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PARAMETRIC STUDIES AND DESIGN RECOMMENDATIONS OF COLD-FORMED STEEL SECTIONS WITH EDGE-STIFFENED CIRCULAR HOLES SUBJECTED TO WEB CRIPPLING

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Abstract

A parametric study of cold-formed steel sections with edge-stiffened circular holes subjected to web crippling under one-flange loading condition was undertaken using finite element analysis. The effect of different hole sizes, edge-stiffener length and distances of the web holes to the near edge of the bearing plate on the web crippling strengths of channel sections were investigated. The web crippling strengths are influenced by various geometry parameters: the ratio of the hole depth to the flat portion of the web, *a/h*, 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* and the ratio of the edge-stiffener length to the flat portion of the web, *q/h*. In order to find the effect of *a/h*, *x/h* and *q/h* ratios on web crippling strength of channel sections with web holes, three separate parametric studies were carried out. The results indicate that with a suitable edge-stiffener length, the web crippling strength of cold-formed steel channel section with holes can be as high as the one without holes. In this paper, based on the finite element results a correlation are established for the web crippling strength of the channel sections without web holes, with unstiffened and edge-stiffened circular web holes corresponding with the ratios *a/h*, *x/h* and *q/h* for the interior-one-flange (IOF) and end-one-flange (EOF) loading conditions, respectively.

Keywords: Cold-formed steel; Web crippling; Finite element analysis; Web openings; Channel section;

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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 (2007) for cold-formed steel sections are reduction factors for web crippling with circular unstiffened 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 circular unstiffened web hole.

Web crippling strength reduction factors for cold-formed steel sections with unstiffened holes under interior-one-flange (IOF) and end-one-flange loading (EOF) have been developed by Yu and Davis (1973), Sivakumaran and Zielonka (1989), LaBoube *et al*. (1999) and Chung (1995). Zhou and Young (2010) have recommended web crippling strength reduction factors of aluminium alloy square hollow section under ITF and ETF loading conditions. Uzzaman *et al*. (2012a, 2012b, 2012c & 2013) and Lian *et al*. (2016a, 2016b, 2017a & 2017b) proposed design recommendations in the form of web crippling strength reduction factor equations for channel-sections with circular unstiffened holes under two-flanges and one-flange loading conditions. Yousefi *et al*. (2016a,2016b,2017a&2017b) also proposed unified strength reduction factor equations for the web crippling strength of cold-formed stainless steel lipped channel-sections with circular unstiffened web openings. However, no design recommendations are available for cold-formed steel sections with edge-stiffener web holes subject to web crippling.

Experimental and numerical investigations have been discussed in Uzzaman *et al* (2017). In this paper, non-linear finite element analyses (FEA) are used to conduct parametric studies to investigate the effects of different hole sizes, edge-stiffener length and distances of the web holes to the near edge of the bearing plate for the interior-one-flange (IOF) and end-one-flange (EOF) loading conditions. The general purpose finite element program ABAQUS (2014) was used for the parametric study. Based on the finite element results a correlation are established for the web crippling strength of the channel sections without web holes, with unstiffened and edge-stiffened circular web holes corresponding with the ratios a/h, x/h and q/h for the interior-one-flange (IOF) and end-one-flange (EOF) loading conditions, respectively.

2. PARAMETRIC STUDY

The finite element model developed closely predicted the experimental ultimate loads and failure modes of the channel sections with and without web holes subjected to web crippling (Uzzaman *et al*, 2017). Using this validated model, A parametric study is performed in the following section to obtained optimized dimensions of the web holes profiles for the cold-formed steel sections

Zhou and Young (2010), Uzzaman *et al*, (2012b, 2012c & 2013) and Lian *et al* (2016b, 2017b) and showed that the ratio of the hole depth to the flat portion of the web, *a/h*, 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* are the primary parameters influencing the web crippling behaviour of the sections with web holes. The study by Yu (2012), while limited to bending, indicates that the ratio of the edge-stiffener length to the flat portion of the web, *q/h* has significantly impact on the strength of cold-formed steel channel sections. In order to find the effect of *a/h*, *x/h* and *q/h* on web crippling strength considering web holes, three separate parametric studies were carried.

