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Cold-formed ferritic stainless steel unlipped channels with web openings subjected to web crippling under interior-two-flange loading condition-part II: parametric study and design equations

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Abstract: A parametric study of unlipped cold-formed ferritic stainless steel sections with circular web openings subjected to web crippling under interior-two-flange (ITF) loading condition is undertaken, using quasi-static finite element analysis, to investigate the effects of web openings and cross-sections sizes. The circular web openings are located either centred or offset to the bearing plates. The strengths obtained from reduction factor equations are first compared to strengths calculated from equations recently proposed for cold-formed stainless steel lipped channel-sections. It is demonstrated that the strength reduction factor equations previously proposed for cold-formed stainless steel lipped channel-sections can be unconservative for cold-formed ferritic stainless steel unlipped channel-sections by up to 10%. Design recommendations in the form of web crippling strength reduction factor equations are proposed, which are conservative when compared to the both experimental and finite element results.

Keywords: Cold-formed ferritic stainless steel; Design recommendations; Reduction factor; Unlipped channel section; Web crippling; Web opening.

Nomenclature

A	Web openings ratio;
a	Diameter of circular web openings;
b_f	Overall flange width of section;
COV	Coefficient of variation;
d	Overall web depth of section;
DL	Dead load;
E	Young’s modulus of elasticity;
FEA	Finite element analysis;
F_m	Mean value of fabrication factor;
h	Depth of the flat portion of web;
L	Length of the specimen;
LL	Live load;
M_m	Mean value of material factor;
N	Length of the bearing plates;
P	Experimental and finite element ultimate web crippling load per web;
P_{ASCE}	Nominal web crippling strength obtained from American Standard;
P_{Euro}	Nominal web crippling strength obtained from European Code;
P_{EXP}	Experimental ultimate web crippling load per web;
P_{FEA}	Web crippling strength per web predicted from finite element (FEA);
$P_{\mathrm{AS/NZS}}$	Nominal web crippling strength obtained from AS/NZ Standard;
P_m	Mean value of tested-to-predicted load ratio;
R	Reduction factor;
R_{P}	Proposed reduction factor;
r_{i}	Inside corner radius of section;

t	Thickness of section;
V_F	Coefficient of variation of fabrication factor;
V_M	Coefficient of variation of material factor;
V_P	Coefficient of variation of tested-to-predicted load ratio;
x	Horizontal clear distance of the web openings to the near edge of the bearing plates;
X	Web openings distance ratio;
θ	Angle between web and bearing surface
β	Reliability index;
ϕ	Resistance factor.

1 Introduction

The design specifications for cold-formed stainless steel structural members can be found in the American Society of Civil Engineers Specification [1], the Australian/New Zealand Standard [2] and the European Code Design of Steel Structures [3]. However, the aforementioned specifications provide design rules for cold-formed stainless steel channel sections without web openings; only in the case of the North American Specification (NAS) [4] are reduction factors for web crippling with web openings presented.

Using the results of finite element analyses, the Authors have recently proposed unified 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 loading conditions covering three different stainless steel grades: duplex grade EN 1.4462; austenitic grade EN 1.4404 and ferritic grade EN 1.4003 [5-9]. The finite element models were validated against the results of experimental tests conducted on cold-formed carbon steel [10-17]. Unlipped channel-sections, however, were not considered, and no experimental tests were conducted. This paper both addresses these issues.

In the literature, for the web crippling strength of cold-formed stainless steel sections, Krovink and van den Berg [18] and Krovink *et al.* [19] considered lipped channel-section without openings. Zhou and Young [20-23] considered the web crippling strength of cold-formed stainless steel tubular sections, again without openings. Research by Lawson *et al.* [24], 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 *et al.* [25] and Keerthan and Mahendran [26] considered the web crippling strength of hollow flange channel beams, again without openings. Sundararajah *et al.* [27] and Gunalan and Mahendran [28] have considered a Direct Strength Method approach for the web crippling strength of channel sections, again without openings. More recent work has included that of Natario *et al.* [29] and Chen *et al.* [30], all without openings.

Experimental and numerical investigations have been discussed in the companion paper [31]. In this study, non-linear quasi-static finite element analysis (FEA) is used to conduct parametric studies to investigate the effect of circular web openings; as shown in Fig. 1, these web openings are either centred or offset to the bearing plates. The cases of both flanges unfastened and fastened to the bearing plates are considered. The general purpose finite element program ABAQUS [32] is used for the numerical investigation. Based on the test data found in the companion paper [31], and the numerical results obtained from this study, an extensive statistics analysis is performed. For cold-formed stainless steel unlipped channel-sections with circular web openings, design recommendations in the form of web crippling strength reduction factor equations are proposed, that are conservative to both the experimental and finite element results.

2 Experimental investigation

Yousefi *et al.* [31] conducted a test programme on cold-formed ferritic stainless steel unlipped channel sections with web openings subjected to web crippling under ITF loading condition, as shown in Fig. 2. The cases of both flanges fastened and flanges unfastened to the bearing 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 openings was varied in order to investigate the effect of the web openings on the web crippling strength. Circular web openings 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 openings to the depth of the flat portion of the webs (a/h) was kept constant 0.4. All test specimens were fabricated with web openings located at the mid-depth of the webs and centred to the bearing plates or with a horizontal clear distance to the near edge of the bearing plates (x), as shown in Fig. 1. The test data reported in the companion paper [31] are used in this paper for the development of web crippling strength reduction factor equations.

3 Numerical Investigation

The non-linear general purpose finite element program ABAQUS [32] was used to simulate the web crippling behaviour of the unlipped channel sections with and without web openings subjected to web crippling. The bearing plates, the channel sections with circular web openings and the contact interfaces between the bearing plates and the channel section were modelled. The details of the FEM are described in the companion paper [31]. 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 [32] 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 [32]. Finite element mesh sizes were 5 mm × 5 mm for the cold-formed stainless steel channel sections and 8 mm × 8 mm for the bearing plates. The bearing plates, the channel section with circular web openings and the interfaces between the bearing plates and the channel section have been modelled. Contact surfaces were defined between the bearing plates and the cold-formed stainless steel section.

4 Parametric Study

The finite element model developed closely predicted the experimental ultimate loads, failure modes and post-buckling behaviour of the channel sections with and without circular web openings subjected to web crippling under ITF loading condition [31]. Using these models, parametric studies were carried out to study the effects of web openings and cross-section sizes on the web crippling strengths of channel sections subjected to web crippling. The cases of both flanges fastened and flanges unfastened to the bearing plates were considered. The web openings were located at the mid-depth of the webs and centred to the bearing plates or with a horizontal clear distance to the near edge of the bearing plates.

The web crippling strength predicted was influenced primarily by the ratio of the 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 opening as defined by the distance of the web opening from the edge of the bearing plates divided by the flat portion of the web. In order to find the effect of a/h, N/h and x/h on the web crippling strength of channel sections with web openings, parametric studies were carried out considering the web openings, different bearing plates lengths, the cross-section sizes and location of the web openings.

The specimens consisted of three different section sizes, having thicknesses (t) ranging from 1.02 mm to 6.0 mm and web slenderness (h/t) values ranging from 27.72 to 246.58. The ratios of the diameter of the 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 50 mm, 75 mm and 100 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 material properties obtained from the coupon tests as presented in the companion paper [31] were used in the finite element models in the parametric study. In Tables 1 to 6, the specimens were labelled such that the nominal dimension of the specimen and the length of the bearing as well as the ratio of the diameter of the web openings to the depth of the flat portion of the webs (a/h) could be identified from the label. Details of the specimens labelling are described in the companion paper [31].

For the centred web opening, a total of 270 specimens was analysed in the parametric study investigating the effect of the ratios of *a/h* and *N/h*. The cross-section dimensions as well as the web crippling strengths (P_{FEA}) per web predicted from the FEA are summarised in Tables 1 and 2 for flanges unfastened and fastened condition, respectively.

