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Wei-Wen Yu International Specialty Conference on Cold-Formed Steel Structures
Baltimore, Maryland, U.S.A, November 9 & 10, 2016

Web Crippling Strength of Cold-Formed Duplex Stainless Steel Lipped Channel-Sections with Web Openings Subjected to Interior-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 interior-one-flange (IOF) loading condition. 742 non-linear elasto-plastic finite element analyses are undertaken, with web openings located either centred beneath 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.

Keywords: Cold-formed stainless steel; Lipped channel-section; Web crippling; Finite element analysis; Strength reduction factor.

1 Introduction

Cold-formed stainless steel sections are becoming more widely used in residential and commercial construction due to their high corrosion resistance and high strength-to-weight ratio. Thin cold-formed stainless steel sections, however, are susceptible to web crippling at points of concentrated loading and this is well-known to be an important design issue. In addition, web openings are also becoming popular, as they improve ease of installation of services. This paper considers the web crippling performance of the duplex EN 1.4462 stainless steel grade. The duplex grade combines the beneficial properties of ferritic and austenitic stainless steels.

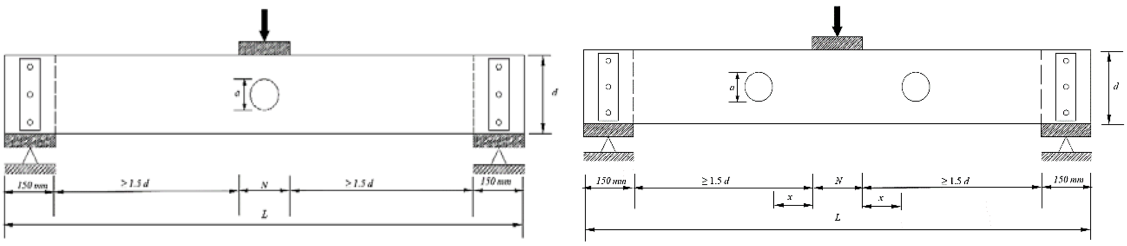
Amongst recent studies on web crippling of cold-formed stainless steel sections, Zhou and Young (2006) studied the web crippling of cold-formed stainless steel tubular sections using yield line mechanism analysis. They proposed web crippling design equations from results of experiments and finite element (FE) models. In a study by Zhou and Young (2007) on stainless steel hollow sections, it was found that the predictions from the ASCE Specification and AS/NZS Standard are generally reliable, except for the ITF loading condition. They proposed a unified web crippling equation for cold-formed stainless steel hollow sections with a single web.

Zhou and Young (2013) considered tubular sections under four loading conditions at elevated temperatures; again, unified web crippling equations were proposed. In other research, Bock and Real (2014) investigated strength curves for web crippling of cold-formed stainless steel hat sections under different loading conditions, according to AISI specification and SEI/ASCE8-02 standard. A new design approach for web crippling was proposed, using strength curves from slenderness-based equations.

For cold-formed carbon steel sections, Uzzaman *et al.* (2012a,b,c, 2013) considered the web crippling strength of cold-formed steel channel sections under the two-flange loading conditions. Validating the finite element models with experimental tests, strength reduction factor equations were proposed to consider web openings. More recently, Lian *et al.* (2016a,b) investigated the behaviour of cold-formed steel channel-sections with circular web openings in the web under the interior-one-flange (IOF) loading condition (see Fig. 1); the cases of both flanges fastened and unfastened to the bearing plates were considered. Strength reduction factor equations were proposed from a parametric study, with experimental test results used the validate the FE models. The web crippling of stainless steel lipped channel-sections, however, has not been addressed in the literature.

