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PARAMETRIC STUDIES AND DESIGN RECOMMENDATIONS OF COLD-FORMED STEEL SECTIONS WITH WEB OPENINGS SUBJECTED TO WEB CRIPPLING

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Abstract: A parametric study of cold-formed steel sections with web openings subjected to web crippling was undertaken using finite element analysis, to investigate the effects of web holes and cross-section sizes on the web crippling strengths of channel sections subjected to web crippling under both interior-two-flange (ITF) and end-two-flange (ETF) loading conditions. In both loading conditions, the openings were located at the mid-depth of the webs. It was demonstrated that the main factors influencing the web crippling strength are the ratio of the hole depth to the flat depth of the web, the ratio of the distance of the hole from the edge of the bearing plates to the flat depth of the web and the ratio of the length of bearing plates to the flat depth of the web. In this paper, design recommendations in the form of web crippling strength reduction factors are proposed; these are shown to be conservative to both the experimental and finite element results.

1. INTRODUCTION

Most design specifications for cold-formed steel structural members provide design rules for cold-formed steel channel sections without web holes; only in the case of the North American specification for cold-formed steel sections [1] are reduction factors for web crippling with holes presented, covering the cases of interior-one-flange (IOF) and end-one-flange loading (EOF), and with the flanges of the sections unfastened to the support. In addition, in the North American specification, the holes are assumed to be located at the mid-height of the specimen and have a longitudinal clear offset distance between the edge of the bearing plates and the web hole.

Web crippling strength reduction factors for cold-formed steel sections under interior-one-flange (IOF) and end-one-flange loading (EOF) have been developed by Yu and Davis [2], Sivakumaran and Zielonka [3], LaBoube et al. [4] and Chung [5]. Zhou and Young [6] have recommended web crippling strength reduction factors of aluminium alloy square hollow sections under ITF and ETF loading conditions. However, no design recommendations are available for cold-formed steel sections with web openings subject to web crippling, under ITF and ETF loading conditions.

Experimental and numerical investigations have been discussed in Uzzaman et al [7-10]. In this paper, non-linear finite element analyses (FEA) are used to conduct parametric studies to investigate the effect of circular web holes on the web crippling strength of lipped channel sections for the interior-two-flange (ITF) and end-two-flange (ETF) loading conditions. The cases of both flanges fastened and unfastened to the support are considered. In both loading conditions, the holes were located with an offset distance to the bearing plate (Type 1 holes) and centred beneath the load or reactions (Type 2 holes). The general purpose finite element program ANSYS [11] was used for the parametric study. Based on the test data found in Uzzaman et al [7-10] and the numerical results obtained from this study an extensive statistics analysis is performed. Design recommendations in the form of web crippling strength reduction factors are proposed for ITF and ETF loading conditions that are shown to be conservative to both the experimental and finite element results.

2. PARAMETRIC STUDY

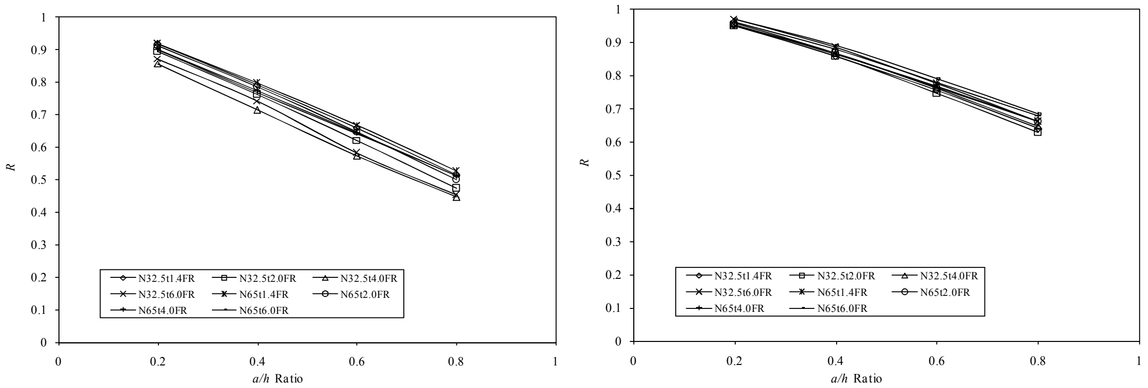
The finite element model developed closely predicted the experimental ultimate loads and failure modes of the channel sections with and without circular web holes subjected to web crippling [7-10]. Using this model, parametric studies were carried out to study the effects of web holes and cross-section sizes on the web crippling strengths of channel sections subjected to web crippling under ITF and ETF loading conditions. The cases of both flange fastened and flange unfastened to the support were considered. The web holes were located at the mid-depth of the webs.

