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Parametric studies and design recommendations of perforated cold-formed ferritic stainless steel unlipped channels subject to web crippling under interior-one-flange and end-one-flange loadings

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ABSTRACT

A finite element and parametric study evaluations into the web crippling strength of perforated cold-formed ferritic stainless steel unlipped channels with circular web perforations under interior-one-flange (IOF) and end-one-flange (EOF) loadings are presented in this paper. The cases of web perforations located offset to the load and reaction bearing plates, are considered. In order to take into account the effect of the circular web perforations, a parametric study involving 288 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 lipped cold-formed stainless steel channels. It is demonstrated that the strength reduction factor equations proposed for lipped cold-formed stainless steel are unreliable and unconservative for the unlipped stainless steel channels as much as 10%. New strength reduction factor equations are then proposed that can be applied to unlipped ferritic stainless steel grade.

1. INTRODUCTION

Cold-formed ferritic stainless steel channels 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 perforations for such sections are also becoming popular in industry (Lawson *et al.* 2015). Such web

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

The authors have previously proposed unified strength reduction factor equations for the web crippling strength of cold-formed stainless steel lipped channel-sections with circular web perforations under the one- and two-flange loading conditions (Yousefi *et al.* 2016, 2017a,b,c). 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.* (2016, 2017), which was a continuation of the work of Uzzaman *et al.* (2012, 2013) who had considered the two-flange loading conditions. When applied to the stainless steel grades, (Yousefi *et al.* 2017d-j) showed that the equations proposed by Lian *et al.* (2016) for the end-one-flange (EOF) loading condition were unconservative by up to 7%. Also, Yousefi *et al.* (2018a-e) showed that the equations proposed by Uzzaman *et al.* (2012, 2013) for the interior-two-flange (ITF) and end-two-flange loading conditions were unconservative for stainless steel channel-sections. Yousefi *et al. (2019a,b,c)* also conducted a series of test programme on unlipped cold-formed ferritic stainless steel channels under one-flange loadings and proposed strength reduction factors due to openins in web.

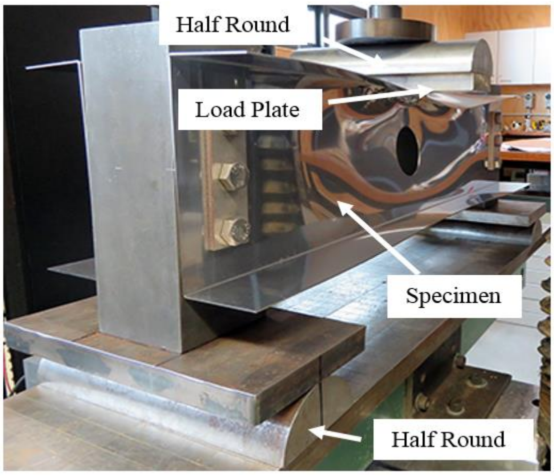
In the literature, for cold-formed stainless steel lipped channel-sections, only Krovink and van den Berg (1994) and Krovink *et al.* (1995) have considered web crippling strength, but limited to sections without perforations. Zhou and Young (2006, 2007, 2008, 2013) have considered the web crippling strength of cold-formed stainless steel tubular sections, again without perforations. Research by Lawson *et al.* (2015), while concerned with circular web perforations, 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. Gunalan and Mahendran (2015) have also considered a Direct Strength Method approach for the web crippling strength of channel sections, again without perforations. For cold-formed carbon steel lipped channel-sections, recent work has included Natario *et al.* (2014) and Gunalan and Mahendran (2015), all without perforations.

This paper considers the web crippling strength of unlipped cold-formed ferritic stainless steel channels with web perforations subject to one-flange loadings, known as interior-one-flange (IOF) and end-one-flange (EOF) loadings, as shown in Fig. 1. Design guidance against web crippling for such cold-formed stainless steel channels are found in SEI/ASCE 8-02, AS/NZS 4673 and EN 1993-1-4 (referring to EN 1993-1-3 for carbon steel). However, no cold-formed stainless steel standard provides strength reduction factor equations for channels having perforations in web. While AISI S136-16 does provide two equations, these equations were developed for cold-formed carbon steel channels.In this paper, the web crippling strength of unlipped cold-formed ferritic grade G430 stainless steel channels having perforations in web subject to interior-one-flange (IOF) and end-one-flange (EOF) loadings is considered, as shown in Fig. 1 and 3. A total of 288 results are presented, comprising 18 laboratory and 270 numerical results. The finite element analysis (FEA) models developed use quasi-static analyses with an implicit integration scheme in ABAQUS (2014). The quasi-static FE model is then used to conduct a parametric investigation to determine the web crippling strength of perforated unlipped channels having different section sizes, load and reaction plates lengths and thicknesses, as well as to examine the suitability of existing design equations recommended by Yousefi et al. (2018a,b). Finally, using laboratory and finite element results, new web crippling strength reduction factor equations are then proposed which are shown to be reliable when compared against laboratory and numerical results.