The effect of the ratios of *a/h* and *N/h* on the reduction factor of the web crippling strength is shown in Figs. 3 and 4 for the C175 specimen. It is seen from Fig. 3(a) that as the parameter *a/h* increases from 0.2 to 0.8, the strength reduction factor decreases. From Fig. 3(b), it can be seen that the reduction in strength is slightly less for the flanges fastened case, compared to the flanges unfastened case. From Fig. 4(a), it can be seen that the reduction in strength is not sensitive to the ratio *N/h*; also, as the parameter *a/h* increases the reduction in strength decreases. From Fig 4(b), it can be seen that for the flanges fastened case that there is almost no reduction in strength for a ratio of *N/h* of unity.

For the offset web opening, a total of 630 specimens was analysed in the parametric study investigating the effect of *a/h* and *x/h*. The cross-section dimensions as well as the web crippling strengths (P_{FEA}) per web predicted from the FEA are summarised in Tables 3 to 6.

The effect of the ratios *a/h* and *x/h* on the reduction factor of the web crippling strength is shown in Figs. 5 and 6 for the C175 specimen. From Fig. 5(a), as can be expected, as the parameter *a/h* increases from 0.2 to 0.8, the strength reduction factor decreases. From Fig. 5(b), it can be again be seen that the reduction in strength is slightly less for the flanges fastened case, compared to the flanges unfastened case. From Fig. 6 (a) it can be seem that the reduction in strength is more sensitive to the ratio *x/h*. The reduction in strength can also be seen to be sensitive to the ratio of *a/h*. From Fig. 6(b), it can again be seen that the reduction in strength is slightly less for the flanges fastened case, compared to the flanges unfastened case.

5 Reliability analysis

The reliability of the cold-formed steel section design rules is evaluated using reliability analysis. The reliability index (β) is a relative measure of the safety of the design. A target reliability index of 2.5 for cold-formed steel structural members is recommended as a lower limit in the NAS Specification [4]. The design rules are considered to be reliable if the reliability index is greater than or equal to 2.5. The load combination of 1.2DL + 1.6LL as specified in the American Society of Civil Engineers Standard [33] was used in the reliability analysis, where DL is the dead load and LL is the live load. The statistical parameters are obtained from Table F1 of the NAS Specification [4] for compression members, where M_m = 1.10, F_m = 1.00, V_M = 0.10, and V_F = 0.05, which are the mean values and coefficients of variation for material properties and fabrication factors.

The statistical parameters P_m and V_P are the mean value and coefficient of variation of load ratio are shown in Table 10 to Table 13, respectively. In calculating the reliability index, the correction factor in the NAS Specification was used. Reliability analysis is detailed in the NAS Specification [4]. In the reliability analysis, a constant resistance factor (ϕ) of 0.85 was used. It is shown that the reliability index (β) is greater than the target value of 2.5 as shown in Table 10 to Table 13.

6 Comparison of the experimental and numerical results with current design strengths for cold-formed stainless steel sections without web openings

As mentioned earlier, the current cold-formed stainless steel design standards [1-3] do not provide design recommendations for cold-formed stainless steel sections with web openings subjected to web crippling under ITF loading conditions, where the web opening is located centred and offset to bearing plates. However, the web crippling strengths for sections without web openings, from tests and FEA results, can be compared with the web crippling strengths obtained from design codes.

For the case of flanges unfastened to the bearing plates, Table 7 shows the comparison of web crippling strength with design strength for the ITF loading condition. The current design standard Eurocode design strength does not consider *h/t* ratios greater than 200. In the Australian/New Zealand Standard and Eurocode comparison, the mean values of the ratios are 0.8 and 0.91 with the corresponding coefficients of variation (COV) of 0.13 and 0.12, respectively.

For the case of flanges fastened to the bearing plates, Table 8 shows the comparison of web crippling strength with design strength for the ITF loading condition. The American Standard and Eurocode provide unreliable web crippling strengths predictions for the case of flanges fastened. A comparison of these values with the corresponding experimental and numerical values indicates that although the American Standard and Eurocode values are lower bound, they are about 32% lower than the experimental and numerical failure loads. It is noted that American Standard and Eurocode are too conservative for the web crippling strengths of cold-formed stainless steel unlipped channel-sections without web openings. For the Australian/New Zealand Standard comparison, the mean values of ratio are 1.04 with the corresponding coefficients of variation (COV) of 0.3. It is noted that design equations are generally unconservative for the unfastened case, however, for the fastened case, the comparison shows design equations are generally too conservative.

7 Reduction factor comparison with Yousefi *et al.* [8] for lipped cold-formed stainless steel section with web openings

As mentioned earlier, Yousefi *et al.* [8] provides strength reduction factor equations for circular web openings located at the mid-depth of the webs and centred to the bearing plates or with a horizontal clear distance to the near edge of the bearing plates. The web crippling strength predicted from test and numerical results were compared with the web crippling strength obtained from Yousefi *et al.* [8].

The equations proposed by Yousefi *et al.* [8] are summarised below:

For centred web opening:

Free case $$R_P = 0.87 - 0.35(\frac{a}{h}) + 0.12(\frac{N}{h}) \leq 1 \qquad (1)$$

Fixed case $$R_P = 0.86 - 0.37(\frac{a}{h}) + 0.27(\frac{N}{h}) \leq 1 \qquad (2)$$

For offset web opening:

Free case $$R_P = 0.91 - 0.17(\frac{a}{h}) + 0.16(\frac{x}{h}) \leq 1 \qquad (3)$$

Fixed case: $$R_P = 0.85 - 0.33(\frac{a}{h}) + 0.21(\frac{x}{h}) \leq 1 \qquad (4)$$

where the limits for the reduction factor in equations (1), (2), (3) and (4) are $h/t \leq 157.68$, $N/t \leq 120.97$, $N/h \leq 1.15$, $a/h \leq 0.8$, and $\theta = 90^{\circ}$.

Table 9 compares of the web crippling strength with that of Yousefi *et al.* [8] for sections with web openings located centred and offset to bearing plates, for both cases of flanges unfastened and fastened to the bearing plates. As can be seen, the equations are generally unconservative especially for the case of the centred web opening with flanges unfastened to bearing plates. The value of P_m is 1.10 with a corresponding COV of 0.04; the design strengths obtained from Yousefi *et al.* [8] for cold-formed stainless steel lipped channel-sections are unconservative for cold-formed ferritic stainless steel unlipped channel-sections by up to 10%. However, as noted previously, the equations proposed by Yousefi *et al.* [8] were for cold-formed stainless steel lipped channel-sections with different grades of stainless steels.

8 Comparison of the experimental and numerical results with current design strengths for cold-formed stainless steel sections with web openings

As mentioned earlier, the current cold-formed stainless steel design standards [1-3] do not provide design recommendations for both lipped and unlipped cold-formed stainless steel sections with web openings subjected to web crippling under ITF loading conditions, where the web opening is located either centred or offset to bearing plates. However, the North American Specification (NAS) [4] provides design rules for cold-formed carbon steel channel-section with web openings under one flange loading. However, the design rules are only for sections with web opening located at the mid-height of the specimen having a horizontal clear distance to the near edge of the bearing plate and for only the case of flange fastened to the bearing plate.

In accordance with NAS [4], for sections with offset web openings under interior-one-flange loading, for the case of the flange fastened to the bearing plate,

$$R = 0.9 - 0.047\frac{a}{h} + 0.053\frac{x}{h} \leq 1.0 \tag{5}$$

where the limits for the reduction factor equation (5) are $N \geq 76$ mm, $h/t \leq 200$, $a/h \leq 0.7$, clear distance between web openings ≥ 457 mm, distance between end of member and edge of web openings $\geq d$, $a \leq 152$mm and $\theta=90^{\circ}$.

Furthermore, for sections with offset web openings under end-one-flange loading, for the case with the flange fastened to the bearing plate,

$$R = 1.01 - 0.325\frac{a}{h} + 0.083\frac{x}{h} \leq 1.0 \tag{6}$$

where the limits for the reduction factor equation (6) are $N \geq 25$ mm, $h/t \leq 200$, $a/h \leq 0.7$, clear distance between holes ≥ 457 mm, distance between end of member and edge of holes $\geq d$, $a \leq 152$mm and $\theta=90^{\circ}$.

