange (EOF) loading condition; (a) With web openings centred above bearing plate, (b) With web openings offset from bearing plate

2 EXPERIMENTAL INVESTIGATION AND FINITE ELEMENT MODELLING

For cold-formed carbon steel, Lian *et al.* [10-11] recently conducted 74 end-one-flange (EOF) tests, in the laboratory, on lipped channel-sections with circular web openings under web crippling (see Figure 1). Figure 3 shows the definition of the symbols used to describe the dimensions of the cold-formed carbon steel lipped channel-sections considered in the test programme. The laboratory tests were used to validate a non-linear geometry elasto-plastic finite element model in ABAQUS [23], which was then used for a parametric study, from which design recommendations were proposed in the form of strength reduction factor equations, relating the loss of strength due to the web openings to the strength of the web without openings. The size of the circular web openings was varied in order to investigate the effect of the web opening size on the web crippling strength. Full details of both the laboratory tests and finite element models can be found in Lian *et al.* [10-11].

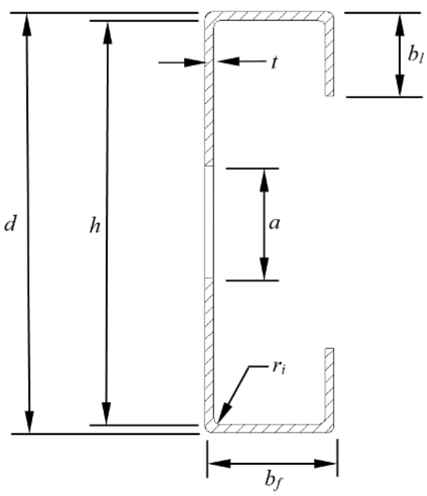
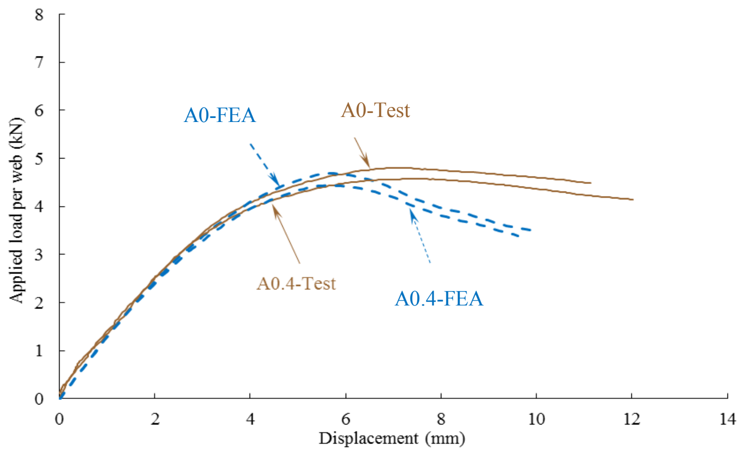


Figure 3: Definition of symbols

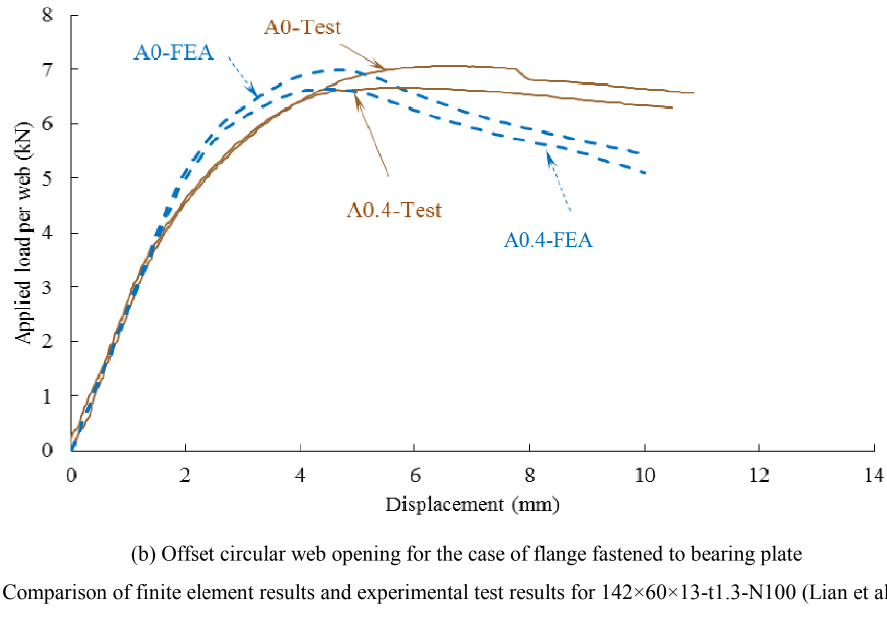
The models have been coded such the nominal dimension of the model and the length of the bearing plate as well as the ratio of the diameter of the circular web openings to the depth of the flat portion of the webs (*a/h*) can be determined from the coding system. As an example, the label "142-N100-A0.2-FR" means the following. The first notation is the nominal depth of the models in millimeters. The notation "*N100*" indicates the length of bearing plate in millimeters (i.e. 100 mm). The notation "*A0.2*" indicates the ratio of the diameter of the openings to the depth of the flat portion of the webs (*a/h*) and are one of 0.2, 0.4, 0.6 and 0.8 (i.e. *A0.2* means *a/h* = 0.2; *A0.4* means *a/h* = 0.4 etc). Plain lipped channel-sections (i.e. without circular web openings) are denoted by "*A0*". The flange unfastened and fastened cases are identified as "*FR*" and "*FX*", respectively. Typical stress-strain curve for the duplex stainless steel material, was taken from Chen and Young [24]. Comparative hot-rolled steel stress strain curves can be found in Yousefi *et al.* [25] and Rezvani *et al*. [26].

