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Web crippling strength of cold-formed duplex stainless steel lipped channels with web openings under end-two-flange loading

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ABSTRACT

A finite element evaluation into the web crippling strength of cold-formed duplex EN1.4462 stainless steel lipped channels with circular web openings under end-two-flange (ETF) loading is presented in this study. The cases of web openings located both centred and offset to the load bearing plates, are considered. In order to take into account the effect of the circular web openings, a parametric study involving 730 finite element analyses was performed; from the results of the parametric study, strength reduction factor equations are determined. The strength reduction factor equations are first compared to equations recently proposed for cold-formed carbon steel lipped channels. It is demonstrated that the strength reduction factor equations proposed for cold-formed carbon steel are conservative for the duplex stainless steel grades by up to 7%. New strength reduction factor equations are then proposed that can be applied to ferritic stainless steel grades.

1. INTRODUCTION

Cold-formed stainless steel sections are most often used for both architectural and structural applications in conditions characterised by high corrosion aggressiveness; not only because they are aesthetically pleasing, but they also have favourable characteristics in terms of strength, durability and formability (Zhao *et al.* 2016). To provide ease of access for services, the use of web openings for such sections are also becoming popular in industry (Lawson *et al.* 2015). Such web

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openings, however, result in the sections being more susceptible to web crippling, especially under concentrated loads in the vicinity of the openings.

The authors have recently proposed unified strength reduction factor equations for the web crippling strength of cold-formed stainless steel channel-sections with circular web openings under the one-flange loading conditions (Yousefi *et al.* 2016a,b,c, 2017a). The equations covered three stainless steel grades: duplex grade EN 1.4462; austenitic grade EN 1.4404 and ferritic grade EN 1.4003. Similar equations for cold-formed carbon steel under end-one-flange loading condition have previously been proposed by Lian *et al.* (2016a,b, 2017a,b), which was a continuation of the work of Uzzaman *et al.* (2012a,b,c, 2013) who had considered the two-flange loading conditions. When applied to the stainless steel grades, (Yousefi *et al.* 2016a,b,c, 2017a) showed that the equations proposed by Lian *et al.* (2016a,b) for the end-one-flange (EOF) loading condition were unconservative by up to 7%. Also, Yousefi *et al.* (2016d, 2017b,c) showed that the equations proposed by Uzzaman *et al.* (2012a, c) for the interior-two-flange (ITF) and end-two-flange loading conditions were unconservative for stainless steel channel-sections. Yousefi *et al. (2017d,e)* also conducted a series of test programme on unlipped cold-formed ferritic stainless steel channels under ITF load and proposed strength reduction factors due to openins in web. The work are summorised in companion study Yousefi *et al. (2017f).*

In the literature, for cold-formed stainless steel lipped channel-sections, only Krovink and van den Berg (1994) and Krovink *et al.* (1995) have considered web crippling strength, but limited to sections without openings. Zhou and Young (2006, 2007, 2008, 2013) have considered the web crippling strength of cold-formed stainless steel tubular sections, again without openings. Research by Lawson *et al.* (2015), while concerned with circular web openings, focussed on the bending strength of the sections and not on the web crippling strength under concentrated loads. In terms of cold-formed carbon steel, Keerthan and Mahendran (2012) considered the web crippling strength of hollow flange channel beams. Sundararajah *et al.* (2016) and Gunalan and Mahendran (2015) have also considered a Direct Strength Method approach for the web crippling strength of channel sections, again without openings. For cold-formed carbon steel lipped channel-sections, recent work has included Natario *et al.* (2014) and Gunalan and Mahendran (2015), all without openings.

This paper considers the case of the web crippling strength of cold-formed stainless steel lipped channels with circular web openings under the end-two-flange (ETF) loading condition (see Fig. 1), and applicability of the proposed equations by Uzzaman *et al.* (2012c, 2013) to the same stainless steel grade, namely the duplex grade EN 1.4462.

2. EXPERIMENTAL AND NUMERICAL INVESTIGATION

For cold-formed carbon steel, Uzzaman *et al.* (2012b, 2013) conducted 100 end-two-flange (ETF) laboratory tests on lipped channel-sections with circular web openings subjected to web crippling (see Fig. 1). Fig. 2 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 size of the circular web openings was varied in order to investigate the effect of the web openings on the web crippling strength. All the test specimens were fabricated with web openings located at the mid-depth of the webs with centred and offset to the bearing plates. The laboratory test results were used to validate a non-linear geometry elasto-plastic finite element model (details of the model can be found in Uzzaman *et al.* (2012b, 2013)), which was then used for a parametric study to investigate the web crippling strength of cold-formed stainless steel lipped channel-sections with circular web openings under the end-two-flange (ETF) loading condition. 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 can be found in Uzzaman *et al.* (2012b, 2013).

a) Centred circular web opening

b) Offset circular web opening

Fig. 1 Experimental analysis of cold-formed steel channel sections under ETF loading condition after Uzzaman et al. (2012b, 2013).