In Section 10 of this paper, four new strength reduction factor equations are proposed. These covered the ITF loading condition for centred and offset web opening, for the case of both flanges unfastened and fastened to the bearing plates.

9 Proposed strength reduction factors

Comparing the failure loads of the channel sections having web openings with that of sections without web openings, as shown in Tables 1 to 6, it can be see that, as expected, the failure load decreases as the size of the web openings increases. It can also be seen that the failure load increases slightly as the length of the bearing plates increases and the distance of the web openings 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 openings. 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 interior-two-flange loading condition for the centred web opening and offset web opening, respectively.

For centred web opening:

For the case where the flanges are unfastened to the bearing plates,

$$R_p = 0.98 - 0.65(\frac{a}{h}) + 0.07(\frac{N}{h}) \le 1 \qquad (7)$$

For the case where the flanges are fastened to the bearing plates,

$$R_p = 0.99 - 0.04(\frac{a}{h}) + 0.03(\frac{N}{h}) \le 1 \qquad (8)$$

For offset web opening:

For the case where the flanges are unfastened to the bearing plates,

$$R_p = 0.94 - 0.62(\frac{a}{h}) + 0.21(\frac{x}{h}) \le 1 \qquad (9)$$

For the case where the flanges are fastened to the bearing plates,

$$R_p = 0.94 - 0.48(\frac{a}{h}) + 0.26(\frac{x}{h}) \le 1 \qquad (10)$$

The limits for the reduction factor equations (7), (8), (9) and (10) are $h/t \leq 200$, $N/t \leq 90.09$, $N/h \leq 0.61$, $a/h \leq 0.8$, and $\theta = 90°$.

10 Comparison of experimental and numerical results with the proposed reduction factor

The values of the strength reduction factor (R) obtained from the experimental and the numerical results are compared with the values of the proposed strength reduction factor (R_p) calculated using Eqs. (7), (8), (9) and (10), as plotted against the ratios a/h and h/t in Figs. 7 to 10, for flanges unfastened and fastened cases, respectively. Tables 10 to 13 summarize a statistical analysis to define the accuracy of the proposed design equations. It is shown that the proposed reduction factors are generally conservative and agree with the experimental and the numerical results for both cases.

For the centred web opening, the mean value of the web crippling reduction factor ratios are 1.01 and 1.00 for the case of flanges unfastened and fastened to the bearing plates, respectively. The corresponding values of COV of 0.05 and 0.04, respectively; similarly, the reliability index values (β) are of 2.83 and 2.81, respectively.

For the offset web opening, the mean value of the web crippling reduction factor ratios are 1.00 and 1.00 for the case of flanges unfastened and fastened to the bearing plates, respectively. The corresponding values of COV of 0.11 and 0.08, respectively; similarly, the reliability index values (β) are of 2.61 and 2.69, respectively. Thus, the proposed strength reduction factor equations are able to predict the influence of the web openings on the web crippling strengths of channel sections for the ITF loading condition.

11 Conclusions

A parametric study of cold-formed stainless steel unlipped channel sections having circular web openings subjected to interior-two-flange (ITF) web crippling loading condition, where circular web openings are located at the either centred or offset to the bearing plates, have been presented. Non-linear finite element models were used in the parametric study, which has been verified against the test results. Evaluation of the experimental and the numerical results show that the ratio a/h, N/h and x/h are the primary parameters that influence the web crippling behaviour of the sections with web openings. In order to determine the effect of the ratio a/h, N/h and x/h on the web crippling strength, parametric studies were carried out considering the web openings, the cross-section sizes and the different bearing plates lengths.

The web crippling strengths of cold-formed stainless steel unlipped channel sections without web openings obtained from test and finite element analysis were compared with the current design strengths calculated from American Society of Civil Engineers Specification [1], the Australian/New Zealand Standard [2] and the European Code Design of Steel Structures [3]. The American Society of Civil Engineers Specification and European Code Design of Steel Structures underestimate the web crippling strengths by around 32%; the Eurocode design strength does not consider h/t ratios greater than 200. The American Standard is over conservative for the web crippling strengths of cold-formed stainless steel unlipped channel sections without web openings.

Only Yousefi *et al.* [8] provides a reduction factor equation for stainless steel lipped channel-sections with the case of circular web openings located either centred or offset to the bearing plates for the cases of flanges unfastened and fastened to the bearing plates. However, the reduction factor equations obtained from Yousefi *et al.* [8] were shown to be unconservative for cold-formed ferritic stainless steel unlipped channel-sections by up to 10%. However, as noted previously, the equations that Yousefi *et al.* [8] proposed are for lipped channel-sections and not unlipped channel-sections. In this paper, strength reduction factor equations are proposed for stainless steel channel-sections without lipped flanges covering different parameters. Openings are located either centred or offset to the bearing plates.

Based on 54 test results and 900 numerical results, four new web crippling strength reduction factor equations were proposed for the ITF loading condition for the cases of both flanges unfastened and flanges fastened to the bearing plates. Reliability analysis was performed to evaluate the reliability of the proposed strength reduction factors. It is shown that the proposed strength reduction factors are generally conservative and agree well with the experimental and numerical results. The proposed strength reduction factors are capable of producing reliable limit state design when calibrated with the resistance factor of 0.85 (ϕ=0.85).

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The Authors declare no potential conflicts of interest with respect to the research, authorship and/or publication of this article.

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List of tables

Table 1 Dimensions and web crippling strengths predicted from finite element analysis in parametric study of *a/h* for centred web opening where flanges unfastened to bearing plates

Specimen	Web	Flange	Thickness	Length	FEA load per web, P_{FEA}				
	d	b_f	t	L	A0	A0.2	A0.4	A0.6	A0.8
	(mm)	(mm)	(mm)	(mm)	(kN)	(kN)	(kN)	(kN)	(kN)
175x60-t1.2-N50-FR	178.63	60.13	1.13	576.00	4.16	4.00	3.65	3.11	2.12
175x60-t4.0-N50-FR	178.63	60.13	4.00	576.00	67.03	61.28	52.77	43.85	35.58
175x60-t6.0-N50-FR	178.63	60.13	6.00	576.00	135.73	125.32	107.67	90.42	73.33
175x60-t1.2-N75-FR	178.56	60.04	1.12	600.67	4.31	4.15	3.78	3.18	2.19
175x60-t4.0-N75-FR	178.56	60.04	4.00	600.67	69.27	64.63	56.48	47.14	38.08
175x60-t6.0-N75-FR	178.56	60.04	6.00	600.67	144.78	133.84	114.68	97.38	80.6
175x60-t1.2-N100-FR	178.49	60.10	1.12	625.67	4.49	4.32	3.93	3.31	2.35
175x60-t4.0-N100-FR	178.49	60.10	4.00	625.67	72.93	68.31	60.11	50.11	40.67
175x60-t6.0-N100-FR	178.49	60.10	6.00	625.67	151.45	138.91	122.87	105.39	88.32
200x75-t1.2-N50-FR	203.86	74.99	1.09	650.00	3.52	3.39	3.11	2.76	1.87
200x75-t4.0-N50-FR	203.86	74.99	4.00	650.00	68.76	62.79	53.84	44.22	35.76
200x75-t6.0-N50-FR	203.86	74.99	6.00	650.00	140.57	131.64	112.97	94.42	76.77
200x75-t1.2-N75-FR	203.44	75.02	1.08	675.67	3.65	3.52	3.22	2.80	1.92
200x75-t4.0-N75-FR	203.44	75.02	4.00	675.67	70.89	65.95	57.37	47.37	38.00
200x75-t6.0-N75-FR	203.44	75.02	6.00	675.67	150.99	138.06	119.41	100.70	82.90
200x75-t1.2-N100-FR	203.64	74.99	1.12	700.33	4.16	4.01	3.67	3.16	2.20
200x75-t4.0-N100-FR	203.64	74.99	4.00	700.33	74.01	69.07	60.36	49.78	39.87
200x75-t6.0-N100-FR	203.64	74.99	6.00	700.33	156.29	143.89	126.14	107.23	89.12
250x100-t1.2-N50-FR	253.55	100.16	1.02	800.67	2.51	2.42	2.25	2.03	1.52
250x100-t4.0-N50-FR	253.55	100.16	4.00	800.67	69.95	64.38	54.63	44.06	34.73
250x100-t6.0-N50-FR	253.55	100.16	6.00	800.67	145.04	134.46	118.41	97.74	79.17
250x100-t1.2-N75-FR	255.03	100.15	1.09	825.67	3.10	2.94	2.78	2.49	1.84
250x100-t4.0-N75-FR	255.03	100.15	4.00	825.67	71.95	66.71	57.55	46.67	36.51
250x100-t6.00-N75-FR	255.03	100.15	6.00	825.67	157.77	145.10	124.41	102.88	84.04
250x100-t1.2-N100-FR	253.50	99.93	1.11	849.50	3.39	3.27	3.04	2.72	1.98
250x100-t4.0-N100-FR	253.50	99.93	4.00	849.50	74.88	68.64	59.62	47.92	37.72
250x100-t6.0-N100-FR	253.50	99.93	6.00	849.50	161.18	149.56	125.56	108.40	88.75