Figure 4 compares the experimental and numerical load-displacement curves for a cold-formed carbon steel lipped channel-section, 142×60×13-t1.3-N100-FR, covering the cases both with and without the circular web openings. As can be seen, there is good agreement between the failure loads of the tested specimens and the finite element results. For cold-formed stainless steel lipped channel-sections, the numerical failure loads with and without circular web openings were then determined for the duplex grade EN 1.4462.

These results were compared with the failure loads calculated in accordance with ASCE [27], NAS [28] and Eurocode-3 [29] (see Table 1). The failure loads predicted from the finite element model are similar to the standard codified failure loads of the sections.



(a) Centred circular web opening for the case of flange unfastened to bearing plate



(b) Offset circular web opening for the case of flange fastened to bearing plate

Figure 4: Comparison of finite element results and experimental test results for 142×60×13-t1.3-N100 (Lian et al. [10-11])

Table 1: Comparison of numerical results with design strength for the case of flange fastened to the bearing plate without circular web opening

Specimen	Web slenderness	Bearing length to thickness ratio	Bearing length to web height ratio	Inside bend radius to thickness ratio	Failure load per web	Web crippling strength per web predicted from current design codes			Comparison		
	h/t	N/t	N/h	r_i/t	P_{FEA} (kN)	P_{NAS} (kN)	P_{ASCE} (kN)	P_{Euro}	P/P_{NAS}	P/P_{ASCE}	P/P_{Euro}
142-N100	114.01	81.3	0.71	3.9	3.11	5.87	2.84	2.73	0.53	1.10	1.14
142-N120	111.67	96	0.86	3.84	3.23	5.95	2.86	2.83	0.54	1.13	1.14
142-N150	112.64	120.97	1.07	3.87	3.55	6.39	3.15	3.24	0.56	1.13	1.10
202-N100	147.62	74.07	0.5	3.7	3.27	6.69	3.31	3.13	0.49	0.99	1.04
202-N120	147.68	88.89	0.6	3.7	3.52	7.17	3.59	3.51	0.49	0.98	1.00
202-N150	147.72	111.11	0.75	3.7	3.89	7.82	4.01	4.08	0.50	0.97	0.95
302-N100	157.69	52.63	0.33	2.63	5.80	11.14	6.02	5.53	0.52	0.96	1.05
302-N120	157.13	63.16	0.4	2.63	6.21	11.90	6.56	6.01	0.52	0.95	1.03
302-N150	157.67	78.95	0.5	2.63	6.85	12.93	7.18	6.87	0.53	0.95	1.00
Mean, Pm									0.52	1.02	1.05
Coefficient of variation									0.05	0.08	0.06

3 PARAMETRIC STUDY FOR DUPLEX STAINLESS STEEL GRADE

In this study, in order to investigate the effect of circular web openings on the web crippling strength of cold-formed stainless steel lipped channel-sections, a total of 728 finite element models of lipped channel-sections with various dimensions and thicknesses were considered for the duplex EN1.4462 stainless steel grade. Table 2 shows the web crippling strengths determined from finite element analyses for the duplex EN 1.4462 stainless steel grade. The web crippling strengths for sections with circular web openings were divided by that for sections without web openings and considered as the strength reduction factor (R). The effects of parameters such as the web opening diameters (*a*), length of bearing plates (*N*) and location of web openings in the web (*x*) on web crippling strength is shown in Figures 5-7 for the C142 specimen. As can be seen, the reduction in strength increases as the parameter *a/h* increases. The reduction in strength of the flange unfastened case is more than fastened case and the reduction in strength increases as the section becomes thinner. Also, it can be seen that the reduction in strength is more sensitive to the horizontal distance of the web opening to the bearing plate and the reduction in strength is slightly less for the flange fastened case, compared with the flange unfastened case.