Zhou and Young [6] and LaBoube et al. [4] showed that the ratios a/h, x/h and N/h are the primary parameters influencing the web crippling behaviour of the sections with web holes. The web crippling strength predicted was influenced primarily by the ratio of the hole depth to the flat portion of the web, a/h, the ratio of the bearing length to the flat portion of the web N/h and the location of the hole as defined by the distance of the hole from the edge of the bearing divided by the flat portion of the web, x/h. In order to determine the effect of a/h and x/h on the web crippling strength for Type 1 web holes and the effect of a/h and N/h on web crippling strength for Type 2 web holes, two separate parametric studies were carried out considering the web holes sizes, the cross-section sizes and location of the holes.

The specimens consisted of two different section sizes, having thicknesses (t) ranging from 1.4 to 6.0 mm and web slendernesses (h/t) values ranging from 31.8 to 176.9. The ratios of the diameter of the holes (a) to the depth of the flat portion of the webs (h) were 0.2, 0.4, 0.6 and 0.8. The ratio of the distance of the web holes (x) to the depth of the flat portion of the webs (h) were 0.2, 0.4 and 0.6. For each series of specimens, the web crippling strengths of the sections without the web holes were obtained. Thus, the ratio of the web crippling strengths for sections with the web holes divided by the sections without the web holes, which is the strength reduction factor (R), was used to quantify the degrading influence of the web holes on the web crippling strengths.

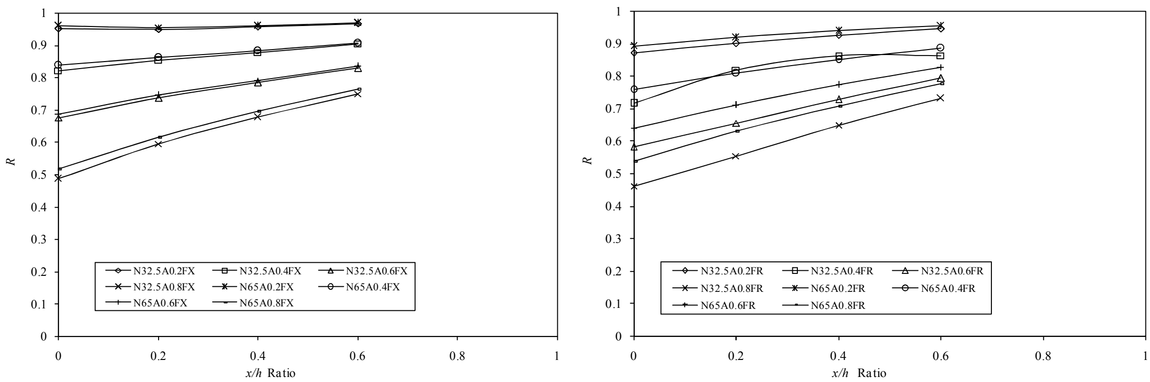
2.1 Effects of a/h and x/h on web crippling strength reduction for Type 1 web holes

A total of 200 specimens for ITF and 140 specimens for ETF loading conditions were analysed in the parametric study to investigate the effect of the ratio a/h. The cross-section dimensions as well as the web crippling strengths per web predicted from the FEA are summarised in Uzzaman et al. [7-10] for flanges unfastened and fastened condition, respectively. A total of 160 specimens for ITF and 160 specimens for ETF loading conditions were analysed in the parametric study investigating the effect of x/h. The cross-section dimensions as well as the web crippling and Uzzaman et al. [7-10]. The effects of a/h and x/h ratio on the web crippling strength on the reduction factor are shown in Fig.1 and Fig.2 for the C202 specimen, respectively. It is seen from these graphs that the parameter a/h and x/h noticeably affects the web crippling strength and the reduction factor. The failure load decreases as the size of the web holes increases and the failure load increases as the distance of the web holes increases.



a) ITF loading condition b) ETF loading condition

Fig. 1: Variation in reduction factors with a/h ratio



a) ITF loading condition b) ETF loading condition

Fig. 2: Variation in reduction factors with x/h ratio

2.2 Effects of a/h and N/h on web crippling strength reduction for Type 2 web holes

A total of 146 specimens for ITF and 146 specimens for ETF loading conditions were analysed in the parametric study to investigate the effects of the ratio a/h and N/h.

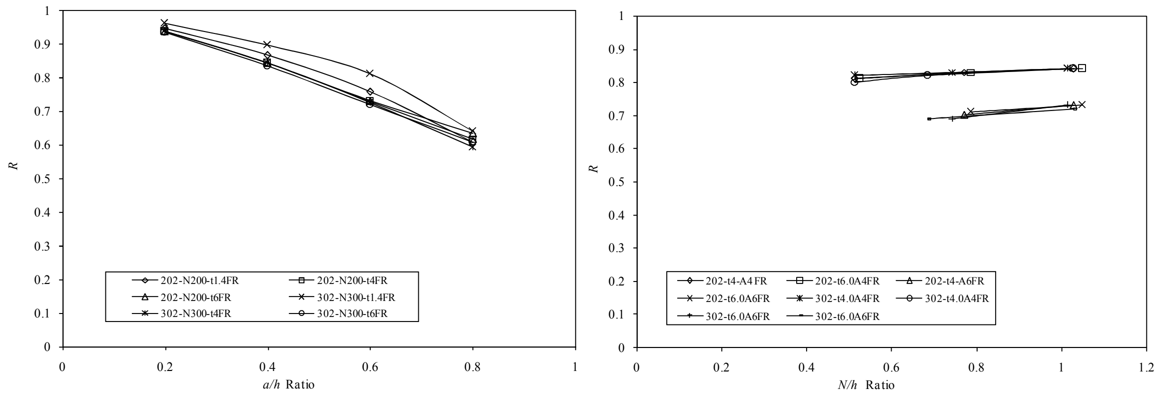


Fig. 3: Variation in reduction factors with a/h and N/h for under ITF loading condition

The cross-section dimensions as well as the web crippling strengths (PFEA) per web predicted from the FEA are summarised in Uzzaman et al. [7-10] for flanges unfastened and fastened condition, respectively. The effects of a/h and N/h ratio on the web crippling strength on the reduction factor for flanges unfastened and fastened condition are shown in Fig.3 and

Fig.4 for the C202 specimen. It can be seen from these graphs that the parameter a/h and N/h noticeably affects the web crippling strength and the reduction factor. The failure load decreases as the size of the web holes increases and the failure load increases as the length of the bearing plates decreases.

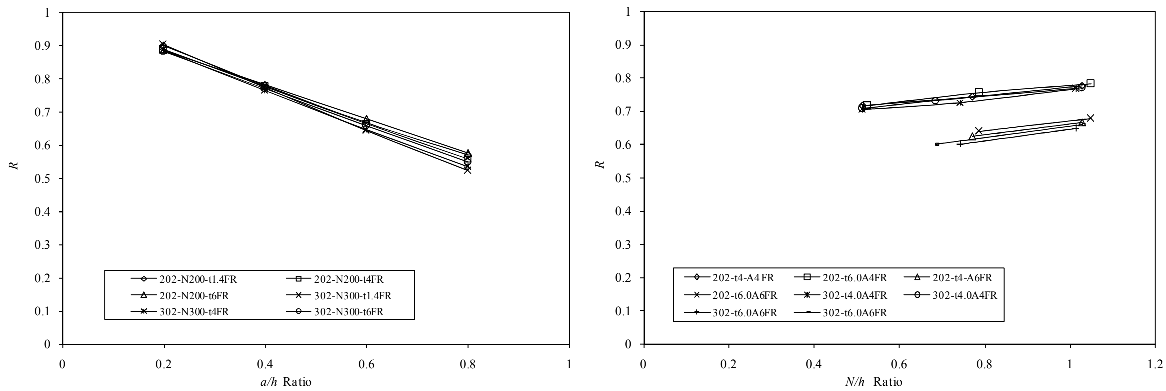


Fig. 4: Variation in reduction factors with a/h and N/h for under ETF loading condition

3. 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 [1]. 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 [12] 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 [1] 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.