Table 2 Dimensions and web crippling strengths predicted from finite element analysis in parametric study of *a/h* for centred web opening where flanges fastened to bearing plates

Specimen	Web	Flange	Thickness	Length	FEA load per web, P_{FEA}				
	d	b_f	t	L	A0	A0.2	A0.4	A0.6	A0.8
	(mm)	(mm)	(mm)	(mm)	(kN)	(kN)	(kN)	(kN)	(kN)
175x60-t1.2-N50-FX	178.40	60.17	1.13	575.00	6.52	6.21	5.48	4.36	3.15
175x60-t4.0-N50-FX	178.40	60.17	4.00	575.00	75.52	73.89	65.82	55.92	45.11
175x60-t6.0-N50-FX	178.40	60.17	6.00	575.00	149.45	145.8	127.86	108.22	84.39
175x60-t1.2-N75-FX	178.30	60.09	1.14	600.00	6.79	6.44	5.71	4.59	3.4
175x60-t4.0-N75-FX	178.30	60.09	4.00	600.00	87.83	84.23	72.8	62.25	50.2
175x60-t6.0-N75-FX	178.30	60.09	6.00	600.00	174.15	162.25	139.28	120.41	96.14
175x60-t1.2-N100-FX	178.43	59.99	1.14	625.67	6.94	6.57	5.86	4.76	3.6
175x60-t4.0-N100-FX	178.43	59.99	4.00	625.67	94.05	87.67	77.72	66.76	54.84
175x60-t6.0-N100-FX	178.43	59.99	6.00	625.67	190.26	172.47	152.07	133.38	112.53
200x75-t1.2-N50-FX	203.68	75.05	1.13	650.00	6.32	6.05	5.47	4.39	3.02
200x75-t4.0-N50-FX	203.68	75.05	4.00	650.00	76.28	75.15	65.91	58.39	46.67
200x75-t6.0-N50-FX	203.68	75.05	6.00	650.00	150.97	148.98	130.03	114.04	88.52
200x75-t1.2-N75-FX	203.63	75.49	1.14	675.67	6.63	6.33	5.71	4.59	3.25
200x75-t4.0-N75-FX	203.63	75.49	4.00	675.67	89.75	89.29	76.02	64.08	51.18
200x75-t6.0-N75-FX	203.63	75.49	6.00	675.67	175.95	170.27	146.46	125.18	99.33
200x75-t1.2-N100-FX	203.61	75.21	1.14	700.33	6.69	6.37	5.77	4.61	3.42
200x75-t4.0-N100-FX	203.61	75.21	4.00	700.33	93.45	87.23	76.69	65.05	52.73
200x75-t6.0-N100-FX	203.61	75.21	6.00	700.33	181.89	167.37	147.5	126.59	102.99
250x100-t1.2-N50-FX	254.17	99.89	1.14	800.00	5.91	5.65	5.21	4.69	3.17
250x100-t4.0-N50-FX	254.17	99.89	4.00	800.00	75.93	75.37	71.04	64.94	54.32
250x100-t6.0-N50-FX	254.17	99.89	6.00	800.00	152.61	151.19	139.88	126.17	102.36
250x100-t1.2-N75-FX	253.87	99.98	1.14	824.33	6.04	5.76	5.33	4.51	3.02
250x100-t4.0-N75-FX	253.87	99.98	4.00	824.33	90.01	89.39	79.14	69.94	51.32
250x100-t6.00-N75-FX	253.87	99.98	6.00	824.33	177.27	176.18	157.82	131.73	103.26
250x100-t1.2-N100-FX	253.55	99.92	1.14	849.67	6.16	5.88	5.45	4.6	3.17
250x100-t4.0-N100-FX	253.55	99.92	4.00	849.67	100.81	94.92	82.03	68.51	54.59
250x100-t6.0-N100-FX	253.55	99.92	6.00	849.67	200.01	194.45	166.19	141.25	112.17

Table 3 Dimensions and web crippling strengths predicted from finite element analysis in parametric study of *a/h* for offset web opening where flanges unfastened to bearing plates

Specimen	Web	Flange	Thickness	Length	FEA load per web, P_{FEA}				
	d	b_f	t	L	A0	A0.2	A0.4	A0.6	A0.8
	(mm)	(mm)	(mm)	(mm)	(kN)	(kN)	(kN)	(kN)	(kN)
175x60-t1.2-N50-FR	178.63	60.13	1.13	576.00	4.16	3.82	3.30	2.75	2.25
175x60-t4.0-N50-FR	178.63	60.13	4.00	576.00	67.03	61.64	53.21	44.50	35.50
175x60-t6.0-N50-FR	178.63	60.13	6.00	576.00	135.73	132.99	117.86	98.98	81.98
175x60-t1.2-N75-FR	178.56	60.04	1.12	600.67	4.31	4.15	3.78	3.18	2.68
175x60-t4.0-N75-FR	178.56	60.04	4.00	600.67	69.27	64.63	56.48	47.14	38.14
175x60-t6.0-N75-FR	178.56	60.04	6.00	600.67	144.78	131.84	114.68	97.38	80.38
175x60-t1.2-N100-FR	178.49	60.10	1.12	625.67	4.49	4.32	3.92	3.30	2.80
175x60-t4.0-N100-FR	178.49	60.10	4.00	625.67	72.93	68.30	60.11	50.10	41.10
175x60-t6.0-N100-FR	178.49	60.10	6.00	625.67	151.44	138.90	122.87	105.37	88.37
200x75-t1.2-N50-FR	203.86	74.99	1.09	650.00	3.52	3.18	2.72	2.27	1.77
200x75-t4.0-N50-FR	203.86	74.99	4.00	650.00	66.39	61.00	52.57	43.86	34.86
200x75-t6.0-N50-FR	203.86	74.99	6.00	650.00	135.09	132.35	117.22	98.34	81.34
200x75-t1.2-N75-FR	203.44	75.02	1.08	675.67	3.65	3.49	3.12	2.52	2.02
200x75-t4.0-N75-FR	203.44	75.02	4.00	675.67	68.61	63.97	55.82	46.48	37.48
200x75-t6.0-N75-FR	203.44	75.02	6.00	675.67	144.12	131.18	114.02	96.72	79.72
200x75-t1.2-N100-FR	203.64	74.99	1.12	700.33	4.16	3.99	3.59	2.97	2.47
200x75-t4.0-N100-FR	203.64	74.99	4.00	700.33	72.6	67.97	59.78	49.77	40.77
200x75-t6.0-N100-FR	203.64	74.99	6.00	700.33	151.11	138.57	122.54	105.04	88.04
250x100-t1.2-N50-FR	253.55	100.16	1.02	800.67	2.51	2.24	1.92	1.57	1.15
250x100-t4.0-N50-FR	253.55	100.16	4.00	800.67	65.38	59.99	51.56	42.85	33.85
250x100-t6.0-N50-FR	253.55	100.16	6.00	800.67	134.08	130.14	114.02	95.12	78.12
250x100-t1.2-N75-FR	255.03	100.15	1.09	825.67	3.1	2.94	2.57	1.97	1.47
250x100-t4.0-N75-FR	255.03	100.15	4.00	825.67	68.06	63.42	55.27	45.93	36.93
250x100-t6.00-N75-FR	255.03	100.15	6.00	825.67	143.57	130.63	113.47	96.17	79.17
250x100-t1.2-N100-FR	253.50	99.93	1.11	849.50	3.39	3.22	2.82	2.2	1.70
250x100-t4.0-N100-FR	253.50	99.93	4.00	849.50	71.83	67.20	59.01	49.00	40.00
250x100-t6.0-N100-FR	253.50	99.93	6.00	849.50	150.34	137.8	121.77	104.27	87.27