This paper considers the web crippling strength of cold-formed stainless steel lipped channel-sections with web openings subjected to the interior-one-flange (IOF) loading condition (see Fig. 2) for the duplex EN 1.4462 grade, as part of the authors' works on one and two flange loadings (Yousefi *et al.* 2016a,b,c,d). Using the general purpose finite element program ABAQUS (2014), 742 non-linear elasto-plastic finite element analyses are undertaken, with web openings located either centred beneath 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 IOF loading condition



(a) (b)

Figure 2: Interior-one-flange (IOF) loading condition; (a) With web openings centred under 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.* (2016a,b) recently conducted 43 interior-one-flange (IOF) tests, in the laboratory, on lipped channel-sections with circular web openings under web crippling (see Fig. 1). Fig. 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 (2014), 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*. (2016a,b).

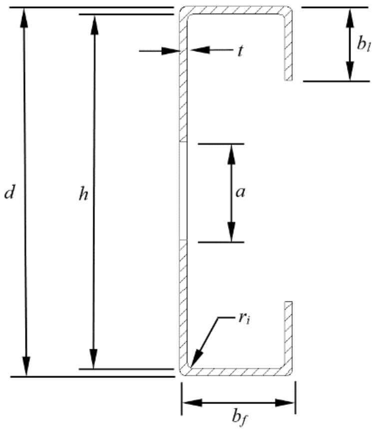


Figure 3: Definition of symbols

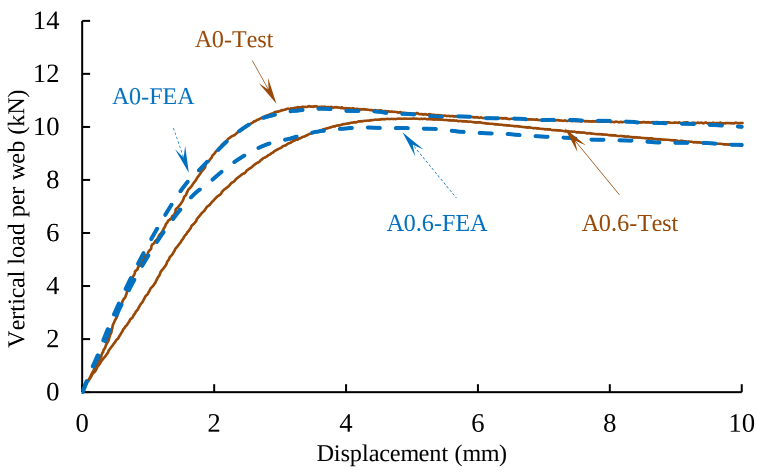
The models have been coded such the nominal dimension of the model and the length of the bearing plate as well as the ratio of the diameter of the circular web openings to the depth of the flat portion of the webs (*a/h*) can be determined from the coding system. As an example, the label "142-N100-A0.2-FR" 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 curves for the three cold-formed stainless steel materials, were taken from Chen and Young (2006) and Arrayago *et. al.* (2015). Comparative hot-rolled steel stress strain curves can be found in Yousefi *et al.* (2014) and Rezvani *et al*. (2015).

Fig. 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 test specimens and that of the finite element analysis.

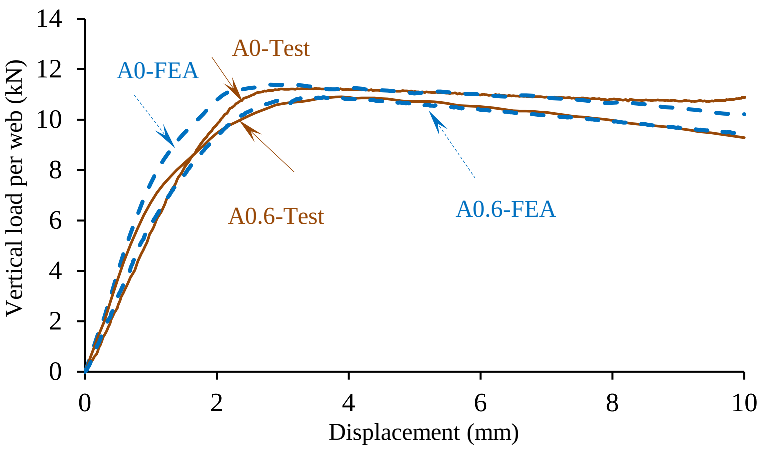
For cold-formed stainless steel lipped channel-sections, the numerical failure loads with and without circular web openings were then determined for the three stainless steel grades: duplex grade EN 1.4462; austenitic grade 1.4404 and ferritic grade 1.4003. These results were compared with the failure loads calculated in accordance with ASCE (2002), NAS (2007) and AS/NZS 4600 (2005) (see Table 1). The failure loads predicted from the finite element model are similar to the codified failure loads of the sections.

Table 1: Comparison of numerical results with design strength for the case of flange unfastened 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*)	$P_{AS/NZS}$	P/P_{NAS}	P/P_{ASCE}	$P/P_{AS/NZS}$
142-N100	109.67	78.74	0.72	3.78	11.57	10.70	10.73	10.70	1.08	1.08	1.08
142-N120	110.00	94.49	0.86	3.78	12.28	11.27	11.87	11.27	1.09	1.03	1.09
142-N150	109.25	117.19	1.07	3.75	12.94	12.24	13.79	12.24	1.06	0.94	1.06
202-N100	144.41	72.46	0.50	3.62	12.56	12.56	11.76	12.53	1.00	1.07	1.00
202-N120	144.38	86.96	0.60	3.62	12.81	13.21	12.97	13.18	0.97	0.99	0.97
202-N150	144.38	108.70	0.75	3.62	13.15	14.10	14.79	15.30	0.93	0.89	0.86
302-N100	157.57	52.63	0.33	2.63	24.64	25.48	21.83	25.91	0.97	1.13	0.95
302-N120	157.51	63.16	0.40	2.63	26.01	26.71	23.05	26.61	0.97	1.13	0.98
302-N150	155.01	77.72	0.50	2.59	27.71	28.61	26.01	29.18	0.97	1.07	0.95
Mean, Pm									1.00	1.04	0.99
Coefficient of variation									0.04	0.07	0.07



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

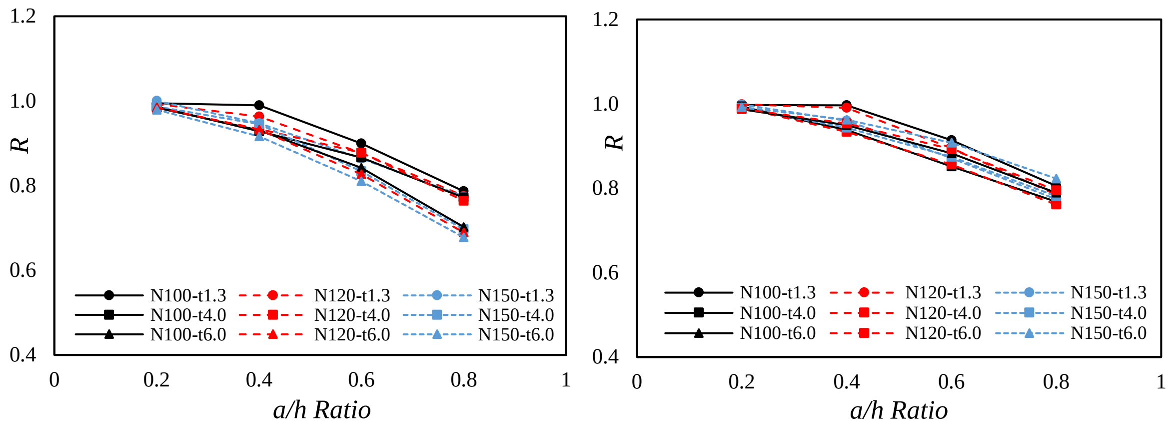


(b) Offset circular web opening for the case of flange fastened to bearing plate

Figure 4: Comparison of finite element results and experimental test results for 142×60×13-t1.3-N100 (Lian *et al.* 2016a,b)