In this study section C240 was used, having a nominal depth and thickness of 240 mm and 1.85 mm, respectively. A length of bearing plate of 50 mm was considered. The specimens were labelled according to the analysis type. For example the label 'X0.2-A0.4' stands for the loading condition, bearing plate length, web holes distance ratio (X0.2 means *x/h*= 0.2) and web holes ratio (A0.4 means *a/h*=0.4). As can been seen on Table 1 and Table 1, Q0.04 stands for the web holes edge-stiffener length ratio *q/h* =0.04.

The ratios of the diameter of the holes (*a*) to the depth of the flat portion of the webs (*h*) were 0.4, 0.6 and 0.8. The ratio *x/h* (the distance of the web holes to the depth of the flat portion of the webs) were 0.2, 0.4 and 0.6. The ratio *q/h* of the length of stiffener to the depth of the flat portion of the webs were 0.04, 0.06 and 0.08.

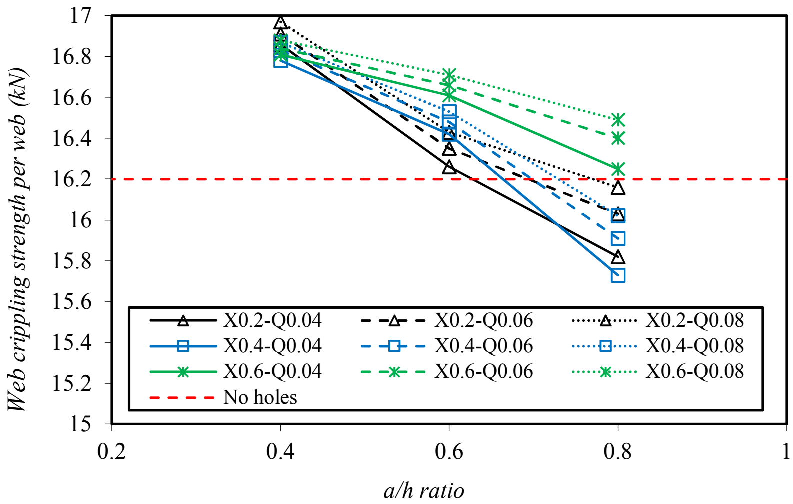
A total of 60 specimens was analysed in the parametric study investigating the effects of the ratio *a/h*, *x/h* and *q/h*. The web crippling strength of the sections without the web holes were obtained. The cross-section dimensions as well as the web crippling strengths (P_{FEA}) per web predicted from the FEA are summarised in Table 1 and Table 2 for the IOF and EOF loading conditions, respectively.

Specimen	Flat web, *h* (mm)	Web holes ratio, (*a/h*)	Diameter of web holes, a (mm)	Holes distanc e ratio, (*x/h*)	Holes distance x (mm)	FEA load per web, P_{FEA} (kN)		
						Web holes edge-stiffener length ratio, Q (*q/h*)		
						Q0.04	Q0.06	Q0.08
A0	233.39	0.0	0.0	0	0.00	16.20	16.20	16.20
X0.2-A0.4	233.39	0.4	93.62	0.2	46.68	16.86	16.91	16.97
X0.2-A0.6	233.39	0.6	140.44	0.2	46.68	16.26	16.35	16.43
X0.2-A0.8	233.39	0.8	187.20	0.2	46.68	15.82	16.03	16.16
X0.4-A0.4	233.39	0.4	93.62	0.4	93.36	16.78	16.83	16.87
X0.4-A0.6	233.39	0.6	140.44	0.4	93.36	16.42	16.48	16.53
X0.4-A0.8	233.39	0.8	187.20	0.4	93.36	15.73	15.91	16.02
X0.6-A0.4	233.39	0.4	93.62	0.6	140.40	16.81	16.84	16.88
X0.6-A0.6	233.39	0.6	140.44	0.6	140.40	16.61	16.66	16.71
X0.6-A0.8	233.39	0.8	187.20	0.6	140.40	16.25	16.40	16.49