Table 4 Dimensions and web crippling strengths predicted from finite element analysis in parametric study of *a/h* for offset web opening where flanges fastened to bearing plates

Specimen	Web	Flange	Thickness	Length	FEA load per web, P_{FEA}				
	d	b_f	t	L	A0	A0.2	A0.4	A0.6	A0.8
	(mm)	(mm)	(mm)	(mm)	(kN)	(kN)	(kN)	(kN)	(kN)
175x60-t1.2-N50-FX	178.40	60.17	1.13	575.00	6.52	6.12	5.43	4.58	3.78
175x60-t4.0-N50-FX	178.40	60.17	4.00	575.00	75.52	74.41	73.82	66.09	58.09
175x60-t6.0-N50-FX	178.40	60.17	6.00	575.00	149.44	148.12	146.3	133.59	116.59
175x60-t1.2-N75-FX	178.30	60.09	1.14	600.00	6.79	6.34	5.71	4.87	4.07
175x60-t4.0-N75-FX	178.30	60.09	4.00	600.00	87.83	86.45	81.98	71.32	63.32
175x60-t6.0-N75-FX	178.30	60.09	6.00	600.00	174.14	172.5	168.44	148.43	131.43
175x60-t1.2-N100-FX	178.43	59.99	1.14	625.67	6.94	6.49	5.87	5.12	4.32
175x60-t4.0-N100-FX	178.43	59.99	4.00	625.67	94.05	91.15	84.33	74.82	66.82
175x60-t6.0-N100-FX	178.43	59.99	6.00	625.67	190.26	187.82	176.42	159.07	142.07
200x75-t1.2-N50-FX	203.68	75.05	1.13	650.00	6.32	5.95	5.33	4.62	3.82
200x75-t4.0-N50-FX	203.68	75.05	4.00	650.00	76.27	75.26	75.73	72.15	64.85
200x75-t6.0-N50-FX	203.68	75.05	6.00	650.00	150.96	149.77	147.83	140.17	126.17
200x75-t1.2-N75-FX	203.63	75.49	1.14	675.67	6.63	6.24	5.60	4.87	4.07
200x75-t4.0-N75-FX	203.63	75.49	4.00	675.67	89.75	88.54	83.57	75.9	67.9
200x75-t6.0-N75-FX	203.63	75.49	6.00	675.67	175.94	174.69	170.34	157.73	141.73
200x75-t1.2-N100-FX	203.61	75.21	1.14	700.33	6.69	6.28	5.68	4.95	4.15
200x75-t4.0-N100-FX	203.61	75.21	4.00	700.33	93.45	88.51	80.11	71.48	63.48
200x75-t6.0-N100-FX	203.61	75.21	6.00	700.33	181.89	175.47	159.2	141.53	124.53
250x100-t1.2-N50-FX	254.17	99.89	1.14	800.00	5.91	5.53	4.96	4.54	3.99
250x100-t4.0-N50-FX	254.17	99.89	4.00	800.00	75.92	74.87	73.12	69.35	63.35
250x100-t6.0-N50-FX	254.17	99.89	6.00	800.00	151.66	150.52	149.92	145.04	132.04
250x100-t1.2-N75-FX	253.87	99.98	1.14	824.33	6.04	5.66	5.08	4.48	3.68
250x100-t4.0-N75-FX	253.87	99.98	4.00	824.33	90	88.89	84.12	77.28	69.28
250x100-t6.00-N75-FX	253.87	99.98	6.00	824.33	177.26	176.09	175.45	168.32	154.32
250x100-t1.2-N100-FX	253.55	99.92	1.14	849.67	6.16	5.79	5.21	4.6	3.8
250x100-t4.0-N100-FX	253.55	99.92	4.00	849.67	108.81	98.97	88.97	79.24	71.24
250x100-t6.0-N100-FX	253.55	99.92	6.00	849.67	200	198.88	193.86	177.02	160.02

Table 5 Dimensions and web crippling strengths predicted from finite element analysis in parametric study of *x/h* for offset web opening where flanges unfastened to bearing plates

Specimen	Web	Flange	Thickness	Length	FEA load per web, P_{FEA}			
	d	b_f	t	L	X0	X0.2	X0.4	X0.6
	(mm)	(mm)	(mm)	(mm)	(kN)	(kN)	(kN)	(kN)
175x60-t1.2-N50-A0-FR	178.63	60.13	1.13	576.00	4.16	4.16	4.16	4.16
175x60-t1.2-N50-A0.2-FR	178.63	60.13	1.13	576.00	3.8	3.81	3.81	3.82
175x60-t1.2-N50-A0.4-FR	178.63	60.13	1.13	576.00	3.2	3.26	3.29	3.32
175x60-t1.2-N50-A0.6-FR	178.63	60.13	1.13	576.00	2.52	2.65	2.78	2.82
175x60-t1.2-N50-A0.8-FR	178.63	60.13	1.13	576.00	1.69	1.98	2.19	2.33
175x60-t1.2-N75-A0-FR	178.56	60.04	1.12	600.67	4.31	4.31	4.31	4.31
175x60-t1.2-N75-A0.2-FR	178.56	60.04	1.12	600.67	3.96	3.96	3.97	3.98
175x60-t1.2-N75-A0.4-FR	178.56	60.04	1.12	600.67	3.35	3.41	3.45	3.5
175x60-t1.2-N75-A0.6-FR	178.56	60.04	1.12	600.67	2.61	2.78	2.9	3.01
175x60-t1.2-N75-A0.8-FR	178.56	60.04	1.12	600.67	1.82	2.10	2.36	2.51
175x60-t1.2-N100-A0-FR	178.49	60.10	1.12	625.67	4.49	4.49	4.49	4.49
175x60-t1.2-N100-A0.2-FR	178.49	60.10	1.12	625.67	4.14	4.15	4.17	4.18
175x60-t1.2-N100-A0.4-FR	178.49	60.10	1.12	625.67	3.56	3.57	3.64	3.69
175x60-t1.2-N100-A0.6-FR	178.49	60.10	1.12	625.67	2.77	2.93	3.08	3.19
175x60-t1.2-N100-A0.8-FR	178.49	60.10	1.12	625.67	2.00	2.27	2.53	2.72
200x75-t1.2-N50-A0-FR	203.86	74.99	1.09	650.00	3.52	3.52	3.52	3.52
200x75-t1.2-N50-A0.2-FR	203.86	74.99	1.09	650.00	3.23	3.24	3.24	3.25
200x75-t1.2-N50-A0.4-FR	203.86	74.99	1.09	650.00	2.73	2.77	2.8	2.81
200x75-t1.2-N50-A0.6-FR	203.86	74.99	1.09	650.00	2.18	2.26	2.34	2.36
200x75-t1.2-N50-A0.8-FR	203.86	74.99	1.09	650.00	1.48	1.84	1.94	2.08
200x75-t1.2-N75-A0-FR	203.44	75.02	1.08	675.67	3.65	3.65	3.65	3.65
200x75-t1.2-N75-A0.2-FR	203.44	75.02	1.08	675.67	3.29	3.3	3.31	3.32
200x75-t1.2-N75-A0.4-FR	203.44	75.02	1.08	675.67	2.78	2.8	2.83	2.84
200x75-t1.2-N75-A0.6-FR	203.44	75.02	1.08	675.67	2.21	2.28	2.36	2.44
200x75-t1.2-N75-A0.8-FR	203.44	75.02	1.08	675.67	1.53	1.73	1.88	2.01
200x75-t1.2-N100-A0-FR	203.64	74.99	1.12	700.33	4.16	4.16	4.16	4.16
200x75-t1.2-N100-A0.2-FR	203.64	74.99	1.12	700.33	3.83	3.86	3.87	3.89
200x75-t1.2-N100-A0.4-FR	203.64	74.99	1.12	700.33	3.25	3.27	3.32	3.38

