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Web crippling behaviour of cold-formed steel channel sections with web holes subjected to interior-one-flange loading condition-Part I: Experimental and numerical investigation

Ying Lian[a], Asraf Uzzaman[b], James B.P. Lim[a,c,*], Gasser Abdelal[d], David Nash[b], Ben Young[e]

[a] SPACE, David Keir Building, Queen's University, Belfast BT9 5AG, UK
[b] Department of Mechanical and Aerospace Engineering, The University of Strathclyde, 75 Montrose Street, Glasgow G1 1XJ, UK
[c] Civil & Environmental Engineering, The University of Auckland, 20 Symonds Street, Auckland, New Zealand
[d] Department of Mechanical and Aerospace Engineering, Queen's University, Belfast BT9 5AH, UK
[e] Department of Civil Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong

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ABSTRACT

Web openings are increasingly used in cold-formed steel beam members of buildings to facilitate ease of services. In this paper, a combination of tests and non-linear finite element analyses is used to investigate the effect of such holes on web crippling under the interior-one-flange (IOF) loading condition; the cases of both flange fastened and flange unfastened to the bearing plate are considered. The results of 61 web crippling tests are presented, with 18 tests conducted on channel sections without web openings and 43 tests conducted on channel sections with web openings. In the case of the tests with web openings, the hole was either located centred beneath the bearing plate or having a horizontal clear distance to the near edge of the bearing plate. A good agreement between the tests and finite element analyses was obtained in term of both strength and failure modes.

1. Introduction

Web openings are increasingly used in cold-formed steel members to facilitate ease of services in buildings. In such members, web crippling can occur at points of concentrated loads [1] (see Fig. 1), and also influenced by the size and position of the openings.

Strength reduction factor equations have recently been proposed by Uzzaman et al. [2–5] for the web crippling strength of cold-formed steel channel sections with circular holes in the web under the end-two-flange (ETF) and interior-two-flange (ITF) loading conditions. This paper extends the work of Uzzaman et al. [2–5] to consider the interior-one-flange (IOF) loading condition for cold-formed steel channel sections with circular holes in the web. The web crippling strength of lipped channel sections for the interior-one-flange (IOF) loading condition, as shown in Fig. 2, are considered. The cases of both flange fastened and flange unfastened to the bearing plate are considered, for cold-formed steel channel sections having circular web holes located centred beneath the bearing plate and also with a horizontal clear distance to the near edge of the bearing plate.

In the literature, for the IOF loading condition, Yu and Davis [6] previously considered the case of both circular and square web openings located and centred beneath the bearing plate with flange unfastened to bearing plate. It should be noted, however, that the test arrangement reported did not use the new established IOF testing procedure [7] in which back-to-back channel section specimens were loaded, but instead used two channel sections connected through their lips. Nevertheless, these tests remain the only reported in the literature for the IOF loading condition where the holes are located and centred beneath the bearing plate. For the circular holes, a total of 10 tests were reported, and all tested with a bearing length of 89 mm. A strength reduction factor equation was proposed but was limited to the aforementioned bearing length.

Again for the IOF loading condition, LaBoube et al. [8] have also considered the case of a circular hole that has a horizontal clear distance to the near edge of the bearing plate, but only for the case where the flange is fastened to the bearing plate. The strength reduction factor equation proposed by LaBoube et al. [8] was subsequently adopted by the North American Specification (NAS) [9] for cold-formed steel sections. This strength reduction factor equation, however, was limited to thicknesses ranged from 0.83 mm to 1.42 mm.

* Corresponding author.
E-mail addresses: ylian01@qub.ac.uk (Y. Lian), asraf.uzzaman@strath.ac.uk (A. Uzzaman), james.lim@auckland.ac.nz (J.B.P. Lim), g.abdelal@qub.ac.uk (G. Abdelal), d.nash@strath.ac.uk (D. Nash), young@hku.hk (B. Young).

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Nomenclature

A	web holes ratio;
a	diameter of circular web holes;
a_{LHS}	diameter of circular web holes positioned left hand side of specimen;
a_{RHS}	diameter of circular web holes positioned right hand side of specimen;
b_f	overall flange width of section;
b_l	overall lip width of section;
COV	coefficient of variation;
d	overall web depth of section;
E	Young's modulus of elasticity;
FEA	finite element analysis;
f_y	material yield strength;
h	depth of the flat portion of web;
L	length of the specimen;
N	length of the bearing plate;
P	experimental and finite element ultimate web crippling load per web;
P_{EXP}	experimental ultimate web crippling load per web;
P_{FEA}	web crippling strength per web predicted from finite element (FEA);
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;
x	horizontal clear distance of the web holes to the near edge of the bearing plate;
ε_f	elongation (tensile strain) at fracture;
$\sigma_{0.2}$	static 0.2% proof stress;
σ_u	static ultimate tensile strength