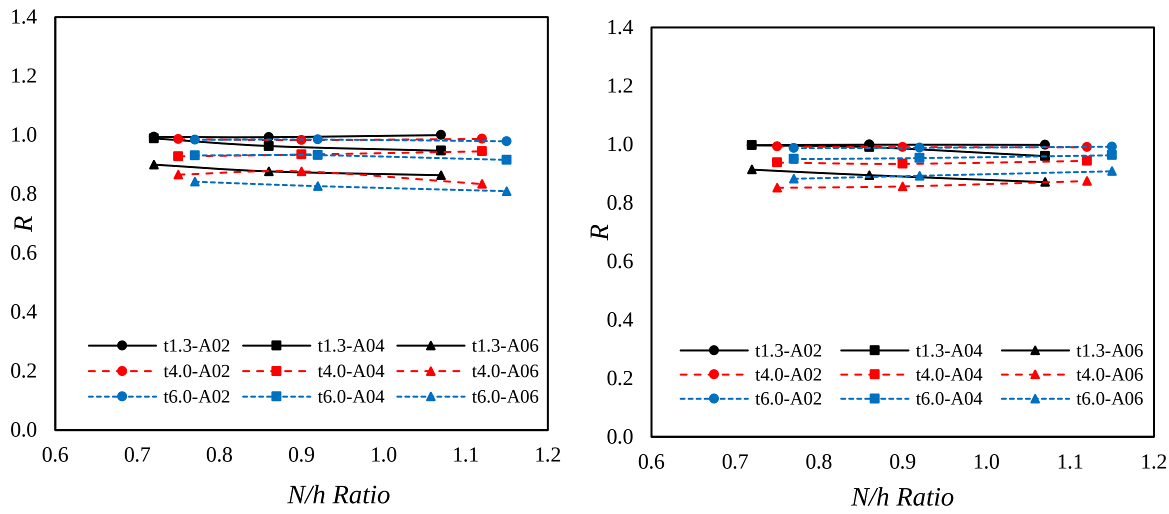
3 Parametric study for duplex stainless steel grade

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 742 finite element models of lipped channel-sections with various dimensions and thicknesses were considered for the three stainless steel grades: duplex EN1.4462, austenitic EN1.4404 and ferretic EN1.4003. Table 2 shows the web crippling strengths determined from finite element analyses for the duplex grade EN 1.4462. 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 Figs. 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.



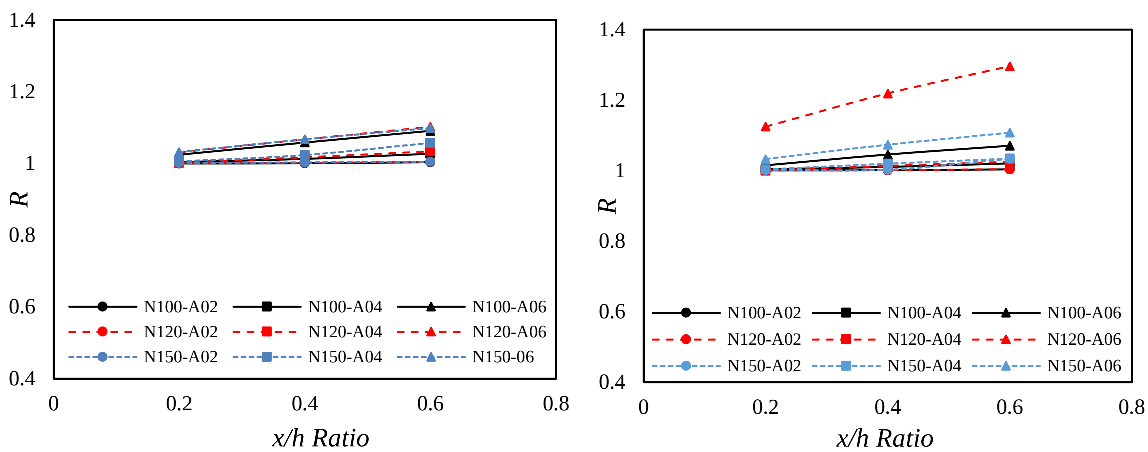
(a) Flange unfastened case (b) Flange fastened case