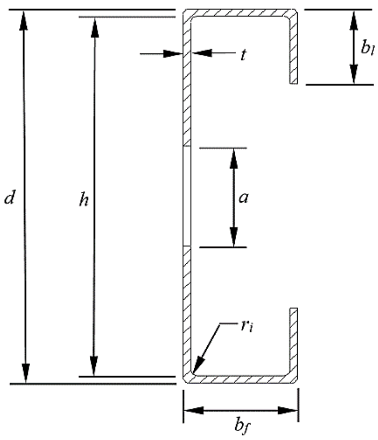
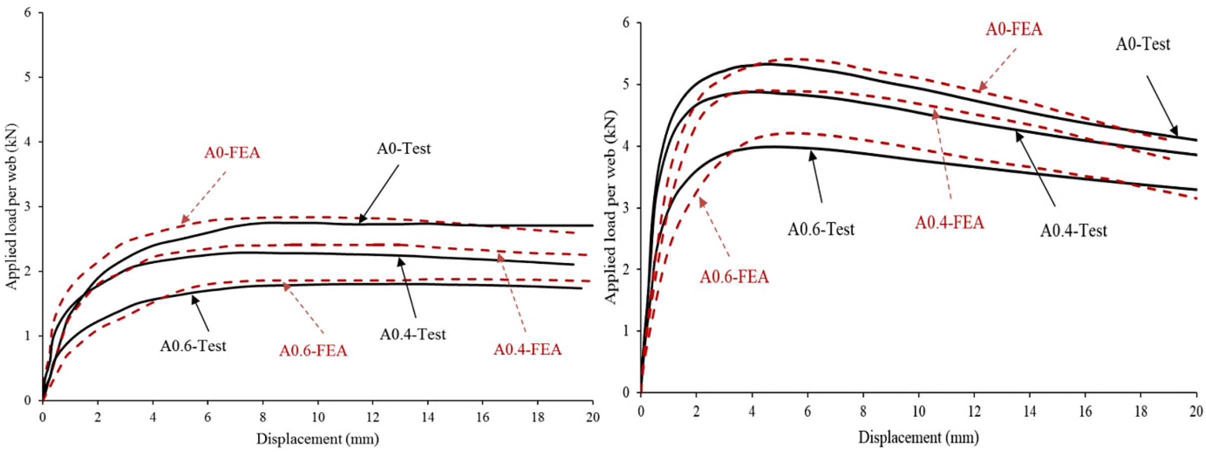


Fig. 2 Definition of symbols

In this study, the non-linear elasto-plastic general purpose finite element program ABAQUS (2014) was used to simulate the cold-formed stainless steel lipped channels with and without circular web openings subjected to web crippling. The bearing plates, the lipped channel-section with circular web openings and the interfaces between the bearing plates and the lipped-channel section were modelled. In the finite element model, the model was based on the centreline dimensions of the cross-sections.

For the finite element model verification, the results of experimental study on lipped carbon steel channel sections 142×60×13-t1.3-N30 and 202×65×13-t1.4-N120 (flanges unfastened and fastened to the bearing plates) for the cases of web holes located centred and offset to the bearing plates under ETF loading condition conducted by Uzzaman *et al.* (2012b, 2013) (see Fig. 1) were compared to the results obtained from the finite element analyses (Fig. 3) using the same material as developed for stainless steel material in this study.



a) Flanges unfastened to bearing plates b) Flanges fastened to bearing plates

Fig. 3 Comparison of finite element results and experimental results by Uzzaman et al. (2012b) for sections with centred circular web opening

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/t*	P_{FEA} *(kN)*	P_{ASCE} *(kN)*	P_{NAS} *(kN)*	P_{ASNZS} *(kN)*	P/P_{ASCE}	P/P_{NAS}	P/ P_{ASNZS}
142-N100	114.01	81.30	0.71	3.90	2.94	2.56	3.12	3.12	1.15	0.94	0.94
142-N120	111.67	96.01	0.86	3.84	3.05	2.73	3.24	3.24	1.12	0.94	0.94
142-N150	112.64	120.97	1.07	3.87	3.37	3.06	3.44	3.44	1.10	0.98	0.98
202-N100	147.62	74.07	0.50	3.70	3.17	2.52	2.94	2.94	1.26	1.08	1.08
202-N120	147.68	88.89	0.60	3.70	3.41	2.97	3.27	3.27	1.15	1.04	1.04
202-N150	147.72	111.11	0.75	3.70	3.76	3.32	3.48	3.48	1.13	1.08	1.08
302-N100	157.69	52.63	0.33	2.63	5.62	5.28	5.40	5.40	1.07	1.04	1.04
302-N120	157.13	63.16	0.40	2.63	6.02	5.43	5.47	5.47	1.11	1.10	1.10
302-N150	157.67	78.95	0.50	2.63	6.64	5.71	5.59	5.59	1.16	1.19	1.19
Mean, Pm									1.14	1.04	1.04
Coefficient of variation									0.16	0.05	0.15

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 three stainless steel grade: duplex grade EN 1.4462 (see Table 1). These results were compared with the failure loads calculated in accordance with ASCE 8-02 (2002), BS 5950-5 (1998), Eurocode-3 (2006), NAS (2007) and AS/NZS 4600 (2005) (see Table 2). The failure loads predicted from the finite element results are generally similar to the standard codified failure loads of the sections. Typical stress-strain curve for the duplex stainless steel material, was taken from Chen and Young (2006). Comparative hot-rolled steel stress strain curves can be found in Yousefi *et al.* (2014) and Rezvani *et al.* (2015).

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 channels, a total of 730 finite element analyses of lipped channels with various dimensions and thicknesses were considered for the duplex stainless steel grades: duplex EN1.4462. The web crippling strength predicted was influenced primarily by the ratio of the circular web opening depth to the flat portion of the web, the ratio of the bearing length to the flat portion of the web and the location of the web hole as defined by the distance of the web opening from the edge of the bearing divided by the flat portion of the web (Uzzaman et al. (2012a,b,c, 2013)). In order to find the effect of a/h, N/h and x/h on the web crippling strength of channel sections with circular web openings, parametric studies were carried out considering the circular web openings, different bearing plate lengths, the cross-section sizes and location of the circular web openings. The cases of both flanges fastened and flanges unfastened to the bearing plates were considered.

The specimens consisted of three different section sizes, having thicknesses (t) ranging from 1.23 mm to 6.0 mm and web slenderness (h/t) values ranging from 111.7 to 157.8. The ratios of the diameter of the circular web openings (a) to the depth of the flat portion of the webs (h) were 0.2, 0.4, 0.6 and 0.8. The ratios of the distance of the web openings (x) to the depth of the flat portion of the web (h) were 0.2, 0.4 and 0.6. Bearing plates of lengths (N) equal to 100 mm, 120 mm and 150 mm are considered. For each series of specimens, the web crippling strengths of the sections without the web openings were obtained. Thus, the ratio of the web crippling strengths for sections with web openings divided by the sections without web openings, which is the strength reduction factor (R), was used to quantify the degrading influence of the web openings on the web crippling strengths.

The parametric study investigated the effect of the ratios of a/h, N/h and x/h. The web crippling strengths (P_{FEA}) per web predicted from the FEA are summarised in Tables 2 to 4 for the duplex grade EN 1.4462. As can be seen from Tables 2 to 4, the failure load of the cold-formed stainless steel sections reduces as web openings are present and continues to reduce with increase in the size of web openings. The results demonstrate that the failure load obtained from the cold-formed stainless steel sections with the case of flanges fastened to bearing plates is in average 25% higher than the case of flanges unfastened to bearing plates for the sections with and without web openings. In addition, for the case of web openings with a horizontal clear distance to the near edge of the bearing plates, the web crippling strength of the sections is higher than the case of web holes located centred above the bearing plates. Moreover, for the same section with different span and bearing plates, the failure loads were found to be different among the results. Based on the results, it was found that the failure load increases as the length of the bearing plates increases and as the length of the sections increases. The effect of the ratios of a/h, N/h and x/h on the reduction factor of the web crippling strength is shown in Figs. 4 to 6 for the C142 specimen.