In calculating the reliability index, the correction factor in the NAS Specification was used. Reliability analysis is detailed in the NAS Specification [1]. 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 Tables 1 and Table 2.

4. COMPARISON OF EXPERIMENTAL AND NUMERICAL RESULTS WITH CURRENT DESIGN STRENGTHS FOR COLD-FORMED STEEL SECTIONS WITHOUT WEB HOLES

As mentioned earlier, the current cold-formed design standards [1, 13, 14] do not provide design rules for cold-formed steel sections with web holes subjected to web crippling under ITF and ETF loading conditions. The web crippling strength predicted from test and FEA results were compared with the web crippling strength obtained from design codes. The comparison of the web crippling test strengths and the numerical results with design strength for ETF and ITF loading conditions are shown in Uzzaman et al. [7-10]. It is noted that for the unfastened case agreement is very good, however, for the fastened case, the comparison is less reliable due to the post buckling strength effect not being fully considered in the design codes.

5. PROPOSED STRENGTH REDUCTION FACTORS

5.1 Proposed strength reduction factor ITF loading condition

Based on both the experimental and numerical results reported by Uzzaman et al. [7-10], two strength reduction factor (R_p) are proposed using bivariate linear regression analysis for the ITF loading condition.

For the flanges unfastened condition;

Type 1 web holes: $$R_P = 1.04 - 0.68\ (\frac{a}{h}) + 0.023\ (\frac{x}{h}) \quad \leq 1 \qquad (1)$$

Type 2 web holes: $$R_P = 1.05 - 0.54\ (\frac{a}{h}) + 0.01\ (\frac{N}{h}) \quad \leq 1 \qquad (2)$$

For the flanges fastened condition;

Type 1 web holes: $$R_P = 1.00 - 0.45\ (\frac{a}{h}) + 0.09\ (\frac{x}{h}) \quad \leq 1 \qquad (3)$$

Type 2 web holes: $$R_P = 1.01 - 0.51\ (\frac{a}{h}) + 0.06\ (\frac{N}{h}) \quad \leq 1 \qquad (4)$$

The limits for the reduction factor Eq.(1), (2), (3) and (4) are $h/t \leq 156$, $N/t \leq 84$, $N/h \leq 0.63$, $a/h \leq 0.8$, and $\theta = 90^0$.

5.2 Proposed strength reduction factor ETF loading condition

Based on both the experimental and numerical results reported by Uzzaman et al. [7-10], two strength reduction factor (R_p) are proposed using bivariate linear regression analysis for the ETF loading condition.

For the flanges unfastened condition;

Type 1 web holes: $$R_P = 0.95 - 0.49\ (\frac{a}{h}) + 0.17\ (\frac{x}{h}) \quad \leq 1 \qquad (5)$$

Type 2 web holes $$R_P = 0.90 - 0.60\ (\frac{a}{h}) + 0.12\ (\frac{N}{h}) \quad \leq 1 \qquad (6)$$

For the flanges fastened condition;

Type 1 web holes $$R_P = 0.96 - 0.36\ (\frac{a}{h}) + 0.14\ (\frac{x}{h}) \quad \leq 1 \qquad (7)$$

Type 2 web holes $$R_P = 0.95 - 0.50\ (\frac{a}{h}) + 0.08\ (\frac{N}{h}) \quad \leq 1 \qquad (8)$$

The limits for the reduction factor Eq.(5), (6), (7) and (8) are $h/t \leq 156$, $N/t \leq 84$, $N/h \leq 0.63$, $a/h \leq 0.8$, and $\theta = 90^0$.