Table 2: Web crippling strengths of duplex stainless steel sections predicted from finite element analysis
a: *a/h* for centred circular web opening case

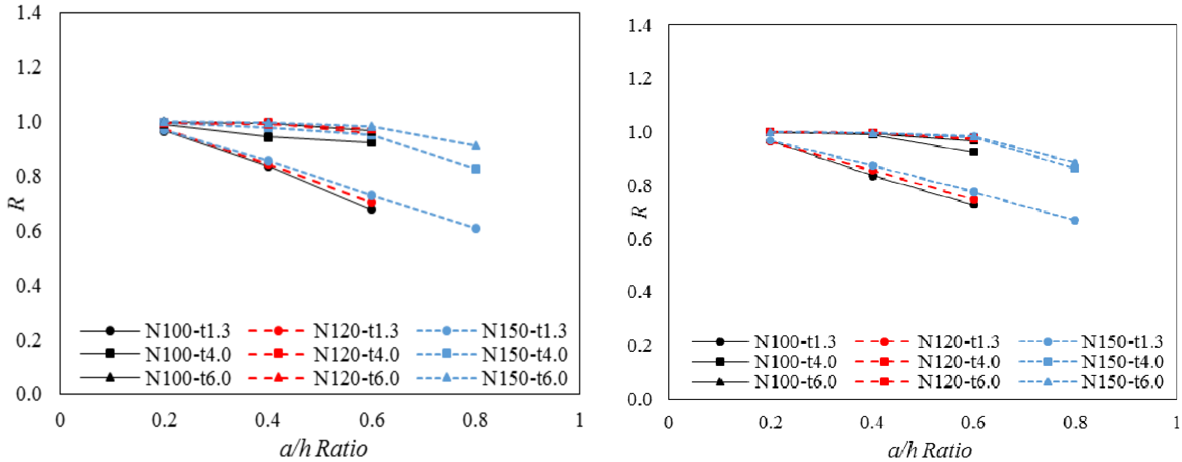
Specimen	Thickness	Unfastened FEA load per web, P_{FEA}					Fastened FEA load per web, P_{FEA}				
	t	*A(0)*	*A(0.2)*	*A(0.4)*	*A(0.6)*	*A(0.8)*	*A(0)*	*A(0.2)*	*A(0.4)*	*A(0.6)*	*A(0.8)*
	(mm)	*(kN)*	*(kN)*	*(kN)*	*(kN)*	*(kN)*	*(kN)*	*(kN)*	*(kN)*	*(kN)*	*(kN)*
142-N100-FR	1.27	2.45	2.37	2.05	1.66	-	3.68	3.55	3.07	2.67	-
142-N100-FR	4.00	21.99	21.79	20.74	20.32	-	27.98	27.94	27.74	25.84	-
142-N100-FR	6.00	31.36	31.33	31.16	30.27	-	34.88	34.84	34.66	33.75	-
142-N120-FR	1.27	2.71	2.64	2.29	1.91	-	3.77	3.63	3.23	2.82	-
142-N120-FR	4.00	20.98	20.92	20.89	20.06	-	27.50	27.47	27.33	26.70	-
142-N120-FR	6.00	30.87	30.74	30.59	30.09	-	34.35	34.32	34.16	33.58	-
142-N150-FR	1.28	2.89	2.80	2.47	2.12	1.76	4.10	3.96	3.58	3.18	2.74
142-N150-FR	4.00	20.93	20.85	20.50	19.96	17.25	26.69	26.67	26.57	26.13	22.95
142-N150-FR	6.00	29.89	29.86	29.73	29.35	27.24	33.75	33.72	33.57	33.20	29.84
202-N100-FR	1.39	2.45	2.38	2.05	-	-	3.72	3.57	3.06	-	-
202-N100-FR	4.00	22.46	21.89	18.06	-	-	30.35	30.12	26.59	-	-
202-N100-FR	6.00	32.57	32.51	31.97	-	-	35.86	35.79	35.46	-	-
202-N120-FR	1.39	2.57	2.49	2.20	1.73	-	3.97	3.80	3.31	2.78	-
202-N120-FR	4.00	22.39	22.36	19.47	14.64	-	30.30	30.18	29.30	22.41	-
202-N120-FR	6.00	32.32	32.27	32.00	29.37	-	35.59	35.53	35.28	33.46	-
202-N150-FR	1.39	2.70	2.62	2.34	1.92	-	4.31	4.13	3.68	3.08	-
202-N150-FR	4.00	22.15	21.73	21.01	16.68	-	29.76	29.68	29.32	27.55	-
202-N150-FR	6.00	31.75	31.70	31.50	30.65	-	35.19	35.14	34.92	34.17	-
302-N100-FR	1.98	4.62	4.47	-	-	-	6.54	6.29	-	-	-
302-N100-FR	4.00	21.45	20.16	-	-	-	30.04	28.95	-	-	-
302-N100-FR	6.00	32.97	32.78	-	-	-	36.34	36.23	-	-	-
302-N120-FR	1.98	4.78	4.61	3.82	-	-	6.93	6.63	5.36	-	-
302-N120-FR	4.00	22.24	20.91	16.82	-	-	30.90	30.13	24.93	-	-
302-N120-FR	6.00	32.90	32.78	31.39	-	-	36.17	36.09	35.36	-	-
302-N150-FR	1.99	5.02	4.89	4.00	-	-	7.55	7.20	5.94	-	-
302-N150-FR	4.00	23.06	21.87	17.95	-	-	31.16	30.78	27.71	-	-
302-N150-FR	6.00	32.67	32.58	31.94	-	-	35.99	35.92	35.57	-	-

b: *a/h* for offset circular web opening case

Specimen	Thickness	Unfastened FEA load per web, P_{FEA}				Fastened FEA load per web, P_{FEA}			
	T	*A(0)*	*A(0.2)*	*A(0.4)*	*A(0.6)*	*A(0)*	*A(0.2)*	*A(0.4)*	*A(0.6)*
	(mm)	*(kN)*	*(kN)*	*(kN)*	*(kN)*	*(kN)*	*(kN)*	*(kN)*	*(kN)*
142-N100-FR	1.27	2.45	2.45	2.40	2.32	3.68	3.66	3.58	3.47
142-N100-FR	4.00	21.97	21.93	21.72	19.95	27.98	27.94	27.62	24.44
142-N100-FR	6.00	31.37	31.31	30.99	28.81	34.88	34.76	34.48	32.60
142-N120-FR	1.27	2.73	2.72	2.68	2.60	3.77	3.76	3.69	3.59
142-N120-FR	4.00	21.72	21.68	21.46	19.51	27.50	27.46	27.11	23.87
142-N120-FR	6.00	30.78	30.71	30.38	28.07	34.35	34.29	33.95	32.02
142-N150-FR	1.28	2.90	2.90	2.87	2.77	4.10	4.08	4.03	3.94
142-N150-FR	4.00	20.94	20.90	20.65	18.53	26.69	26.66	26.23	24.41
142-N150-FR	6.00	29.89	29.83	29.46	26.90	33.75	33.68	33.34	31.28
202-N100-FR	1.39	2.45	2.42	2.32	2.14	3.72	3.71	3.62	3.41
202-N100-FR	4.00	22.46	22.34	21.90	20.44	30.35	30.27	29.92	27.82
202-N100-FR	6.00	32.57	32.48	32.09	30.75	35.86	35.76	35.36	34.06
202-N120-FR	1.39	2.57	2.53	2.44	2.28	3.97	3.95	3.85	3.68
202-N120-FR	4.00	22.39	22.28	21.86	20.71	30.30	30.23	29.86	26.11
202-N120-FR	6.00	32.32	32.23	31.85	30.47	35.59	35.50	35.10	33.80
202-N150-FR	1.39	2.70	2.67	2.57	2.44	4.31	4.29	4.19	4.06
202-N150-FR	4.00	22.15	22.06	21.77	20.57	29.76	29.69	29.32	26.84
202-N150-FR	6.00	31.75	31.66	31.29	29.80	35.19	35.10	34.71	33.39
302-N100-FR	1.98	4.62	4.62	4.40	4.08	6.54	6.41	6.19	5.94
302-N100-FR	2.00	21.45	21.22	20.65	19.82	30.04	29.93	29.56	28.62
302-N100-FR	4.00	32.97	32.85	32.39	31.08	36.34	36.24	35.80	34.50
302-N120-FR	1.98	4.78	4.78	4.57	4.30	6.93	6.81	6.63	6.41
302-N120-FR	2.00	22.24	22.03	21.50	20.63	30.90	30.79	30.39	29.20
302-N120-FR	4.00	32.90	32.79	32.33	31.00	36.17	36.07	35.64	34.33
302-N150-FR	1.99	5.09	5.05	4.89	4.63	7.55	7.47	7.31	7.06
302-N150-FR	2.00	23.06	22.90	22.39	21.38	31.16	31.05	30.63	29.30
302-N150-FR	4.00	32.67	32.56	32.11	30.78	35.99	35.90	35.47	34.18

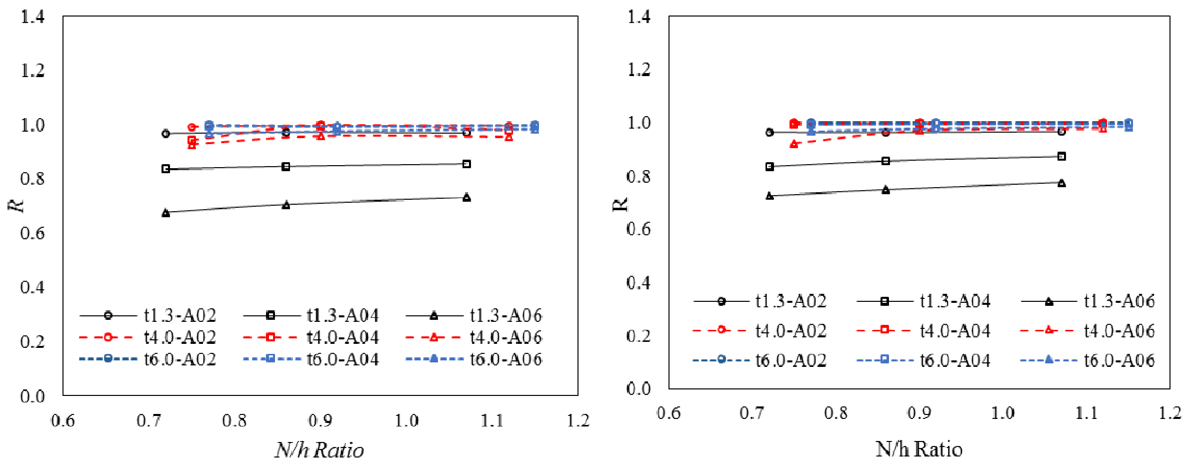
c: *x/h* for offset circular web opening case

Specimen	Thickness	Unfastened FEA load per web, $P_{(FEA)}$				Fastened FEA load per web, P_{FEA}			
	t	*X(0)*	*X(0.2)*	*X(0.4)*	*X(0.6)*	*X(0)*	*X(0.2)*	*X(0.4)*	*X(0.6)*
	(mm)	*(kN)*	*(kN)*	*(kN)*	*(kN)*	*(kN)*	*(kN)*	*(kN)*	*(kN)*
142-N100-A0-FR	1.27	2.38	2.38	2.38	2.38	3.63	3.63	3.63	3.63
142-N100-A0.2-FR	1.27	2.33	2.34	2.35	2.36	3.57	3.58	3.60	3.62
142-N100-A0.4-FR	1.27	2.18	2.22	2.26	2.29	3.39	3.44	3.50	3.53
142-N100-A0.6-FR	1.27	1.99	2.07	2.14	2.20	3.16	3.24	3.32	3.37
142-N100-A0.8-FR	1.27	---	---	---	---	---	---	---	---
142-N120-A0-FR	1.27	2.68	2.68	2.68	2.68	3.74	3.74	3.74	3.74
142-N120-A0.2-FR	1.27	2.63	2.64	2.65	2.63	3.68	3.69	3.71	3.73
142-N120-A0.4-FR	1.27	2.39	2.43	2.47	2.39	3.51	3.56	3.61	3.63
142-N120-A0.6-FR	1.27	2.22	2.29	2.36	2.22	3.29	3.37	3.43	3.47
142-N120-A0.8-FR	1.27	---	---	---	---	---	---	---	---
142-N150-A0-FR	1.28	2.74	2.74	2.74	2.74	4.07	4.07	4.07	4.07
142-N150-A0.2-FR	1.28	2.69	2.70	2.70	2.71	4.01	4.02	4.04	4.06
142-N150-A0.4-FR	1.28	2.56	2.60	2.62	2.65	3.86	3.91	3.94	3.96
142-N150-A0.6-FR	1.28	2.42	2.47	2.53	2.57	3.66	3.71	3.75	3.79
142-N150-A0.8-FR	1.28	2.38	2.47	2.53	2.55	---	---	---	---
202-N100-A0-FR	1.39	2.26	2.26	2.26	2.26	3.72	3.72	3.72	3.72
202-N100-A0.2-FR	1.39	2.21	2.22	2.22	2.37	3.63	3.64	3.68	3.71
202-N100-A0.4-FR	1.39	2.05	2.17	2.23	2.26	3.45	3.54	3.55	3.61
202-N100-A0.6-FR	1.39	1.81	1.86	1.92	1.98	3.08	3.21	3.33	3.38
202-N120-A0-FR	1.39	2.38	2.38	2.38	2.38	3.96	3.96	3.96	3.96
202-N120-A0.2-FR	1.39	2.28	2.28	2.29	2.42	3.67	3.71	3.93	3.96
202-N120-A0.4-FR	1.39	2.16	2.19	2.21	2.37	3.65	3.74	3.80	3.85
202-N120-A0.6-FR	1.39	1.92	2.07	2.07	2.22	3.39	3.49	3.56	3.61
202-N150-A0-FR	1.45	2.51	2.51	2.51	2.51	4.33	4.33	4.33	4.33
202-N150-A0.2-FR	1.45	2.46	2.47	2.47	2.60	4.26	4.29	4.32	4.34
202-N150-A0.4-FR	1.45	2.30	2.32	2.35	2.50	4.08	4.15	4.17	4.19
202-N150-A0.6-FR	1.45	2.11	2.19	2.25	2.37	3.80	3.88	3.93	4.01
302-N100-A0-FR	1.98	4.05	4.05	4.05	4.05	6.52	6.52	6.52	6.52
302-N100-A0.2-FR	1.98	3.95	3.97	4.01	4.05	6.35	6.49	6.50	6.54
302-N120-A0-FR	1.96	4.21	4.21	4.21	4.21	6.90	6.90	6.90	6.90
302-N120-A0.2-FR	1.96	4.14	4.18	4.22	4.23	6.71	6.78	6.85	6.89
302-N120-A0.4-FR	1.96	3.83	3.97	4.04	4.05	6.45	6.60	6.65	6.67
302-N120-A0.6-FR	1.96	3.38	3.61	3.72	3.78	---	---	---	---
302-N150-A0-FR	1.99	4.53	4.53	4.53	4.53	7.88	7.88	7.88	7.88
302-N150-A0.2-FR	1.99	4.43	4.48	4.51	4.50	7.58	7.60	7.64	7.67
302-N150-A0.4-FR	1.99	4.11	4.24	4.31	4.32	7.19	7.24	7.26	7.41
302-N150-A0.6-FR	1.99	3.68	3.89	3.99	4.06	---	---	---	---