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

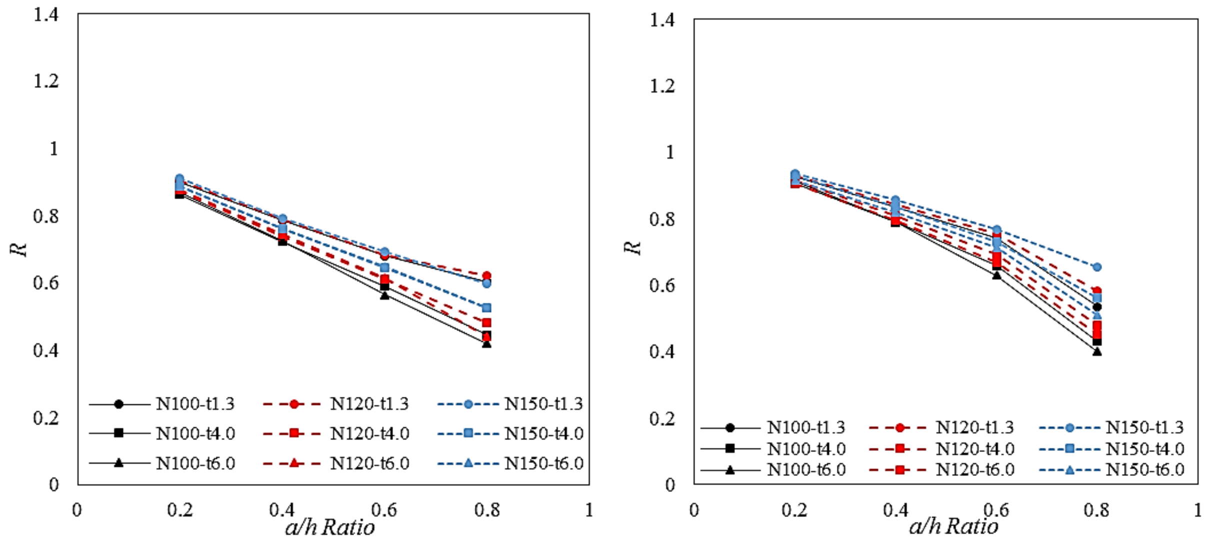
Specimen	Thickness	Unfastened FEA load per web, P_{FEA}					Fastened FEA load per web, P_{FEA}				
	t	*A(0)*	*A(0.2)*	*A(0.4)*	*A(0.6)*	*A(0.8)*	*A(0)*	*A(0.2)*	*A(0.4)*	*A(0.6)*	*A(0.8)*
	(mm)	*(kN)*	*(kN)*	*(kN)*	*(kN)*	*(kN)*	*(kN)*	*(kN)*	*(kN)*	*(kN)*	*(kN)*
142-N100	1.27	3.34	3.01	2.62	2.27	2.01	5.57	5.16	4.66	4.13	2.98
142-N100	4.00	46.82	40.39	33.83	27.62	20.82	74.15	67.29	58.58	48.78	25.39
142-N100	6.00	114.74	99.47	83.03	51.75	40.15	169.62	154.59	133.85	106.70	46.40
142-N120	1.27	3.60	3.26	2.84	2.46	2.52	6.18	5.74	5.20	4.65	3.60
142-N120	4.00	51.20	44.74	37.81	31.30	24.73	84.10	77.00	67.97	58.16	33.89
142-N120	6.00	125.16	109.72	92.97	76.91	55.31	194.88	176.45	155.14	130.30	69.02
142-N150	1.28	4.02	3.66	3.18	2.78	2.40	7.11	6.66	6.08	5.46	4.64
142-N150	4.00	57.70	51.29	43.94	37.26	30.43	97.98	90.89	81.73	71.58	55.16
142-N150	6.00	140.18	124.51	106.81	91.07	73.48	227.83	208.56	186.57	162.23	116.43
202-N100	1.39	3.04	2.75	2.33	2.01	1.82	5.27	4.84	4.29	3.52	2.93
202-N100	4.00	37.72	31.90	26.13	22.25	19.60	62.08	55.33	46.59	36.25	25.35
202-N100	6.00	96.81	81.88	64.30	53.00	40.75	151.34	132.80	111.58	79.65	47.52
202-N120	1.39	3.23	2.92	2.48	2.05	1.86	5.72	5.28	4.69	3.63	3.02
202-N120	4.00	40.61	34.56	28.34	22.71	19.95	69.47	62.50	52.26	37.39	26.13
202-N120	6.00	105.25	89.91	70.91	54.34	41.67	169.64	149.80	127.15	82.16	48.80
202-N150	1.39	3.48	3.17	2.72	2.28	1.90	6.41	5.96	5.33	4.64	3.14
202-N150	4.00	45.22	39.37	31.99	25.88	20.46	80.39	70.52	63.51	52.42	27.24
202-N150	6.00	117.65	102.26	82.37	64.36	42.96	196.97	176.28	151.83	123.27	50.82
302-N100	1.98	5.39	4.84	4.08	3.65	3.22	9.56	8.65	7.54	6.55	5.43
302-N100	4.00	30.04	27.10	21.89	19.76	17.51	48.94	43.60	37.03	31.95	24.49
302-N100	6.00	74.39	65.16	54.03	48.56	41.97	124.84	108.66	92.01	77.88	52.93
302-N120	1.98	5.65	5.05	4.11	3.69	3.28	10.17	9.25	7.78	6.71	5.55
302-N120	4.00	31.77	27.10	22.14	19.99	17.72	53.45	47.87	38.59	32.72	24.99
302-N120	6.00	83.43	69.47	55.29	49.37	42.81	139.05	121.14	96.43	79.90	54.08
302-N150	1.99	6.04	5.43	4.48	3.79	3.47	11.14	10.23	8.88	6.94	5.73
302-N150	4.00	34.26	29.30	23.89	20.43	18.14	60.53	54.77	45.38	33.87	25.73
302-N150	6.00	91.23	76.74	60.97	50.51	43.66	156.18	139.21	114.85	82.77	55.61