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

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	11.57	11.50	11.45	10.41	9.10	12.76	12.72	12.72	11.66	9.98
142-N100-FR	4.00	93.12	91.83	86.44	80.68	71.84	112.57	111.80	105.57	95.87	86.45
142-N100-FR	6.00	174.70	171.91	162.61	147.12	122.67	201.87	199.27	191.73	178.14	171.28
142-N120-FR	1.27	12.28	12.19	11.83	10.77	9.53	13.49	13.48	13.37	12.07	10.59
142-N120-FR	4.00	97.41	95.77	90.95	85.47	74.45	120.57	119.45	112.55	103.25	91.75
142-N120-FR	6.00	173.11	170.45	161.34	143.15	119.29	201.42	199.08	191.99	179.79	160.09
142-N150-FR	1.28	12.94	12.94	12.26	11.18	10.02	14.37	14.35	13.80	12.52	11.12
142-N150-FR	4.00	97.86	96.56	92.51	81.59	68.18	128.76	127.50	121.49	112.61	100.54
142-N150-FR	6.00	162.37	158.99	148.73	131.58	110.03	197.41	195.84	190.05	179.26	162.44
202-N100-FR	1.39	12.56	12.47	11.96	10.63	-	13.51	13.50	13.49	12.60	-
202-N100-FR	4.00	93.07	92.40	88.79	80.58	-	108.50	107.91	104.75	93.06	-
202-N100-FR	6.00	188.63	184.77	173.76	158.15	-	227.47	226.40	217.24	195.81	-
202-N120-FR	1.39	12.81	12.71	12.09	10.81	-	15.18	15.17	15.14	13.60	-
202-N120-FR	4.00	97.11	96.36	91.70	83.85	-	116.44	115.64	109.98	98.16	-
202-N120-FR	6.00	191.80	188.23	177.94	160.81	-	230.69	229.94	221.98	203.79	-
202-N150-FR	1.39	13.15	13.02	12.27	11.14	-	16.45	16.45	16.05	14.17	-
202-N150-FR	4.00	102.42	101.16	95.83	89.27	-	128.20	126.06	117.79	106.42	-
202-N150-FR	6.00	188.24	186.47	179.66	159.06	-	238.28	229.36	222.60	207.03	-
302-N100-FR	1.98	24.64	24.63	23.83	22.17	-	26.27	26.26	25.67	23.37	-
302-N100-FR	4.00	93.86	93.80	93.20	85.10	-	104.53	104.29	102.32	94.27	-
302-N100-FR	6.00	196.88	195.50	187.10	169.77	-	230.30	229.11	203.98	194.41	-
302-N120-FR	1.98	26.01	25.97	25.30	22.38	-	27.17	27.16	27.12	23.49	-
302-N120-FR	4.00	97.47	97.47	95.87	86.44	-	111.32	111.12	110.55	97.50	-
302-N120-FR	6.00	202.58	201.16	193.42	174.59	-	241.24	239.93	233.04	199.24	-
302-N150-FR	1.99	27.71	27.51	26.10	23.24	-	28.56	28.55	28.54	24.25	-
302-N150-FR	4.00	103.08	102.77	98.41	89.34	-	120.82	120.58	118.63	101.37	-
302-N150-FR	6.00	210.15	208.63	199.80	179.71	-	247.08	246.04	240.85	205.67	-