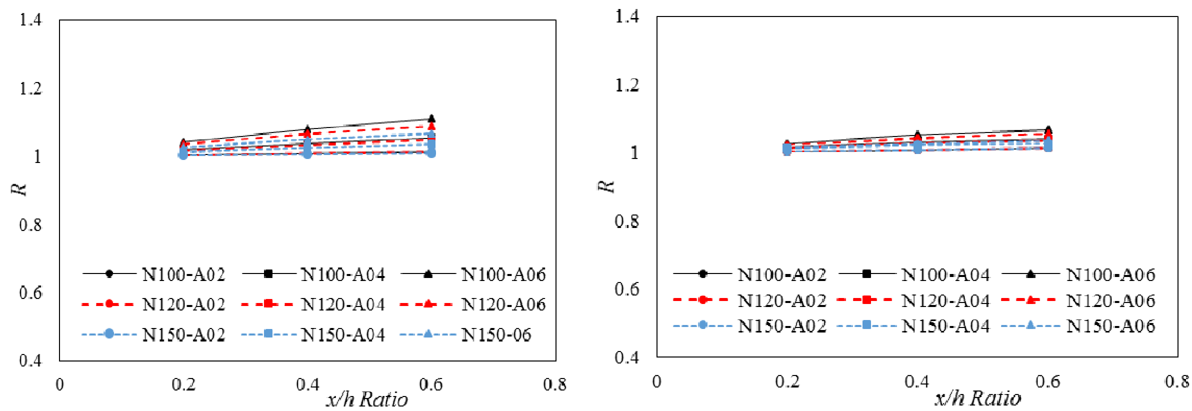
(a) Flange unfastened case (b) Flange fastened case

Figure 5: Variation in reduction factors with *a/h* ratio for C142 section with centered web opening



(a) Flange unfastened case (b) Flange fastened case

Figure 6: Variation in reduction factors with *N/h* for C142 section with centred web opening



(a) Flange unfastened case (b) Flange fastened case

Figure 7: Variation in reduction factors with *x/h* for C142 section with offset web opening

4 PROPOSED STRENGTH REDUCTION FACTORS

Table 2 shows the dimensions considered and web crippling strengths of the duplex grade stainless steel sections predicted from the finite element analysis. Using bivariate linear regression analysis, four new strength reduction factor equations (R_p) for duplex stainless steel EN 1.4462 grade with web openings are proposed. The equations are as follows:

For centred web opening:

For the case where the flange is unfastened to the bearing plate,

$$R_p = 1.11 - 0.37(\frac{a}{h}) - 0.04(\frac{N}{h}) \leq 1 \quad (1)$$

For the case where the flange is fastened to the bearing plate,

$$R_p = 1.08 - 0.33(\frac{a}{h}) - 0.01(\frac{N}{h}) \leq 1 \quad (2)$$

For offset web opening:

For the case where the flange is unfastened to the bearing plate,

$$R_p = 0.91 + 0.19(\frac{a}{h}) + 0.11(\frac{x}{h}) \leq 1 \quad (3)$$

For the case where the flange is fastened to the bearing plate,

$$R_p = 0.89 + 0.24(\frac{a}{h}) + 0.11(\frac{x}{h}) \leq 1 \quad (4)$$

The limits for the reduction factor equations (1), (2), (3) and (4) are $h/t \leq 157.8$, $N/t = 120.97$, $N/h \leq 1.15$, $a/h \leq 0.8$, and $\theta = 90$°.

5 COMPARISON OF NUMERICAL RESULTS WITH PROPOSED REDUCTION FACTORS

For the duplex stainless steel grade, the values of the strength reduction factor (R) obtained from the numerical results are compared with the values of the proposed strength reduction factor (R_p) calculated using Eqs. (1)-(4). The results for C142 are shown in Figure 8. In order to evaluate the accuracy of proposed equations, extensive statistical reliability analyses are performed. The results are summarized in Table 3.

It should be noted, in calculating the reliability index, the resistance factor of ϕ=0.85 was used, corresponding to the reliability index β from the NAS specification. According to the NAS specification, design rules are reliable if the reliability index are more than 2.5. As can be seen in Table 3, the proposed reduction factors are a good match with the numerical results for the both cases of flanges unfastened and flanges fastened to the bearing plates.

For example, for the centred circular web opening, the mean value of the web crippling reduction factor ratios are 1.00 and 1.01 for the cases of flange unfastened and flange fastened to the bearing plate, respectively. The corresponding values of COV are 0.03 and 0.03, respectively. Similarly, the reliability index values (β) are 2.82 and 2.86, respectively. For the offset circular web opening, the mean value of the web crippling reduction factor ratios are 1.04 and 1.04 for the cases of flange unfastened and flange fastened to the bearing plate, respectively. The corresponding values of COV are 0.04 and 0.05, respectively. Similarly, the reliability index values (β) are 2.97 and 2.94, respectively.