Table 3 Web crippling strengths of duplex stainless steel sections predicted from finite element analysis: a/h for offset circular web opening

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	1.27	3.34	3.31	3.27	3.25	5.58	5.57	5.56	5.55
142-N100	4.00	46.82	46.80	46.73	46.62	74.15	74.13	74.12	74.11
142-N100	6.00	114.74	114.69	114.58	114.37	171.90	171.89	171.88	171.85
142-N120	1.27	3.62	3.60	3.58	3.53	6.19	6.18	6.17	6.16
142-N120	4.00	51.21	51.18	51.11	50.99	84.10	84.08	84.07	84.05
142-N120	6.00	125.16	125.11	124.98	124.76	194.88	194.85	194.84	194.80
142-N150	1.28	4.03	4.02	3.99	3.95	7.12	7.11	7.10	7.09
142-N150	4.00	57.70	57.67	57.60	57.48	98.28	98.27	98.26	98.23
142-N150	6.00	140.18	140.13	139.99	139.77	227.83	227.81	227.80	227.76
202-N100	1.39	3.05	3.04	2.98	2.89	5.27	5.26	5.24	5.18
202-N100	4.00	37.72	37.69	37.63	37.50	62.08	62.06	62.05	62.03
202-N100	6.00	96.81	96.76	96.68	96.51	151.35	151.31	151.29	151.26
202-N120	1.39	3.23	3.22	3.17	3.07	5.72	5.71	5.69	5.64
202-N120	4.00	40.61	40.58	40.52	40.40	69.47	69.45	69.43	69.42
202-N120	6.00	105.25	105.19	104.93	104.93	169.64	169.63	169.60	169.56
202-N150	1.39	3.49	3.47	3.41	3.30	6.43	6.41	6.38	6.33
202-N150	4.00	45.23	45.18	45.09	44.62	80.39	80.36	80.35	80.32
202-N150	6.00	117.65	117.57	117.42	117.13	196.97	196.93	196.91	196.85
302-N100	1.98	5.40	5.38	5.28	5.10	9.56	9.55	9.48	9.30
302-N100	2.00	30.04	29.99	29.82	29.44	48.96	48.93	48.91	48.85
302-N100	4.00	78.33	78.26	78.13	77.84	65.08	57.86	44.18	43.35
302-N120	1.98	5.66	5.63	5.28	5.25	5.32	4.72	3.91	3.52
302-N120	2.00	31.77	31.73	31.62	31.35	28.89	24.42	20.10	18.27
302-N120	4.00	83.43	82.34	82.20	81.90	75.69	62.55	49.29	44.31
302-N150	1.99	6.04	6.02	5.93	5.75	11.14	11.12	11.07	10.98
302-N150	2.00	34.27	34.22	34.12	33.88	31.02	26.31	21.63	18.63
302-N150	4.00	91.23	91.14	91.03	90.80	82.88	69.35	53.65	45.33