200x75-t1.2-N100-A0.6-FR	203.64	74.99	1.12	700.33	2.6	2.7	2.81	2.91
200x75-t1.2-N100-A0.8-FR	203.64	74.99	1.12	700.33	1.83	2.07	2.27	2.42
250x100-t1.2-N50-A0-FR	253.55	100.16	1.02	800.67	2.51	2.51	2.51	2.51
250x100-t1.2-N50-A0.2-FR	253.55	100.16	1.02	800.67	2.31	2.32	2.33	2.34
250x100-t1.2-N50-A0.4-FR	253.55	100.16	1.02	800.67	1.96	1.97	1.98	1.99
250x100-t1.2-N50-A0.6-FR	253.55	100.16	1.02	800.67	1.6	1.62	1.65	1.66
250x100-t1.2-N50-A0.8-FR	253.55	100.16	1.02	800.67	1.15	1.23	1.3	1.33
250x100-t1.2-N75-A0-FR	255.03	100.15	1.07	825.67	2.94	2.94	2.94	2.94
250x100-t1.2-N75-A0.2-FR	255.03	100.15	1.07	825.67	2.7	2.71	2.72	2.73
250x100-t1.2-N75-A0.4-FR	255.03	100.15	1.07	825.67	2.32	2.33	2.34	2.35
250x100-t1.2-N75-A0.6-FR	255.03	100.15	1.07	825.67	1.89	1.92	1.95	1.97
250x100-t1.2-N75-A0.8-FR	255.03	100.15	1.07	825.67	1.38	1.47	1.56	1.6
250x100-t1.2-N100-A0-FR	253.50	99.93	1.11	849.50	3.39	3.39	3.39	3.39
250x100-t1.2-N100-A0.2-FR	253.50	99.93	1.11	849.50	3.11	3.12	3.13	3.14
250x100-t1.2-N100-A0.4-FR	253.50	99.93	1.11	849.50	2.68	2.69	2.7	2.73
250x100-t1.2-N100-A0.6-FR	253.50	99.93	1.11	849.50	2.19	2.23	2.27	2.31
250x100-t1.2-N100-A0.8-FR	253.50	99.93	1.11	849.50	1.59	1.72	1.82	1.88

Table 6 Dimensions and web crippling strengths predicted from finite element analysis in parametric study of *x/h* for offset web opening where flanges fastened to bearing plates

Specimen	Web	Flange	Thickness	Length	FEA load per web, P_{FEA}			
	d	b_f	t	L	X0	X0.2	X0.4	X0.6
	(mm)	(mm)	(mm)	(mm)	(kN)	(kN)	(kN)	(kN)
175x60-t1.2-N50-A0-FX	178.40	60.17	1.13	575.00	6.52	6.52	6.52	6.52
175x60-t1.2-N50-A0.2-FX	178.40	60.17	1.13	575.00	5.90	5.98	6.05	6.12
175x60-t1.2-N50-A0.4-FX	178.40	60.17	1.13	575.00	4.93	5.20	5.38	5.54
175x60-t1.2-N50-A0.6-FX	178.40	60.17	1.13	575.00	3.92	4.34	4.71	4.99
175x60-t1.2-N50-A0.8-FX	178.40	60.17	1.13	575.00	2.95	3.64	4.14	4.52
175x60-t1.2-N75-A0-FX	178.30	60.09	1.14	600.00	6.79	6.79	6.79	6.79
175x60-t1.2-N75-A0.2-FX	178.30	60.09	1.14	600.00	6.17	6.21	6.28	6.36
175x60-t1.2-N75-A0.4-FX	178.30	60.09	1.14	600.00	5.23	5.48	5.67	5.83
175x60-t1.2-N75-A0.6-FX	178.30	60.09	1.14	600.00	4.22	4.67	5.00	5.28
175x60-t1.2-N75-A0.8-FX	178.30	60.09	1.14	600.00	3.37	3.99	4.46	4.81
175x60-t1.2-N100-A0-FX	178.43	59.99	1.14	625.67	6.94	6.94	6.94	6.94
175x60-t1.2-N100-A0.2-FX	178.43	59.99	1.14	625.67	6.29	6.37	6.45	6.52
175x60-t1.2-N100-A0.4-FX	178.43	59.99	1.14	625.67	5.42	5.64	5.81	6.02
175x60-t1.2-N100-A0.6-FX	178.43	59.99	1.14	625.67	4.56	4.90	5.25	5.49
175x60-t1.2-N100-A0.8-FX	178.43	59.99	1.14	625.67	3.69	4.27	4.72	5.04
200x75-t1.2-N50-A0-FX	203.68	75.05	1.13	650.00	6.32	6.32	6.32	6.32
200x75-t1.2-N50-A0.2-FX	203.68	75.05	1.13	650.00	5.77	5.85	5.89	5.95
200x75-t1.2-N50-A0.4-FX	203.68	75.05	1.13	650.00	4.90	5.10	5.26	5.39
200x75-t1.2-N50-A0.6-FX	203.68	75.05	1.13	650.00	3.92	4.32	4.63	4.83
200x75-t1.2-N50-A0.8-FX	203.68	75.05	1.13	650.00	2.76	3.46	3.95	4.31
200x75-t1.2-N75-A0-FX	203.63	75.49	1.14	675.67	6.63	6.63	6.63	6.63
200x75-t1.2-N75-A0.2-FX	203.63	75.49	1.14	675.67	6.06	6.13	6.19	6.25
200x75-t1.2-N75-A0.4-FX	203.63	75.49	1.14	675.67	5.18	5.39	5.56	5.68
200x75-t1.2-N75-A0.6-FX	203.63	75.49	1.14	675.67	4.19	4.60	4.92	5.10
200x75-t1.2-N75-A0.8-FX	203.63	75.49	1.14	675.67	3.16	3.79	4.27	4.62
200x75-t1.2-N100-A0-FX	203.61	75.21	1.14	700.33	6.69	6.69	6.69	6.69
200x75-t1.2-N100-A0.2-FX	203.61	75.21	1.14	700.33	6.13	6.21	6.27	6.32
200x75-t1.2-N100-A0.4-FX	203.61	75.21	1.14	700.33	5.29	5.49	5.66	5.77
200x75-t1.2-N100-A0.6-FX	203.61	75.21	1.14	700.33	3.42	4.74	5.04	5.21