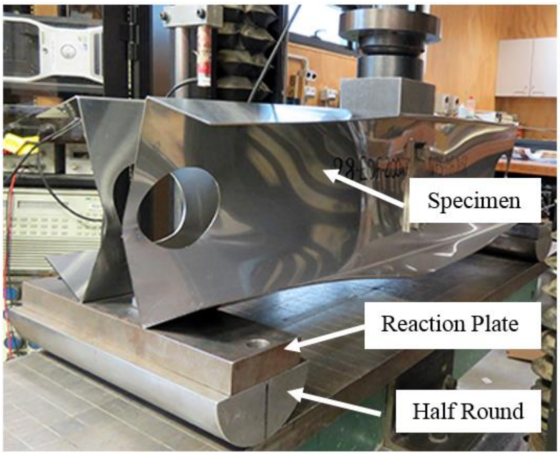
2. EXPERIMENTAL AND NUMERICAL INVESTIGATION

For cold-formed ferritic stainless steel, in previous study Yousefi *et al.* (2019d) conducted 18 one-flange laboratory tests on unlipped channel-sections with circular web perforations subjected to web crippling (see Fig. 1). Fig. 2 shows the definition of the symbols used to describe the dimensions of the cold-formed ferritic stainless steel unlipped channel-sections considered in the test programme. The size of the circular web perforations was varied in order to investigate the effect of the web perforations on the web crippling strength. All the test specimens were fabricated with web perforations located at the mid-depth of the webs with centred 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 Yousefi *et al.* (2019d)), which was then can be used for a parametric study to investigate the web crippling strength of cold-formed stainless steel unlipped channel-sections with circular web perforations under the interior-one-flange (IOF) and end-one-flange (EOF) loading conditions. In this research, recommendations are proposed in the form of strength reduction factor equations, relating the loss of strength due to the web perforations to the strength of the web without perforations. The size of the circular web perforations are varied in order to investigate the effect of the web perforation size on the web crippling strength. Full details of both the laboratory tests can be found in companion paper by Yousefi *et al.* (2019d).

In this study, the non-linear elasto-plastic general purpose finite element program ABAQUS (2014) was used to simulate the cold-formed ferritic stainless steel unlipped channels with circular web perforations subjected to web crippling. The bearing plates, the lipped channel-section with circular web perforations and the interfaces between the bearing plates and the unlipped-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 conducted in the companion study for the cases of web holes located centred to the bearing plates under IOF and EOF loading conditions conducted by Yousefi *et al.* (2019d) (see Fig. 1) were compared to the results obtained from the finite element analyses (Fig. 3).



(a) IOF loading



(b) EOF loading

Fig. 1 Experimental analysis of cold-formed stainless steel channel sections under IOF and EOF loading conditions

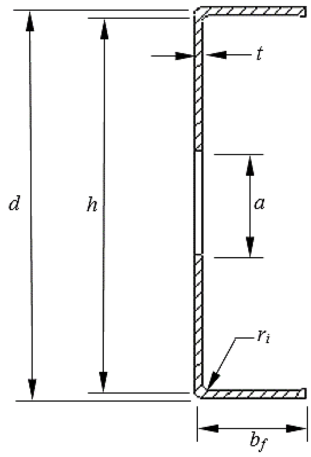
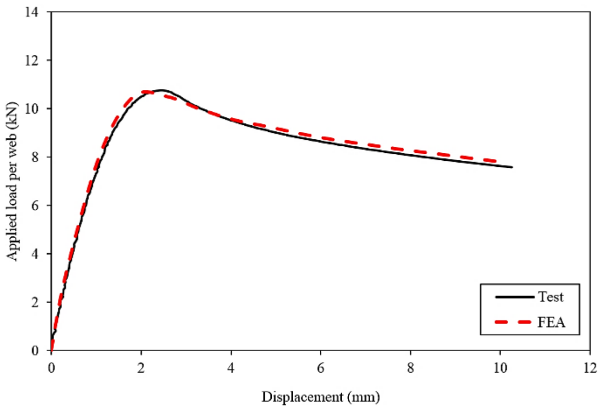
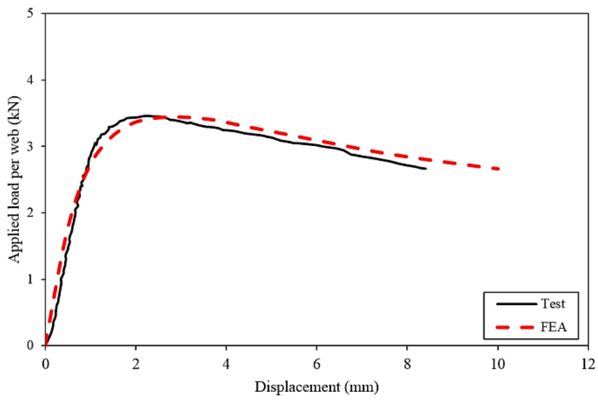


Fig. 2 Definition of symbols



a) IOF loading condition



b) EOF loading condition

Fig. 3 Comparison of finite element results and experimental results by Yousefi et al. (2019d) for sections with centred circular web perforation