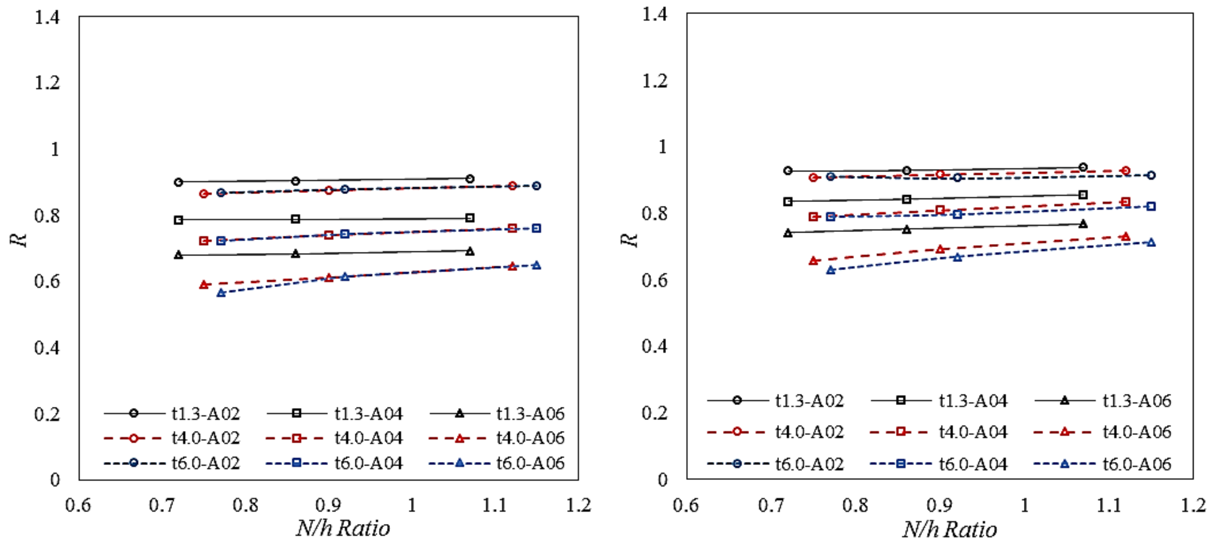
Table 4 Web crippling strengths of duplex stainless steel sections predicted from finite element analysis: x/h for offset circular web opening

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	1.27	3.34	3.34	3.34	3.34	5.58	5.58	5.58	5.58
142-N100-A0.2	1.27	3.15	3.18	3.22	3.24	5.39	5.43	5.47	5.51
142-N100-A0.4	1.27	2.86	2.96	3.03	3.09	5.12	5.21	5.30	5.38
142-N100-A0.6	1.27	2.59	2.72	2.83	2.93	4.87	5.01	5.13	5.24
142-N120-A0	1.27	3.61	3.61	3.61	3.61	6.18	6.18	6.18	6.18
142-N120-A0.2	1.27	3.43	3.47	3.49	3.52	6.01	6.04	6.08	6.12
142-N120-A0.4	1.27	3.16	3.24	3.31	3.37	5.75	5.84	5.92	6.00
142-N120-A0.6	1.27	2.91	3.03	3.12	3.22	5.54	5.68	5.79	5.89
142-N150-A0	1.28	4.03	4.03	4.03	4.03	7.11	7.11	7.11	7.11
142-N150-A0.2	1.28	3.87	3.89	3.92	3.94	6.95	6.98	7.02	7.05
142-N150-A0.4	1.28	3.62	3.67	3.75	3.81	6.70	6.79	6.87	6.95
142-N150-A0.6	1.28	3.40	3.50	3.59	3.68	6.49	6.64	6.75	6.85
202-N100-A0	1.39	3.05	3.05	3.05	3.05	5.27	5.27	5.27	5.27
202-N100-A0.2	1.39	2.86	2.90	2.92	2.95	5.04	5.07	5.11	5.14
202-N100-A0.4	1.39	2.56	2.66	2.72	2.78	4.71	4.79	4.87	4.94
202-N100-A0.6	1.39	2.26	2.39	2.48	2.53	4.36	4.47	4.57	4.66
202-N120-A0	1.39	3.23	3.23	3.23	3.23	5.72	5.72	5.72	5.72
202-N120-A0.2	1.39	3.05	3.09	3.11	3.13	5.50	5.53	5.56	5.60
202-N120-A0.4	1.39	2.75	2.85	2.91	2.97	5.18	5.25	5.33	5.40
202-N120-A0.6	1.39	2.46	2.58	2.68	2.77	4.88	4.99	5.08	5.17
202-N150-A0	1.45	3.49	3.49	3.49	3.49	6.41	6.41	6.41	6.41
202-N150-A0.2	1.45	3.32	3.35	3.37	3.39	6.21	6.23	6.27	6.30
202-N150-A0.4	1.45	3.04	3.11	3.18	3.24	5.90	5.97	6.05	6.15
202-N150-A0.6	1.45	2.75	2.86	2.96	3.05	5.64	5.75	5.84	5.92
302-N100-A0	1.98	5.40	5.40	5.40	5.40	9.56	9.56	9.56	9.56
302-N100-A0.2	1.98	5.03	5.09	5.15	5.22	8.99	9.07	9.12	9.18
302-N120-A0	1.96	5.66	5.66	5.66	5.66	10.00	10.00	10.00	10.00
302-N120-A0.2	1.96	5.27	5.33	5.40	5.47	9.64	9.70	9.75	9.81
302-N120-A0.4	1.96	4.83	4.87	5.00	5.15	9.11	9.19	9.24	9.36
302-N150-A0	1.99	6.04	6.04	6.04	6.04	11.14	11.14	11.14	11.14
302-N150-A0.2	1.99	5.67	5.73	5.80	5.87	10.68	10.74	10.80	10.84
302-N150-A0.4	1.99	5.07	5.24	5.40	5.55	10.04	10.19	10.31	10.42