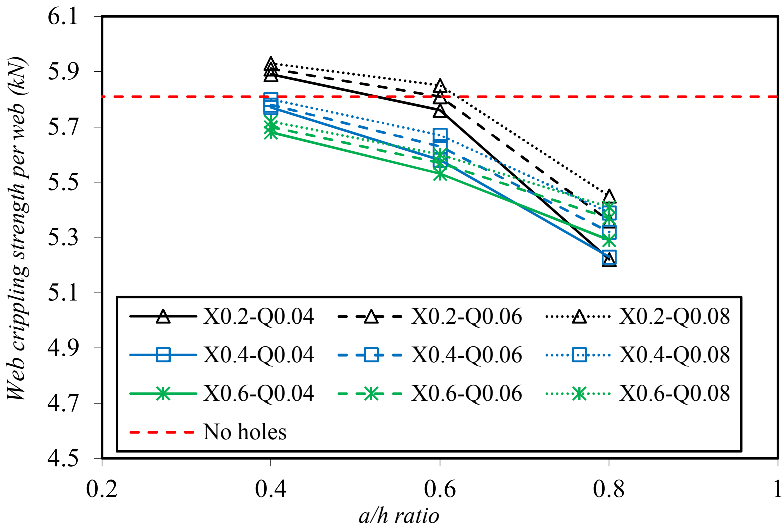
Table.1 Web crippling strengths predicted from FEA for IOF loading condition

Specimen	Flat web, *h* (mm)	Web holes ratio, (a/h)	Diameter of web holes, a (mm)	Holes distanc e ratio, (x/h)	Holes distance x (mm)	FEA load per web, P_{FEA} (kN)		
						Web holes edge-stiffener length ratio, Q (q/h)		
						Q0.04	Q0.06	Q0.08
A0	233.39	0.0	0.0	0	0.00	5.81	5.81	5.81
X0.2-A0.4	233.39	0.4	93.4	0.2	46.68	5.89	5.91	5.93
X0.2-A0.6	233.39	0.6	140.0	0.2	46.68	5.76	5.81	5.85
X0.2-A0.8	233.39	0.8	186.7	0.2	46.68	5.22	5.36	5.45
X0.4-A0.4	233.39	0.4	93.4	0.4	93.36	5.77	5.78	5.80
X0.4-A0.6	233.39	0.6	140.0	0.4	93.36	5.58	5.63	5.67
X0.4-A0.8	233.39	0.8	186.7	0.4	93.36	5.23	5.32	5.39
X0.6-A0.4	233.39	0.4	93.4	0.6	140.03	5.68	5.70	5.72
X0.6-A0.6	233.39	0.6	140.0	0.6	140.03	5.53	5.57	5.60
X0.6-A0.8	233.39	0.8	186.7	0.6	140.03	5.29	5.37	5.41

Fig.9 Web crippling strengths predicted from FEA for EOF loading



(a) IOF loading condition



(b) EOF loading condition

Fig.1 Effect of *a/h* ratio on web crippling strength

2.1 Effect of *a/h* on web crippling strength

As can be seen from Fig.1, as the web hole diameter ratio *a/h* increases from 0.4 to 0.8, the web crippling strength decreases against different web holes locations and length of the edge-stiffeners for both loading conditions.