6. COMPARISON OF THE EXPERIMENT AND NUMERICAL RESULTS WITH THE PROPOSED REDUCTION FACTOR

For ITF loading condition, 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. (1), (2), (3) and (4). Table 1 summarizes a statistical analysis to define the accuracy of the proposed design equations. The values of the proposed reduction factor are generally conservative and agree well with the experimental and the numerical results for ITF loading conditions. As can be seen, the proposed reduction factors are generally conservative and agree with the experimental and the numerical results for all cases. The mean value of the web crippling reduction factor ratio are 1.00, 1.01, 1.02 and 1.00 with corresponding values of COV of 0.04, 0.04, 0.07 and 0.03, and reliability index (β) of 2.83, 2.87, 2.81 and 2.86 for the flanges are unfastened and fastened conditions with both types of web holes. Thus, the proposed strength reduction factor equations are able to predict the influence of the web holes on the web crippling strengths of channel sections for the ITF loading condition.

Table 1 Statistical analysis for the comparison of the strength reduction factor for ITF loading condition

Statistical parameters	*R* (Test & FEA) / Eq. (1)	*R* (Test & FEA) / Eq. (2)	*R* (Test & FEA) / Eq. (3)	*R* (Test & FEA) / Eq. (4)
	Unfastened	Fastened	Unfastened	Fastened
	Type 1 holes	Type 2 holes	Type 1 holes	Type 2 holes
Mean, P_m	1.00	1.01	1.02	1.00
Coefficient of variation, V_p	0.04	0.04	0.07	0.03
Reliability index, β	2.83	2.87	2.81	2.86
Resistance factor, ϕ	0.85	0.85	0.85	0.85

For ETF loading condition, 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. (5), (6), (7) and (8).

Table 2 Statistical analysis for the comparison of the strength reduction factor for ITF loading condition

Statistical parameters	*R* (Test & FEA) / Eq. (5)	*R* (Test & FEA) / Eq. (6)	*R* (Test & FEA) / Eq. (7)	*R* (Test & FEA) / Eq. (8)
	Unfastened	Fastened	Unfastened	Fastened
	Type 1 holes	Type 2 holes	Type 1 holes	Type 2 holes
Mean, P_m	1.00	1.00	1.00	1.00
Coefficient of variation, V_p	0.05	0.03	0.06	0.03
Reliability index, β	2.80	2.85	2.80	2.86
Resistance factor, ϕ	0.85	0.85	0.85	0.85

Table 2 summarizes a statistical analysis to define the accuracy of the proposed design equations. The values of the proposed reduction factor are generally conservative and agree well with the experimental and the numerical results for ETF loading conditions. As can be seen, the proposed reduction factors are generally conservative and agree with the experiment and the numerical results for both load cases. The mean value of the web crippling reduction factor ratio are 1.00, 1.00, 1.00 and 1.00 with the corresponding COV of 0.05, 0.03, 0.06 and 0.03, and reliability index (β) of 2.80, 2.85, 2.80 and 2.86 for the flanges are unfastened and fastened conditions with both types of web holes, respectively. Thus, the proposed strength reduction factor equations are able to predict the influence of the web holes on the web crippling strengths of channel sections for the ITF loading condition.

5 Conclusions

The main conclusions are:

1. A parametric study of lipped channel sections with circular web holes subjected to web crippling has been presented. The web holes are located at the mid-depth of the webs and centred beneath the bearing plates;
2. A non-linear finite element model was used in the parametric study, which has been verified against experiment results. Evaluation of the experimental and the numerical results shows that the ratios a/h, x/h and N/h are the primary parameters influencing the web crippling behaviour of the sections with web holes. In order to determine the effect of the ratios a/h, x/h and N/h on the web crippling strength, parametric studies were carried out considering the web holes, the cross-section sizes and the different bearing plate lengths.
3. Based on the available data obtained from the experimental and numerical investigations, web crippling strength reduction factor equations were proposed for the ITF and ETF loading conditions for the cases of both flanges unfastened and fastened to the support.
4. Reliability analysis was performed to evaluate the reliability of the proposed strength reduction factors. It was shown that the proposed strength reduction factors are generally conservative and agree well with the experimental and the numerical results.

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Notation

A	Web holes ratio
a	Diameter of circular web holes
COV	Coefficient of variation
DL	Dead load
FEA	Finite element analysis
F_m	Mean value of fabrication factor
h	Depth of the flat portion of web
LL	Live load
M_m	Mean value of material factor

N	Length of the bearing plate
P_m	Mean value of tested-to-predicted load ratio
R	Reduction factor
R_P	Proposed reduction factor
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 holes to the near edge of the bearing plate
β	Reliability index
ϕ	Resistance factor

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