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	11.50	11.46	11.27	10.95	12.73	12.71	12.63	12.53
142-N100-FR	4.00	93.24	93.15	92.67	91.75	112.63	112.62	112.55	112.49
142-N100-FR	6.00	166.59	166.08	164.37	160.39	201.87	201.39	199.44	186.56
142-N120-FR	1.27	12.19	12.11	11.90	11.41	13.45	13.44	13.43	13.38
142-N120-FR	4.00	97.47	97.33	96.72	95.53	120.57	120.57	120.47	120.24
142-N120-FR	6.00	166.56	166.09	164.36	159.70	201.42	200.93	198.95	186.40
142-N150-FR	1.28	12.97	12.87	12.53	11.88	14.39	14.38	14.34	14.27
142-N150-FR	4.00	97.77	97.39	96.13	93.66	128.76	128.73	128.48	125.80
142-N150-FR	6.00	158.21	157.58	155.68	152.08	197.41	196.97	195.04	184.86
202-N100-FR	1.39	12.36	12.07	11.44	10.37	14.27	14.27	14.17	14.03
202-N100-FR	4.00	93.01	92.74	91.86	90.03	108.50	108.47	108.37	108.25
202-N100-FR	6.00	184.32	183.61	181.12	175.45	227.47	226.95	224.65	212.61
202-N120-FR	1.39	12.61	12.35	11.65	10.51	14.34	14.34	14.24	14.06
202-N120-FR	4.00	97.07	96.78	95.72	93.16	116.44	116.41	116.30	116.13
202-N120-FR	6.00	185.87	185.13	182.63	176.05	230.69	229.99	227.02	213.26
202-N150-FR	1.39	12.95	12.67	11.93	10.90	16.45	16.44	16.30	16.05
202-N150-FR	4.00	102.38	101.94	100.36	95.45	127.48	127.41	127.27	126.92
202-N150-FR	6.00	187.98	187.16	184.31	176.30	229.87	229.12	225.97	212.56
302-N100-FR	1.98	22.75	22.66	22.29	21.36	26.27	26.26	26.15	25.72
302-N100-FR	2.00	93.88	93.48	91.97	88.40	104.53	104.52	104.46	104.31
302-N100-FR	4.00	194.66	193.59	189.95	178.72	230.30	230.06	228.73	212.81
302-N120-FR	1.98	24.06	23.91	23.10	21.95	27.17	27.15	26.96	26.57
302-N120-FR	2.00	97.50	96.93	95.23	90.39	111.36	111.35	111.21	111.02
302-N120-FR	4.00	197.85	196.83	192.58	176.63	241.24	240.59	237.63	226.42
302-N150-FR	1.99	25.42	25.08	24.17	22.58	28.56	28.53	28.38	27.19
302-N150-FR	2.00	103.09	102.44	100.01	93.97	120.82	120.80	120.74	120.02
302-N150-FR	4.00	202.77	201.35	195.45	184.86	247.08	246.05	241.93	227.42