Table 3: Statistical analysis of strength reduction factor for duplex stainless steel grade

Statistical parameters	Centred circular web opening $R_{(FEA)} / R_p$		Offset circular web opening $R_{(FEA)} / R_p$	
	Unfastened to bearing plate	Fastened to bearing plate	Unfastened to bearing plate	Fastened to bearing plate
Number of data	69	69	84	81
Mean, P_m	0.99	1.00	1.04	1.04
Coefficient of variation, V_p	0.09	0.08	0.04	0.05
Reliability index, β	2.62	2.69	2.97	2.95
Resistance factor, ϕ	0.85	0.85	0.85	0.85

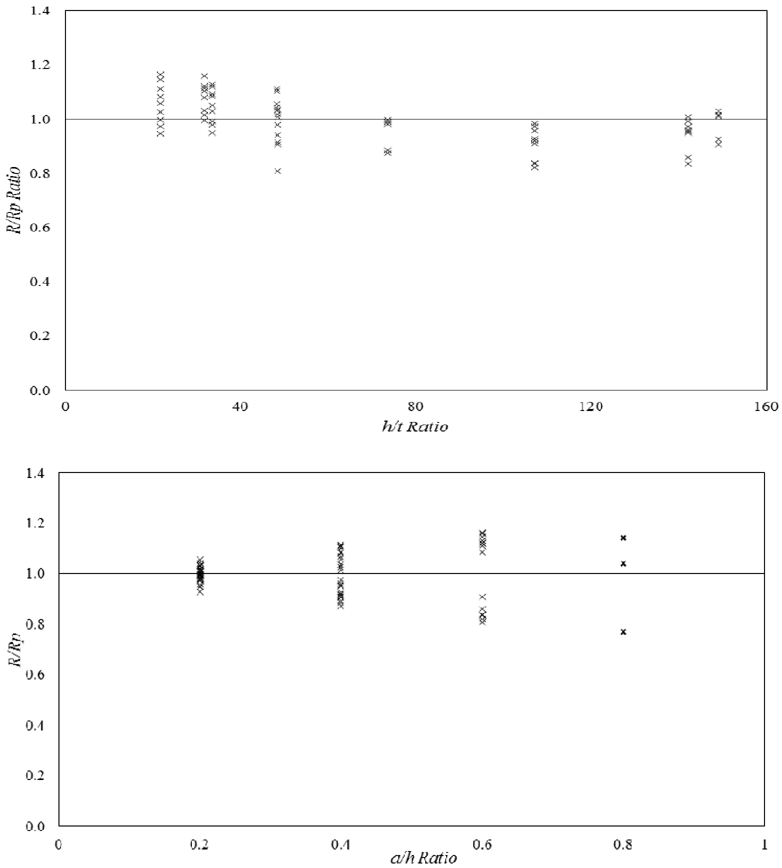


Figure 8: Comparison of strength reduction factor for centred web opening where flange unfastened to bearing plate

Therefore, the proposed strength reduction factor equations are able to reliably predict the influence of the circular web openings on the web crippling strengths of cold-formed stainless steel lipped channel-sections under the interior-one-flange (IOF) loading condition.

6 CONCLUSIONS

In this paper, the effect of web openings on the end-one-flange (EOF) loading condition of cold-formed stainless steel lipped channel-sections was investigated for duplex grade EN 1.4462. 728 non-linear elasto-plastic finite element analyses were conducted with different sizes of channel-section and opening. From the results of the finite element parametric study, four new web crippling strength reduction factor equations were proposed for the cases of both flange unfastened and flange fastened to the bearing plates. In order to evaluate the reliability of the proposed reduction factor equations, a reliability analysis was undertaken. It was demonstrated that the proposed strength reduction factors are generally conservative and agree well with the finite element results. It was shown that the proposed strength reduction factors provide a reliable design criteria when calibrated with a resistance factor of 0.85 $(\varphi = 0.85)$.

REFERENCES

[1] Nethercot, D. A., Salih, E. L. and Gardner, L. (2011). "Behaviour and design of stainless steel bolted connections", *Advances in Structural Engineering*, Vol. 14, No. 4, pp. 647-658.
[2] Theofanous, M., and Gardner L. (2012). "Effect of element interaction and material nonlinearity on the ultimate capacity of stainless steel cross-sections", S*teel and Composite Structures,* Vol. 12, No. 1, pp. 73-92.
[3] Kiymaz, G. and Seckin, E. (2014). "Behavior and design of stainless steel tubular member welded end connections", S*teel and Composite Structures*, Vol 17, No. 3, pp. 253-269.
[4] Lawson, R. M., Basta, A. and Uzzaman, A. (2015). "Design of stainless steel sections with circular openings in shear", *Journal of Constructional Steel Research*, Vol 112, pp. 228-241.
[5] Yousefi, A. M., Lim, J.B.P., Uzzaman, A., Lian, Y., Clifton, G.C. and Young, B. (2016a). "Web crippling strength of cold-formed stainless steel lipped channel-sections with web openings subjected to Interior-One-Flange loading condition", S*teel and Composite Structures,* Vol. 21, No. 3, pp. 629-659.

[6] Yousefi, A. M., James B.P. Lim, Asraf Uzzaman, Ying Lian, G Charles Clifton, Ben Young (2016b), "Design of cold-formed stainless steel lipped channel-sections with web openings subjected to web crippling under End-One-Flange loading condition", *Advances in Structural Engineering.*

[7] Yousefi, A. M., Asraf Uzzaman , James B.P. Lim, G. Charles Clifton, Ben Young (2016c), "Numerical investigation of web crippling strength in cold-formed stainless steel lipped channels with web openings subjected to interior-two-flange loading condition", S*teel and Composite Structures.*

[8] Yousefi, A. M., Asraf Uzzaman , James B.P. Lim, G. Charles Clifton, Ben Young (2016c), "Web crippling strength of cold-formed stainless steel lipped channels with web perforations under interior-two-flange loading", *Advances in Structural Engineering.*

[9] Yousefi, A. M., James B.P. Lim, Asraf Uzzaman, Ying Lian, G. Charles Clifton, Ben Young (2016d), "Web Crippling Strength of Cold-Formed Duplex Stainless Steel Lipped Channel-Sections with Web Openings Subjected to Interior-One-Flange Loading Condition", *Proceeding of The Wei-Wen Yu International Specialty Conference on Cold-Formed Steel Structures,* Baltimore, Maryland, USA. November.