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

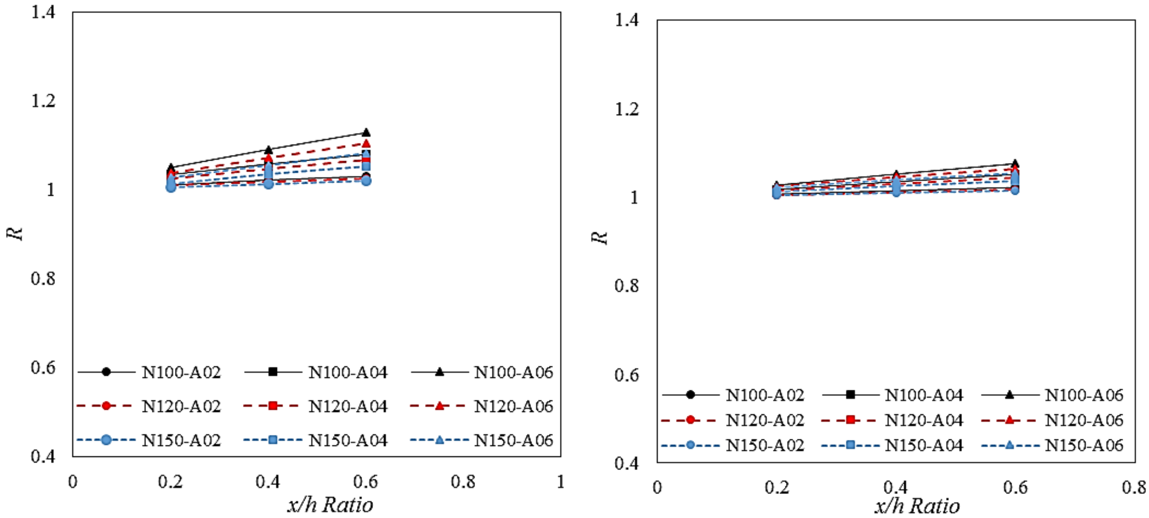
Fig. 4 Variation in reduction factors with *a/h* ratio for C142 section with centered web opening



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

Fig. 5 Variation in reduction factors with N/h for C142 section with centred web opening

Fig. 4 shows the ratio of the circular web opening depth to the flat portion of the web (*a/h)* versus the strength reduction factor, for the three stainless steel grades. As can be seen, the reduction in strength increases as the parameter *a/h* increases for all three stainless steels, in particular for the ferritic grade with lower thickness (1.3mm). The reduction in strength of the ferritic grade 6 mm thick section is smallest and the reduction in strength increases as the section becomes thinner. It can be seen that when the *a/h* ratio increases from 0.2 to 0.6, the reduction in strength for the ferritic grade increases by 28%.



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

Fig. 6 Variation in reduction factors with x/h for C142 section with offset web opening

Fig. 5 shows the ratio of the bearing length to the flat portion of the web (*N/h)* versus the strength reduction factor, for the three stainless steel grades. As can be seen, the reduction in strength is not sensitive to the ratio *N/h* and the 6 mm thick sections have the smallest reduction in strength or the highest strength reduction factor.

Fig. 6 shows the ratio of the circular web hole location to the flat portion of the web (*x/h)* versus the strength reduction factor, for the three stainless steel grades. As can be seen, the reduction in strength is sensitive to the horizontal distance of the web openings to the bearing plates. As the ratio of *x/h* decreases from 0.6 to 0.2, the strength reduction factor decreases by 7%. Also, it can again be seen that the reduction in strength is less for the austenitic grade compared to that of the other two stainless steel grades.