200x75-t1.2-N100-A0.8-FX	203.61	75.21	1.14	700.33	3.22	3.93	4.41	4.81
250x100-t1.2-N50-A0-FX	254.17	99.89	1.14	800.00	5.91	5.91	5.91	5.91
250x100-t1.2-N50-A0.2-FX	254.17	99.89	1.14	800.00	5.38	5.49	5.50	5.53
250x100-t1.2-N50-A0.4-FX	254.17	99.89	1.14	800.00	4.63	4.83	4.92	4.99
250x100-t1.2-N50-A0.6-FX	254.17	99.89	1.14	800.00	3.83	4.14	4.35	4.48
250x100-t1.2-N50-A0.8-FX	254.17	99.89	1.14	800.00	2.62	3.23	3.69	3.94
250x100-t1.2-N75-A0-FX	253.87	99.98	1.14	824.33	6.04	6.04	6.04	6.04
250x100-t1.2-N75-A0.2-FX	253.87	99.98	1.14	824.33	5.52	5.58	5.66	5.75
250x100-t1.2-N75-A0.4-FX	253.87	99.98	1.14	824.33	4.78	4.96	5.06	5.13
250x100-t1.2-N75-A0.6-FX	253.87	99.98	1.14	824.33	3.96	4.30	4.49	4.61
250x100-t1.2-N75-A0.8-FX	253.87	99.98	1.14	824.33	2.79	3.42	3.83	4.08
250x100-t1.2-N100-A0-FX	253.55	99.92	1.14	849.67	6.16	6.16	6.16	6.16
250x100-t1.2-N100-A0.2-FX	253.55	99.92	1.14	849.67	5.66	5.71	5.76	5.79
250x100-t1.2-N100-A0.4-FX	253.55	99.92	1.14	849.67	4.94	5.10	5.19	5.27
250x100-t1.2-N100-A0.6-FX	253.55	99.92	1.14	849.67	4.11	4.45	4.63	4.75
250x100-t1.2-N100-A0.8-FX	253.55	99.92	1.14	849.67	3.08	3.61	3.99	4.28

Table 7 Comparison of experimental and numerical results with design strength for case of flanges unfastened to bearing plates

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	r_i/t	P (kN)	P_{ASCE} (kN)	$P_{AS/NZS}$ (kN)	P_{Euro} (kN)	P/P_{ASCE}	$P/P_{AS/NZS}$	P/P_{Euro}
175x60-t1.2-N50-A0-FR	156.08	44.25	0.28	1.06	4.16	3.67	4.49	4.12	1.13	0.93	1.01
175x60-t4.0-N50-A0-FR	42.66	12.50	0.29	0.30	67.03	71.57	92.58	80.17	0.94	0.72	0.84
175x60-t6.0-N50-A0-FR	27.77	8.33	0.30	0.20	135.73	168.16	219.10	188.35	0.81	0.62	0.72
175x60-t1.2-N75-A0-FR	157.49	66.96	0.43	1.07	4.31	3.68	4.50	4.12	1.17	0.96	1.04
175x60-t4.0-N75-A0-FR	42.66	18.75	0.44	0.30	69.27	72.14	93.32	80.81	0.96	0.74	0.86
175x60-t6.0-N75-A0-FR	27.77	12.50	0.45	0.20	144.78	169.06	220.27	189.36	0.86	0.66	0.76
175x60-t1.2-N100-A0-FR	157.49	89.29	0.57	1.07	4.49	3.78	4.62	4.23	1.19	0.97	1.06
175x60-t4.0-N100-A0-FR	42.66	25.00	0.59	0.30	72.93	72.71	94.06	81.45	1.00	0.78	0.90
175x60-t6.0-N100-A0-FR	27.77	16.67	0.60	0.20	151.45	169.96	221.44	190.36	0.89	0.68	0.80
200x75-t1.2-N50-A0-FR	184.64	45.87	0.25	1.10	3.52	2.89	3.51	3.24	1.22	1.00	1.09
200x75-t4.0-N50-A0-FR	48.86	12.50	0.26	0.30	68.76	70.08	90.60	78.51	0.98	0.76	0.88
200x75-t6.0-N50-A0-FR	31.91	8.33	0.26	0.20	140.57	165.94	216.12	186.17	0.85	0.65	0.76
200x75-t1.2-N75-A0-FR	186.37	69.44	0.37	1.11	3.65	2.88	3.50	3.24	1.27	1.04	1.13
200x75-t4.0-N75-A0-FR	48.86	18.75	0.38	0.30	70.89	70.64	91.33	79.13	1.00	0.78	0.90
200x75-t6.0-N75-A0-FR	31.91	12.50	0.39	0.20	150.99	166.83	217.28	186.86	0.91	0.69	0.81
200x75-t1.2-N100-A0-FR	179.64	89.29	0.50	1.07	4.16	3.32	4.03	3.73	1.25	1.03	1.12
200x75-t4.0-N100-A0-FR	48.86	25.00	0.51	0.30	74.01	71.20	92.05	79.76	1.04	0.80	0.93
200x75-t6.0-N100-A0-FR	31.91	16.67	0.52	0.20	156.29	167.72	218.44	187.86	0.93	0.72	0.83
250x100-t4.0-N50-A0-FR	61.39	12.50	0.20	0.30	69.95	67.08	86.60	75.15	1.04	0.81	0.93
250x100-t6.0-N50-A0-FR	40.26	8.33	0.21	0.20	145.04	161.46	210.12	180.86	0.90	0.69	0.80
250x100-t4.0-N75-A0-FR	61.39	18.75	0.31	0.30	71.95	67.61	87.29	75.75	1.06	0.82	0.95
250x100-t6.0-N75-A0-FR	40.26	12.50	0.31	0.20	157.77	162.32	211.24	181.83	0.97	0.75	0.87
250x100-t4.0-N100-A0-FR	61.39	25.00	0.41	0.30	74.88	68.15	87.98	76.35	1.10	0.85	0.98
250x100-t6.0-N100-A0-FR	40.26	16.67	0.41	0.20	161.18	163.19	212.37	182.80	0.99	0.76	0.88
Mean, P_m									1.02	0.80	0.91
Coefficient of variation, V_p									0.13	0.13	0.12

Table 8 Comparison of experimental and numerical results with design strength for case of flanges fastened to bearing plates

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	r_i/t	P (kN)	P_{ASCE} (kN)	$P_{AS/NZS}$ (kN)	P_{Euro} (kN)	P/P_{ASCE}	$P/P_{AS/NZS}$	P/P_{Euro}
175x60-t1.2-N50-A0-FX	155.88	44.25	0.28	1.06	6.52	3.68	4.50	4.12	1.77	1.45	1.58
175x60-t4.0-N50-A0-FX	42.60	12.50	0.29	0.30	75.52	71.58	92.60	80.18	1.06	0.82	0.94
175x60-t6.0-N50-A0-FX	27.73	8.33	0.30	0.20	149.45	168.18	219.12	188.37	0.89	0.68	0.79
175x60-t1.2-N75-A0-FX	154.40	65.79	0.43	1.05	6.79	3.87	4.74	4.34	1.75	1.43	1.56
175x60-t4.0-N75-A0-FX	42.58	18.75	0.44	0.30	87.83	72.16	93.35	80.83	1.22	0.94	1.09
175x60-t6.0-N75-A0-FX	27.72	12.50	0.45	0.20	174.15	169.09	220.31	189.39	1.03	0.79	0.92
175x60-t1.2-N100-A0-FX	154.52	87.72	0.57	1.05	6.94	3.97	4.86	4.45	1.75	1.43	1.56
175x60-t4.0-N100-A0-FX	42.61	25.00	0.59	0.30	94.05	72.72	94.08	81.46	1.29	1.00	1.15
175x60-t6.0-N100-A0-FX	27.74	16.67	0.60	0.20	190.26	169.98	221.47	190.38	1.12	0.86	1.00
200x75-t1.2-N50-A0-FX	178.25	44.25	0.25	1.06	6.32	3.23	3.93	3.63	1.96	1.61	1.74
200x75-t4.0-N50-A0-FX	48.92	12.50	0.26	0.30	76.28	70.07	90.58	78.49	1.09	0.84	0.97
200x75-t6.0-N50-A0-FX	31.95	8.33	0.26	0.20	150.97	165.92	216.09	186.14	0.91	0.70	0.81
200x75-t1.2-N75-A0-FX	176.62	65.79	0.37	1.05	6.63	3.41	4.15	3.83	1.94	1.60	1.73
200x75-t4.0-N75-A0-FX	48.91	18.75	0.38	0.30	89.75	70.63	91.31	79.12	1.27	0.98	1.13
200x75-t6.0-N75-A0-FX	31.94	12.50	0.39	0.20	175.95	166.81	217.26	186.84	1.05	0.81	0.94
200x75-t1.2-N100-A0-FX	176.61	87.72	0.50	1.05	6.69	3.50	4.26	3.93	1.91	1.57	1.70
200x75-t4.0-N100-A0-FX	48.90	25.00	0.51	0.30	93.45	71.19	92.04	79.75	1.31	1.02	1.17
200x75-t6.0-N100-A0-FX	31.94	16.67	0.52	0.20	181.89	167.70	218.42	187.84	1.08	0.83	0.97
250x100-t4.0-N50-A0-FX	61.54	12.50	0.20	0.30	75.93	67.04	86.55	75.11	1.13	0.88	1.01
250x100-t6.0-N50-A0-FX	40.36	8.33	0.21	0.20	152.61	161.40	210.04	180.79	0.95	0.73	0.84
250x100-t4.0-N75-A0-FX	61.47	18.75	0.31	0.30	90.01	67.59	87.27	75.73	1.33	1.03	1.19
250x100-t6.0-N75-A0-FX	40.31	12.50	0.31	0.20	177.27	162.29	211.21	181.79	1.09	0.84	0.98
250x100-t4.0-N100-A0-FX	61.39	25.00	0.41	0.30	100.81	68.15	87.98	76.35	1.48	1.15	1.32
250x100-t6.0-N100-A0-FX	40.26	16.67	0.41	0.20	200.01	163.19	212.37	182.80	1.23	0.94	1.09
Mean, P_m									1.32	1.04	1.18
Coefficient of variation, V_p									0.34	0.30	0.31