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	11.13	11.13	11.13	11.13	12.12	12.12	12.12	12.12
142-N100-A0.2-FR	1.27	10.99	10.99	11.00	11.03	12.04	12.05	12.06	12.08
142-N100-A0.4-FR	1.27	10.50	10.54	10.64	10.79	11.75	11.80	11.87	11.99
142-N100-A0.6-FR	1.27	9.56	9.80	10.12	10.44	11.09	11.26	11.60	11.88
142-N100-A0.8-FR	1.27	8.15	8.76	9.21	9.60	---	---	---	---
142-N120-A0-FR	1.27	11.88	11.88	11.88	11.88	12.99	12.99	12.99	12.99
142-N120-A0.2-FR	1.27	11.70	11.71	11.72	11.76	12.91	12.92	12.93	12.96
142-N120-A0.4-FR	1.27	11.07	11.09	11.26	11.45	12.56	12.56	12.73	12.88
142-N120-A0.6-FR	1.27	9.85	10.16	10.52	10.86	11.66	11.95	12.40	12.74
142-N120-A0.8-FR	1.27	8.43	9.05	9.53	9.85	9.55	10.74	11.64	12.38
142-N150-A0-FR	1.28	12.75	12.75	12.75	12.75	14.42	14.42	14.42	14.42
142-N150-A0.2-FR	1.28	12.56	12.58	12.60	12.62	13.87	13.90	13.91	14.34
142-N150-A0.4-FR	1.28	11.64	11.70	11.91	12.31	13.35	13.40	13.62	13.81
142-N150-A0.6-FR	1.28	10.35	10.68	11.04	11.37	12.26	12.66	13.16	13.58
142-N150-A0.8-FR	1.28	8.96	9.53	9.98	10.27	10.29	11.36	12.21	12.98
202-N100-A0-FR	1.39	12.40	12.40	12.40	12.40	13.50	13.50	13.50	13.50
202-N100-A0.2-FR	1.39	12.10	12.11	12.12	12.14	13.39	13.40	13.41	13.47
202-N100-A0.4-FR	1.39	10.98	11.06	11.21	11.41	12.26	12.27	12.44	12.67
202-N100-A0.6-FR	1.39	9.46	9.76	10.08	10.36	11.28	11.53	11.98	12.44
202-N120-A0-FR	1.39	12.69	12.69	12.69	12.69	15.16	15.16	15.16	15.16
202-N120-A0.2-FR	1.39	12.35	12.37	12.38	12.39	15.05	15.05	15.07	15.14
202-N120-A0.4-FR	1.39	11.19	11.41	11.44	11.63	14.30	14.35	14.63	14.90
202-N120-A0.6-FR	1.39	9.66	9.96	10.26	10.53	13.00	13.38	13.95	14.54
202-N150-A0-FR	1.45	14.28	14.28	14.28	14.28	16.45	16.45	16.45	16.45
202-N150-A0.2-FR	1.45	13.87	13.88	13.89	13.94	16.26	16.27	16.30	16.38
202-N150-A0.4-FR	1.45	12.61	12.71	12.88	13.06	15.28	15.38	15.71	16.04
202-N150-A0.6-FR	1.45	11.00	11.30	11.60	11.85	13.78	14.23	14.87	15.52
302-N100-A0-FR	1.98	24.25	24.25	24.25	24.25	25.62	25.62	25.62	25.62
302-N100-A0.2-FR	1.98	24.00	24.01	24.03	24.09	26.55	26.56	25.60	25.58
302-N120-A0-FR	1.96	25.23	25.23	25.23	25.23	26.63	26.63	26.63	26.63
302-N120-A0.2-FR	1.96	24.80	24.83	24.86	24.94	26.51	26.53	26.62	26.59
302-N120-A0.4-FR	1.96	22.74	22.87	23.29	23.79	24.46	24.66	25.34	25.45
302-N120-A0.6-FR	1.96	18.80	20.00	21.35	23.24	23.25	23.30	24.50	24.59
302-N150-A0-FR	1.99	27.55	27.55	27.55	27.55	28.10	28.10	28.10	28.10
302-N150-A0.2-FR	1.99	26.79	26.83	26.87	27.02	27.93	28.02	28.10	28.41
302-N150-A0.4-FR	1.99	24.26	24.40	24.87	25.44	26.90	27.25	27.63	27.83
302-N150-A0.6-FR	1.99	20.84	21.56	22.58	23.74	23.84	24.86	26.59	26.70

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,

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

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

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

For offset web opening:

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

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

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

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

The limits for the reduction factor equations (3), (4), (5) and (6) are $h/t \le 157.8$, $N/t \le 120.97$, $N/h \le 1.15$, $a/h \le 0.8$, and $\theta = 90^0$.

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 Fig. 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. 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.