4. PROPOSED STRENGTH REDUCTION FACTORS

Tables 2 to 4 show 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,

$$R_p = 0.97 - 0.59(\frac{a}{h}) + 0.01(\frac{N}{h}) \leq 1 \quad (1)$$

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

$$R_p = 1.02 - 0.76(\frac{a}{h}) + 0.09(\frac{N}{h}) \leq 1 \quad (2)$$

For offset web opening:
For the case where the flange is unfastened to the bearing plate,

$$R_p = 0.93 + 0.03(\frac{a}{h}) + 0.05(\frac{x}{h}) \le 1 \quad (3)$$

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

$$R_p = 0.98 + 0.02(\frac{a}{h}) + 0.01(\frac{x}{h}) \le 1 \quad (4)$$

The limits for the reduction factor equations (1), (2), (3) and (4) are $h/t \le 157.68$, $N/t \le 120.97$, $N/h \le 1.15$, and $\theta = 90^o$.

5. Comparison of numerical results with proposed reduction factors

For the duplex stainless steels grades, 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) to (4). The results for C142, C202 and C302 are shown in Fig. 7. In order to evaluate the accuracy of proposed equations, extensive statistical reliability analyses are performed. The results are summarized in Table 5. 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 North American Specification (NAS, 2007). The load combination of 1.2DL + 1.6LL as specified in the NAS specification was used in the reliability analysis, where DL is the dead load and LL is the live load. In this study, M_m= 1.10 and V_M= 0.10, which are the mean and coefficients of variation for the material properties factors, F_m= 1.00 and V_F= 0.05, which are the mean and coefficients of variation for the fabrication factors, and V_q= 0.21, which is the coefficient of variation of load effect were used. According to the NAS specification, design rules are reliable if the reliability index is more than 2.5. As can be seen in Table 8, 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.

Table 5: 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	108	108	81	81
Mean, P_m	1.00	1.00	1.00	1.00
Coefficient of variation, V_p	0.10	0.13	0.02	0.01
Reliability index, β	2.62	2.51	2.84	2.85
Resistance factor, ϕ	0.85	0.85	0.85	0.85

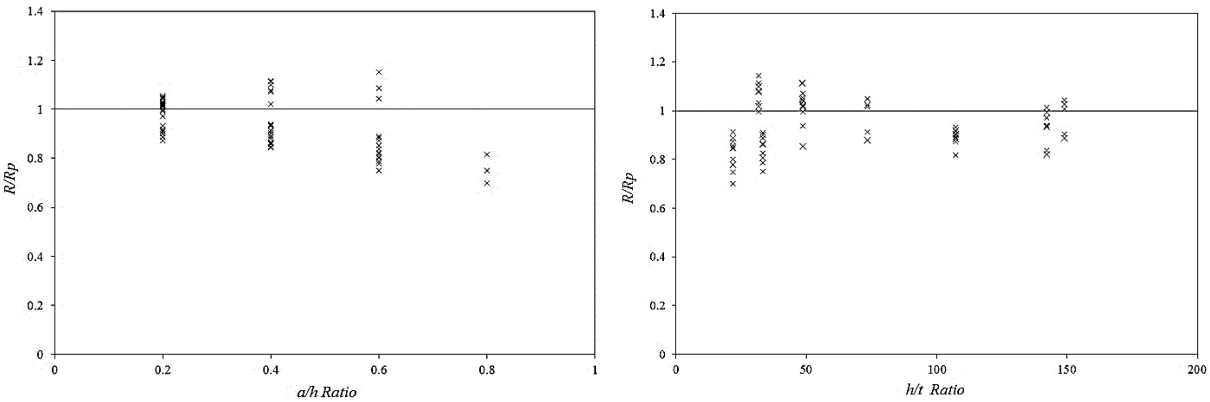


Fig. 7 Comparison of strength reduction factor for centred web opening where flange fastened to bearing plates

For example, for the centred circular web opening, the mean value of the web crippling reduction factor ratios are 1.00 and 1.00 for the cases of flanges unfastened and flanges fastened to the bearing plates, respectively. The corresponding values of COV are 0.10 and 0.13, respectively. Similarly, the reliability index values (β) are 2.62 and 2.51, respectively. For the offset circular web opening, the mean value of the web crippling reduction factor ratios are 1.00 and 1.00 for the cases of flanges unfastened and flanges fastened to the bearing plates, respectively. The corresponding values of COV are 0.02 and 0.01, respectively. Similarly, the reliability index values (β) are 2.84 and 2.85, 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 channels under end-two-flange (ETF) loading.

6. CONCLUSIONS

In this paper, the effect of web openings on the end-two-flange (ETF) loading condition of cold-formed stainless steel lipped channel-sections was investigated for duplex grade EN 1.4462. 730 non-linear elasto-plastic finite element analyses were conducted with different sizes of channel-section and openings. 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 (ϕ=0.85).

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