Table 9 Comparison of web crippling strength reduction factor with reduction factors equations proposed by Yousefi *et al.* [8]
(a) Flanges unfastened to the bearing plates

Specimen	Failure load without web openings $P_{(A0)}$ (kN)	Failure load with web openings $P_{(\text{Web opening})}$		Reduction factor $R=P_{(\text{Web opening})}/P_{(A0)}$		Factored resistance *(Eq. 7)*	Factored resistance *(Eq. 9)*	Comparison with factor resistance from Yousefi *et al.* R/R_{Lipped}	
		Centred	Offset	Centred	Offset	Centred	Offset	Centred	Offset
175x60-t1.2-N50-A0.2-FR	4.16	4	3.82	0.96	0.92	0.83	0.96	1.15	0.96
175x60-t1.2-N75-A0.2-FR	4.31	4.15	4.15	0.96	0.96	0.85	0.96	1.13	1.00
175x60-t1.2-N75-A0.4-FR	4.31	3.78	3.78	0.88	0.88	0.78	0.93	1.12	0.95
175x60-t1.2-N100-A0.2-FR	4.49	4.32	4.32	0.96	0.96	0.87	0.96	1.11	1.00
175x60-t1.2-N100-A0.4-FR	4.49	3.93	3.92	0.88	0.87	0.80	0.93	1.10	0.94
200x75-t6.0-N50-A0.2-FR	140.57	131.64	132.35	0.94	0.94	0.83	0.96	1.13	0.98
200x75-t6.0-N50-A0.4-FR	140.57	112.97	117.22	0.80	0.83	0.76	0.93	1.06	0.90
200x75-t4.0-N100-A0.2-FR	74.01	69.07	67.97	0.93	0.92	0.86	0.96	1.08	0.95
200x75-t4.0-N100-A0.4-FR	74.01	60.36	59.78	0.82	0.81	0.79	0.93	1.03	0.87
250x100-t6.0-N50-A0.2-FR	145.04	139.46	130.14	0.96	0.90	0.82	0.96	1.17	0.94
250x100-t6.0-N50-A0.4-FR	145.04	118.41	114.02	0.82	0.79	0.75	0.92	1.08	0.85
250x100-t4.0-N100-A0.2-FR	74.88	68.64	67.20	0.92	0.90	0.85	0.96	1.08	0.93
250x100-t4.0-N100-A0.4-FR	74.88	59.62	59.01	0.80	0.79	0.78	0.93	1.02	0.85
Mean, Pm								1.10	0.93
Coefficient of variation, Vp								0.04	0.06

(b) Flanges fastened to the bearing plates

Specimen	Failure load without web openings $P_{(A0)}$	Failure load with web openings $P_{(\text{Web opening})}$		Reduction factor $R=P_{(\text{Web opening})}/P_{(A0)}$		Factored resistance *(Eq. 8)*	Factored resistance *(Eq. 10)*	Comparison with factor resistance from Yousefi *et al.* R/R_{Lipped}	
	(kN)	Centred	Offset	Centred	Offset	Centred	Offset	Centred	Offset
175x60-t1.2-N50-A0.2-FX	6.52	6.21	6.12	0.95	0.94	0.86	0.89	1.10	1.06
175x60-t1.2-N75-A0.2-FX	6.79	6.44	6.34	0.95	0.93	0.90	0.89	1.05	1.04
175x60-t1.2-N75-A0.4-FX	6.79	5.71	5.71	0.84	0.84	0.83	0.83	1.02	1.02
175x60-t1.2-N100-A0.2-FX	6.94	6.57	6.49	0.95	0.94	0.94	0.90	1.01	1.04
175x60-t1.2-N100-A0.4-FX	6.94	5.86	5.87	0.84	0.85	0.87	0.83	0.98	1.02
200x75-t6.0-N50-A0.2-FX	150.97	148.98	150.77	0.99	1.00	0.86	0.89	1.15	1.12
200x75-t6.0-N50-A0.4-FX	150.97	130.03	149.83	0.86	0.99	0.78	0.83	1.10	1.20
200x75-t4.0-N100-A0.2-FX	93.45	87.23	88.51	0.93	0.95	0.92	0.90	1.01	1.05
200x75-t4.0-N100-A0.4-FX	93.45	76.69	80.11	0.82	0.86	0.85	0.83	0.97	1.03
250x100-t6.0-N50-A0.2-FX	152.61	151.19	151.52	0.99	0.99	0.84	0.89	1.18	1.11
250x100-t6.0-N50-A0.4-FX	152.61	139.88	149.92	0.92	0.98	0.77	0.82	1.19	1.19
250x100-t4.0-N100-A0.2-FX	100.81	94.92	98.97	0.94	0.98	0.90	0.90	1.05	1.10
250x100-t4.0-N100-A0.4-FX	100.81	82.03	88.97	0.81	0.88	0.82	0.83	0.99	1.06
Mean, Pm								1.06	1.08
Coefficient of variation, Vp								0.07	0.06

Table 10 Statistical analysis for comparison of strength reduction factor for centred web opening where flanges unfastened to bearing plates

Statistical parameters	R (Test & FEA) / R_p (0.98-0.26 (a/h)+0.06 (N/h))
Number of data	99
Mean, P_m	1.01
Coefficient of variation, V_p	0.05
Reliability index, β	2.83
Resistance factor, ϕ	0.85

Table 11 Statistical analysis for comparison of strength reduction factor for centred web opening where flanges fastened to bearing plates

Statistical parameters	R (Test & FEA) / R_p (0.95-0.06 (a/h)+0.01 (N/h))
Number of data	93
Mean, P_m	1.00
Coefficient of variation, V_p	0.04
Reliability index, β	2.81
Resistance factor, ϕ	0.85

Table 12 Statistical analysis for comparison of strength reduction factor for offset web opening where flanges unfastened to bearing plates

Statistical parameters	R (Test & FEA) / R_p (0.99-0.26(a/h)+0.11 (x/h))
Number of data	188
Mean, P_m	1.00
Coefficient of variation, V_p	0.11
Reliability index, β	2.61
Resistance factor, ϕ	0.85

Table 13 Statistical analysis for comparison of strength reduction factor for offset web opening where flanges fastened to bearing plates

Statistical parameters	R (Test & FEA) / R_p (0.99-0.14 (a/h)+0.07 (x/h))
Number of data	188
Mean, P_m	1.00
Coefficient of variation, V_p	0.08
Reliability index, β	2.69
Resistance factor, ϕ	0.85