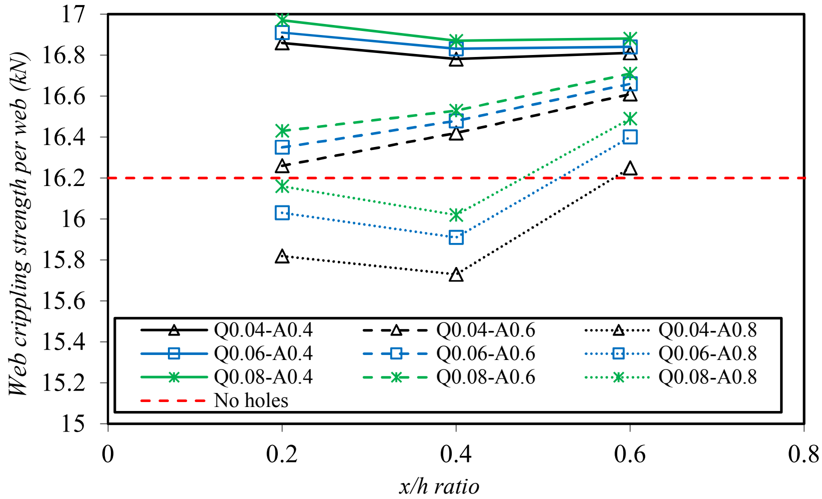
2. 2 Effect of *x/h* on web crippling strength

Fig.2 (a) shows the effect of web holes distance ratio *x/h* web crippling strength for the IOF loading condition. With the respect of web holes diameter ratio A0.6, the results show the increase of web crippling strength when web holes distance ratio *x/h* increases from 0.2 to 0.6. For smaller web hole diameter ratio A0.4, web crippling strength decrease when web holes distance ratio *x/h* increases from 0.2 to 0.6. For the bigger hole diameter ratio A0.8, web crippling strength decrease but eventually it increases when web holes distance ratio *x/h* increases 0.4 to 0.6.

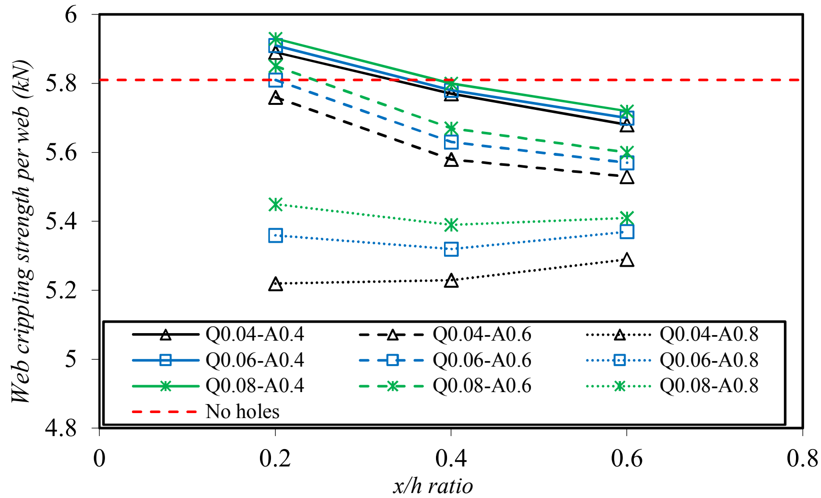
Fig.2 (b) shows the effect of web holes distance ratio *x/h* web crippling strength for the EOF loading condition. With the respect of web holes diameter ratio A0.4 and A0.6, the results show the decrease of web crippling strength when web holes distance ratio *x/h* increases from 0.2 to 0.6. For the bigger hole diameter ratio A0.8, web crippling strength decrease but eventually it increases when web holes distance ratio *x/h* increases 0.4 to 0.6.

2. 3 Effect of q/h on web crippling strength

It is seen from Fig.3 the parameter *q/h* noticeably affects the web crippling strength. Web crippling strengths are improved when the sections have edge-stiffened circular holes in the web and the increasingly grows as the hole diameter becomes larger for the IOF and EOF loading conditions.