[10] Lian, Y., Uzzaman A., Lim J.B.P., Abdelal G., Nash D., Young B. (2016a), "Effect of web holes on web crippling strength of cold-formed steel channel sections under end-one-flange loading condition - Part I: Tests and finite element analysis", *Thin-Walled Structures,* **107**, 443-452.

[11] Lian, Y., Uzzaman A., Lim J.B.P., Abdelal G., Nash D., Young B. (2016b), "Effect of web holes on web crippling strength of cold-formed steel channel sections under end-one-flange loading condition - Part II: Parametric study and proposed design equations", *Thin-Walled Structures,* **107**, 489-501.

[12] Uzzaman, A., Lim, J. B.P., Nash, D, Rhodes J., and Young, B. (2012a). "Web crippling behaviour of cold-formed steel channel sections with offset web holes subjected to end-two-flange loading", *Thin-Walled Structures*, Vol. 50, pp. 76-86.

[13] Uzzaman, A., Lim, J. B.P., Nash, D, Rhodes J., and Young, B. (2012b). "Cold-formed steel sections with web openings subjected to web crippling under two-flange loading conditions-part I: Tests and finite element analysis", *Thin-Walled Structures*, Vol. 56, pp. 38-48.

[14] Uzzaman, A., Lim, J. B.P., Nash, D, Rhodes J., and Young, B. (2012c). "Cold-formed steel sections with web openings subjected to web crippling under two-flange loading conditions-part II: Parametric study and proposed design equations", *Thin-Walled Structures*, Vol. 56, pp. 79-87.

[15] Uzzaman, A., Lim, J. B.P., Nash, D, Rhodes J., and Young, B. (2013). "Effect of offset web holes on web crippling strength of cold-formed steel channel sections under end-two-flange loading condition", *Thin-Walled Structures*, Vol. 65, pp. 34-48.

[16] Korvink, S.A., van den Berg, G.J. and van der Merwe, P. (1995). "Web crippling of stainless steel cold-formed beams", J*ournal of Constructional Steel Research*, Vol. 34, No. 2-3, pp. 225-248.

[17] Zhou, F. and Young, B. (2006). "Yield line mechanism analysis on web crippling of cold-formed stainless steel tubular sections under two-flange loading", *Engineering Structures*, Vol. 28, No. 6, pp. 880-892.

[18] Zhou, F. and Young, B. (2007). "Cold-formed high-strength stainless steel tubular sections subjected to web crippling", *Journal of structural engineering*, Vol. 133, No. 3, pp. 368-377.

[19] Zhou, F. and Young, B. (2008). "Web crippling of cold-formed stainless steel tubular sections", *Advances in Structural Engineering*, Vol. 11, No. 6, pp. 679-691.

[20] Zhou, F. and Young, B. (2013). "Web crippling behaviour of cold-formed duplex stainless steel tubular sections at elevated temperatures", *Engineering Structures*, Vol. 57, pp.51-62.

[21] Keerthan, P., and Mahendran, M. (2012). "Shear behaviour and strength of LiteSteel beams with web openings", *Advances in Structural Engineering*, Vol. 15, No. 2, pp. 171-184.

[22] Keerthan, P., Mahendran, M. and Steau, E. (2014). "Experimental study of web crippling behaviour of hollow flange channel beams under two flange load cases", *Thin-Walled Structures*, Vol. 85, pp. 207-219.

[23] ABAQUS. (2014), Analysis User's Manual-Version 6.14-2 ABAQUS Inc., USA.

[24] Chen, J., and Young, B. (2006). "Stress–strain curves for stainless steel at elevated temperatures", *Engineering Structures*, Vol. 28, No. 2, pp. 229-239.

[25] Yousefi, A. M., Mojtaba Hosseini and Nader Fanaie (2014), "Vulnerability Assessment of Progressive Collapse of Steel Moment Resistant Frames". *Trends in Applied Sciences Research, 9: 450-460.*

[26] Rezvani, F. H., Yousefi, A. M., & Ronagh, H. R. (2015), "Effect of span length on progressive collapse behaviour of steel moment resisting frames". *Structures,* 3, 81-89.

[27] ASCE 8-02 (2002), Specification for the Design of Cold-Formed Stainless Steel Structural Members: SEI/ASCE 8-02, Reston, VA.

[28] NAS (2007). North American Specification for the Design of Cold-Formed Steel Structural Members: American Iron and Steel Institute, AISI S100-2007, AISI Standard.

[29] Eurocode-3 (2006), Design of steel structures: Part 1.3: General rules — Supplementary rules for cold-formed thin gauge members and sheeting, in: ENV 1993-1-3, European Committee for Standardization, Brussels, Belgium.