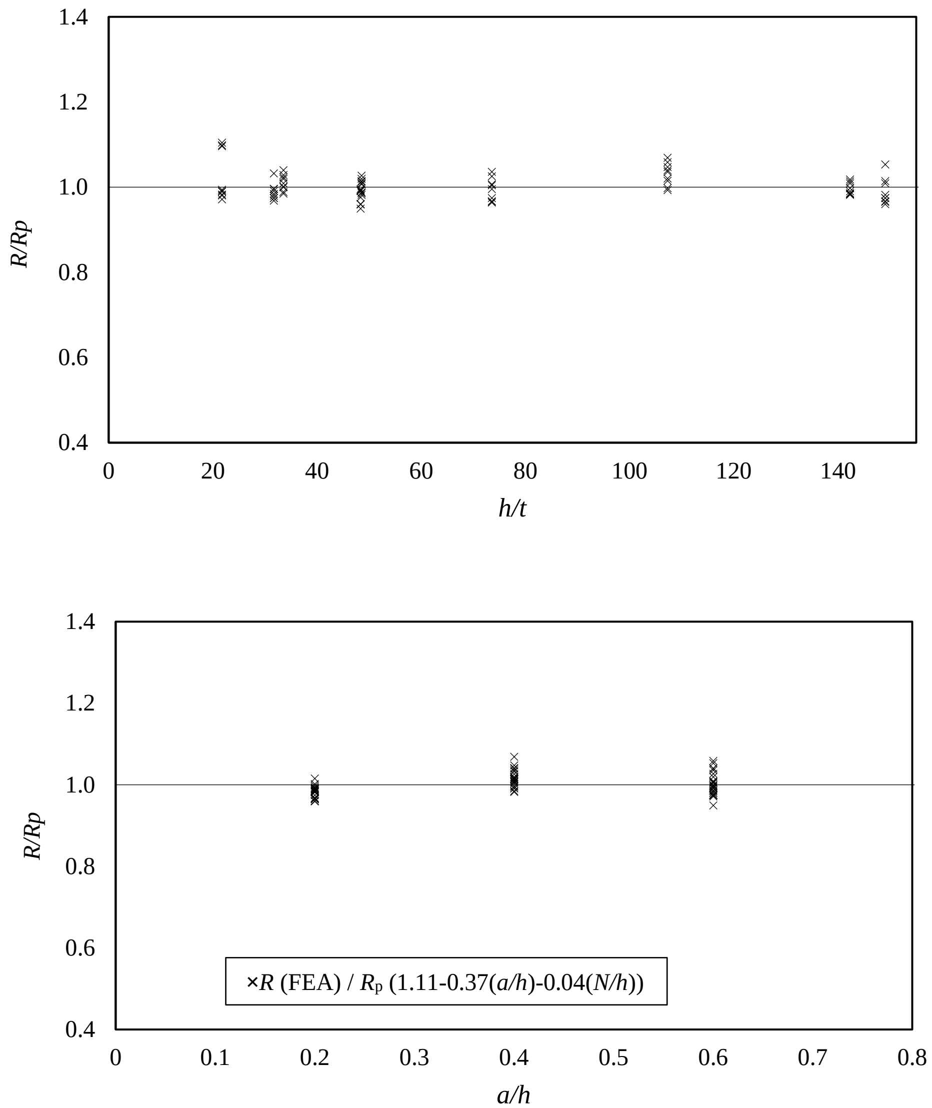


Figure 8: Comparison of strength reduction factor for centred web opening where flange unfastened to bearing plate

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	90	90	84	81
Mean, P_m	1.00	1.01	1.04	1.04
Coefficient of variation, V_p	0.03	0.03	0.04	0.05
Reliability index, β	2.82	2.86	2.97	2.94
Resistance factor, ϕ	0.85	0.85	0.85	0.85

6 Conclusions

In this paper, the effect of web openings on the interior-one-flange (IOF) loading condition of cold-formed stainless steel lipped channel-sections was investigated for duplex grade EN 1.4462. 742 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 $(\varphi = 0.85)$.

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