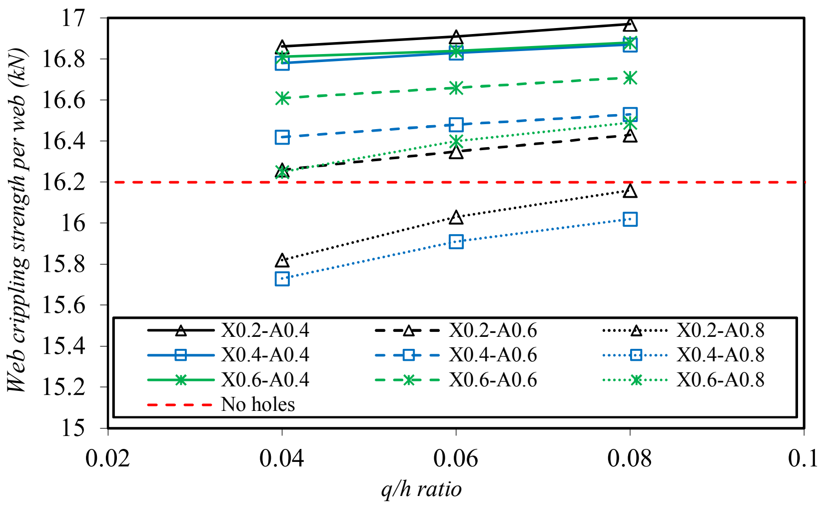


(a) IOF loading condition

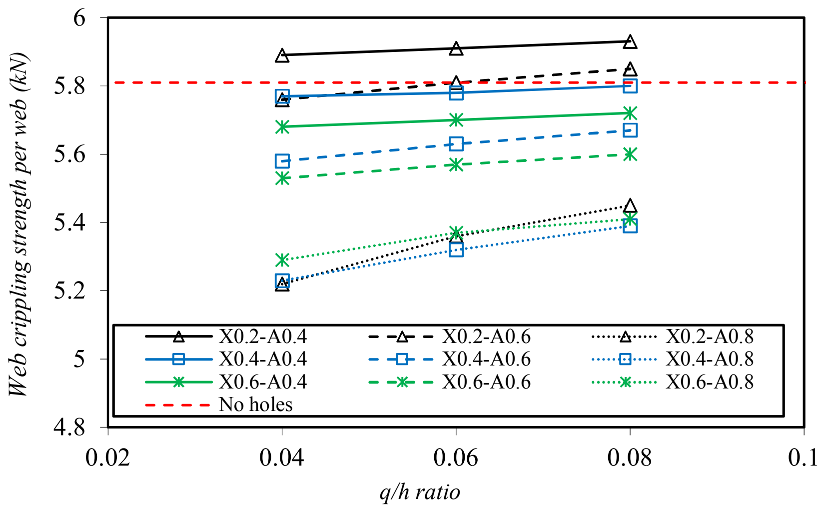


(b) EOF loading condition

Fig.2 Effect of *x/h* ratio on web crippling strength



(a) IOF loading condition



(b) EOF loading condition

Fig.3 Effect of *q/h* ratio on web crippling strength.

4. Conclusions

A parametric study was carried out to study the effects of web holes sizes, location of the holes and length of the edge-stiffener on the web crippling strengths of the channel sections. It is shown that the ratios *a/h*, *x/h* and *q/h* are the primary parametric relationships influencing the web crippling behaviour of the sections with the web holes. Based on the finite element results a correlation was established for the web crippling strength of the channel sections without web holes, with unstiffened and edge-stiffened circular web holes corresponding with the ration *a/h*, *x/h* and *q/h* for the IOF and EOF loading conditions, respectively. In order to restore original the web crippling strength for the IOF loading condition for a section having a web hole ratio *a/h* of 0.6 with holes distance ratio *x/h* of 0.2, it can be recommended that the holes edge-stiffener length ratio *q/h* be at least 0.04. Similarly, for the EOF loading condition, it can be recommended that the holes edge-stiffener length ratio *q/h* be at least 0.06.

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