Other similar work described in the literature include that of Sivakumaran and Zielonka [10] who considered rectangular web openings located and centred beneath the bearing plate under the interior-one-flange loading condition, and Zhou and Young [11] who proposed strength reduction factor equations for aluminium alloy square sections with circular web openings located and centred beneath the bearing plates under end- and interior-two flange loading conditions. Recent research on web crippling of cold-formed steel channel sections, other than that by Uzzaman et al. [2–5] who again considered only the two-flange loading conditions, has not covered the case of holes [12–15].

In this study, a test programme was conducted on lipped channel sections with circular web holes subject to web crippling. In addition, the general purpose finite element analysis (FEA) program ABAQUS [16] was used for the numerical investigation. The finite element model (FEM) included geometric and material non-linearities; the results of the finite element analysis were verified against laboratory test results. Both the failure loads as well as the modes of failure predicted from the finite element analyses were in good agreement with the laboratory test results.

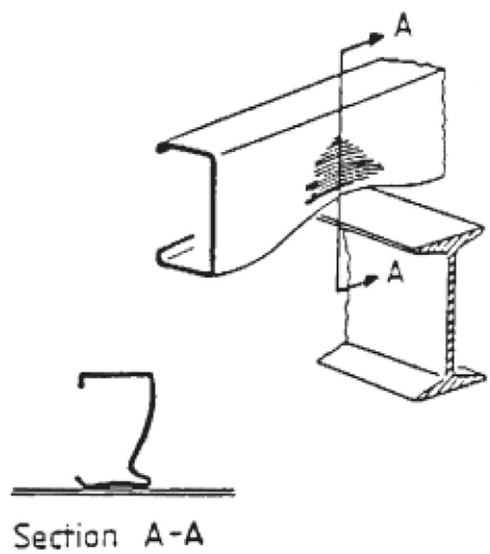

Fig. 1. Web crippling at a support point [1].

2. Experiment investigation

2.1. Test specimens

A test programme was conducted on lipped channel sections, as shown in Fig. 3, with circular web holes subjected to web crippling. Fig. 3 shows the definition of the symbols used to describe the dimensions of the cold-formed steel lipped channel sections considered in the test programme. Fig. 4 shows a schematic view of the test set-up. As can be seen from Fig. 4, each test comprised a pair of channel sections with load transfer blocks bolted between them. Washer plates of thickness 6 mm were bolted to the outside of the webs of the channel sections.

The size of the web holes was varied in order to investigate the effect of the web holes on the web crippling behaviour. Circular holes with a nominal diameter (a) ranging from 55 mm to 179 mm were considered in the experimental investigation. The ratio of the diameter of the holes to the depth of the flat portion of the webs (a/h) was 0.2, 0.4 and 0.6. All test specimens were fabricated with web holes located at the mid-depth of the webs and centred beneath the bearing plate and with a horizontal clear distance to the near edge of the bearing plate (x), as shown in Fig. 4(b).

Channel sections without holes were also tested. The test specimens consisted three different section sizes, having nominal thicknesses ranged from 1.2 mm to 2.0 mm; the nominal depth of the webs and the flange widths ranged from 142 mm to 302 mm. The measured web slenderness (h/t) values of the channel sections ranged from 109 to 157.8. The specimen lengths (L) were determined according to the NAS [9]. Generally, the distance between bearing plates was set to be 1.5 times the overall depth of the web (d) rather than 1.5 times the depth of the flat portion of the web (h), the latter being the minimum specified in the specification.

Tables 1 and 2 show the measured test specimen dimensions for the flange unfastened and fastened to the bearing plate, respectively, using the nomenclature defined in Figs. 2 and 3 for the IOF loading condition. The bearing plates were fabricated using high strength steel having a nominal yield strength of 560 MPa and a thickness of 25 mm. Three lengths of bearing plates (N) were used: 100 mm, 120 mm and 150 mm.

2.2. Specimens labelling

In Tables 1 and 2, the specimens were labelled such that the nominal dimension of the specimen and the length of the bearing plates, as well as the ratio of the diameter of the holes to the depth of the flat portion of the webs (a/h) could be identified from the label. For example, the labels “202×65×15-t1.4-N100-A0-FR”, “202×65×15-t1.4-N100-MA0.4-FR” “202×65×15-t1.4-N100-A0-FX” and “202×65×15-t1.4-N100-MA0.4-FX” are explained as follows: