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EXPERIMENTAL AND NUMERICAL INVESTIGATION OF COLD-FORMED STEEL SECTIONS WITH WEB OPENINGS UNDER ONE-FLANGE LOADING CONDITION SUBJECTED TO WEB CRIPPLING

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Abstract: *Web openings could be used in cold-formed steel beam members, such as wall studs or floor joints, to facilitate ease of services in buildings. 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 interior-one-flange (IOF) and end-one-flange (EOF) loading condition; the cases of both flanges fastened and unfastened to the bearing plates are considered. A non-linear finite element model is described, and the results compared against the laboratory test results; a good agreement was obtained in terms of both strength and failure modes.*

1 INTRODUCTION

Cold-formed steel sections are increasingly used in residential and commercial construction as both primary and secondary framing members. Web crippling at points of concentrated load or reaction is well-known to be a significant problem, particularly in thin walled beams. To improve the buildability of buildings composed of cold-formed steel channel-sections, openings in the web are often required, for ease of installation of electrical or plumbing services. Strength reduction factor equations have recently been proposed by Uzzaman et al. [1-4] 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. [1-4] to consider the interior-one-flange (IOF) and end-

one-flange (EOF) loading conditions for cold-formed steel channel sections with circular holes in the web.

There has been little research on the web crippling of cold-formed steel sections with web holes. LaBoube *et al.* [5] have previously considered the case of a circular hole having a horizontal clear distance to the near edge of the bearing plates, but only for the case where the flanges are fastened to the bearing plates. The strength reduction factor equation proposed by LaBoube *et al.* [5] was subsequently adopted by the North American Specification (NAS) [6] for cold-formed steel sections. This strength reduction factor equation, however, was limited to thicknesses ranged from 0.83 mm to 1.42 mm. Other work described in the literature include that of Yu and Davis [7] who studied the case of both circular and square web openings located and centred beneath the bearing plates under interior-one-flange loading condition, and Sivakumaran and Zielonka [8] who considered the case of rectangular web openings located and centred beneath the bearing plates under the interior-one-flange loading condition, and Zhou and Young [9] 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.* who again considered only the two-flange loading conditions, has not covered the case of holes [1-4].

In buildings, web openings can either be located with an offset distance to the bearing plate centred beneath the load or reactions (Type 1 holes), or centred beneath the load or reactions (Type 2 holes). Furthermore, the flanges can be either fastened or unfastened to the support. In the literature on web crippling with web openings, no research has been conducted on cold-formed steel section under either ITF or ETF loading conditions.

In this paper, a combination of experiments and non-linear finite element analyses (FEA) are used to investigate the effect of web holes on the web crippling strength of lipped channel sections for the EOF loading condition; the cases of both flange fastened and unfastened to the support are considered. The general purpose finite element program ABAQUS [10] was used for the numerical investigation and a good agreement between the experimental tests and FEA was obtained.

2 EXPERIMENT INVESTIGATION

2.1 Test specimens

A test programme was conducted on lipped channel sections, as shown in figure 1, with circular web holes subjected to web crippling. 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 above the bearing plates and with a horizontal clear distance to the near edge of the bearing plates (x). Channel sections without holes were also tested. The test specimens consisted of three different section sizes, having nominal thicknesses ranging from 1.2 mm to 2.0 mm; the nominal depth of the webs and the flange widths ranging from 142 mm to 302 mm. The measured web slenderness (h/t) values of the channel sections ranged from 111.7 to 157.8. The specimen lengths (L) were determined according to the NAS [6]. 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. 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.

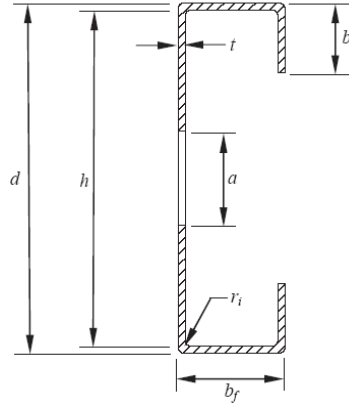


Figure 1: Lipped channel section with hole

2.2 Material properties

Tensile coupon tests were carried out to determine the material properties of the channel specimens. The tensile coupons were taken from the centre of the web plate in the longitudinal direction of the untested specimens. The tensile coupons were prepared and tested according to the British Standard for Testing and Materials [11] for the tensile testing of metals using 12.5 mm wide coupons of a gauge length 50 mm. The coupons were tested in an MTS displacement controlled testing machine using friction grips. Two strain gauges and a calibrated extensometer of 50 mm gauge length were used to measure the longitudinal strain. The material properties obtained from the tensile coupon tests are summarised in Lian *et al.* [12-15].

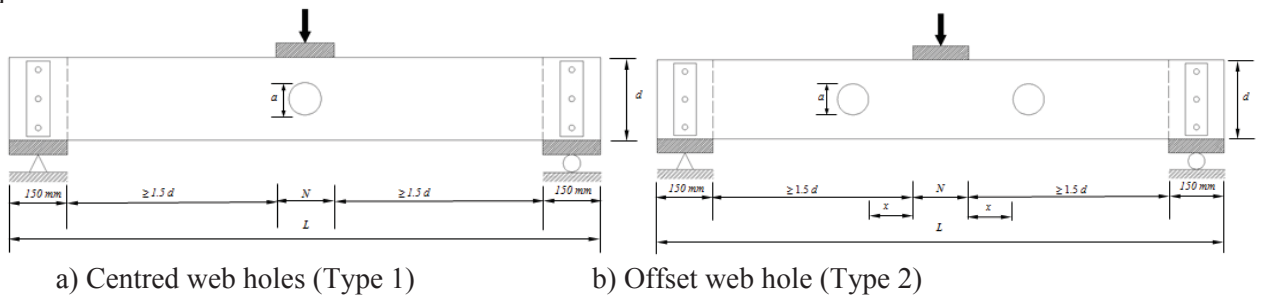


Figure 2: Schematic view of test arrangement for IOF loading condition (Front view)

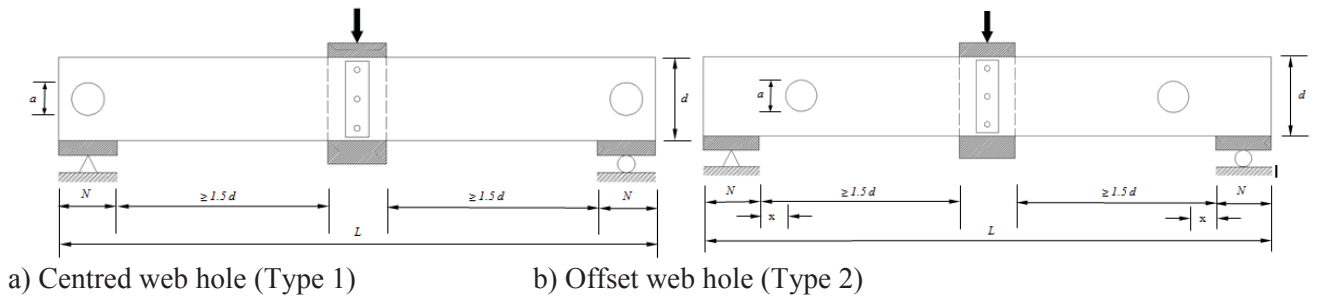


Figure 3: Schematic view of test arrangement for EOF loading condition (Front view)

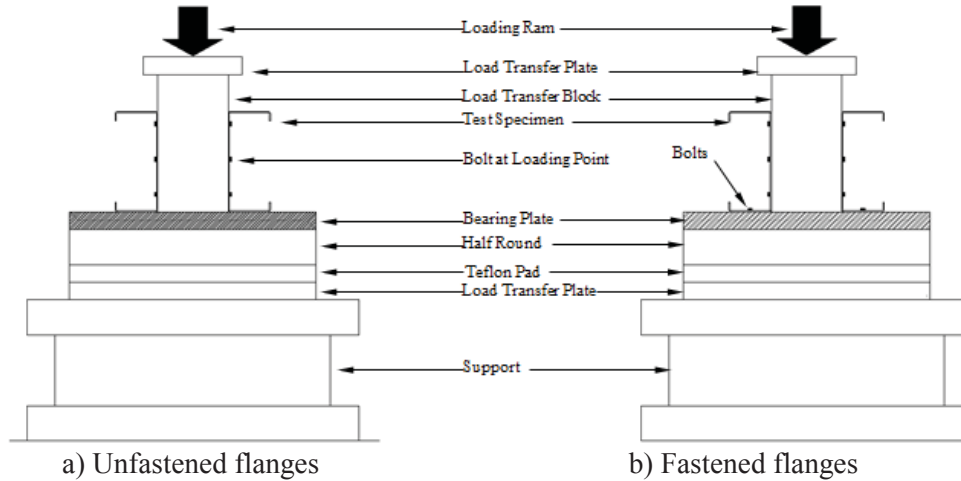


Figure 4: Schematic view of test arrangement (End view)

2.3 Test rig and procedure

The specimens were tested under the interior-one-flange (IOF) and end-one-flange (EOF) loading condition specified in the NAS Specification [6], as shown in Figure 2 and Figure 3, respectively. For the IOF loading conditions, the specimens were bolted to load transfer blocks at each end of the specimens. A bearing plate was positioned at the mid-length of the specimens. For the EOF loading conditions, two channel specimens were used to provide symmetric loading. The specimens were bolted to a load transfer block at the central loading point. Two identical bearing plates of the same width were positioned at both ends of the specimen. Hinge supports were simulated by two half rounds in the line of action of the force. A servo-controlled Tinius-Olsen testing machine was used to apply a concentrated compressive force to the test specimens. Displacement control was used to drive the hydraulic actuator at a constant speed of 0.05 mm/min for all the test specimens. The load was applied through the load transfer plate bolted to the channel-sections. All the bearing plates were fabricated using high strength steel having a nominal yield stress of 560 MPa, and thickness of 25 mm. In the experimental investigation, three different lengths of bearing plates (N) were used, namely, 100 mm, 120 mm and 150 mm. The experimental investigation also considered flanges of the channel section specimens fastened or unfastened to the bearing plates, as shown in Figure 4(a) and Figure 4(b). For the case of the flanges fastened test set-up, the flanges were bolted to the bearing plates.

2.4 Test results

A total of 61 specimens were tested under the IOF loading condition and 100 specimens were tested under EOF loading condition considering flanges unfastened and fastened conditions. The experimental ultimate web crippling loads and failure modes of the specimens under IOF and EOF loading condition are given in Lian et al. [12-15]. Typical examples of the load-deflection curve obtained from a specimen both without and with web holes, and the comparisons with the numerical results, are shown in Figure 7 and Figure 8.

3 NUMERICAL INVESTIGATION

3.1 General

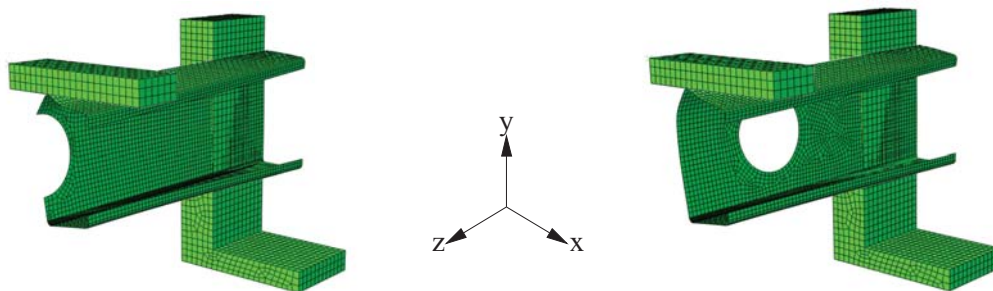
The non-linear general purpose finite element program ABAQUS [10] was used to simulate the web crippling behaviour of the channel sections. The bearing plates, the load transfer block, the channel sections and the contact between the bearing plates and the channel section and load transfer block were modelled. The measured cross-section dimensions and the material properties from the tests were used. The channel sections of the model were based on the centreline dimensions of the cross-section. Specific modelling issues are described in the following subsection.

3.2 Geometry and material properties

One-half of the test set-up was modelled using symmetry about the horizontal planes for IOF loading condition is shown in figure 5. One-quarter of the test set-up was modelled using symmetry about both the vertical transverse and horizontal planes for EOF loading condition is shown in figure.6. Contact surfaces are defined between the bearing plate and the cold-formed steel section. The value of Young's modulus was 203 kN/mm² and Poisson's ratio was 0.3. ABAQUS required the material stress-strain curve input as true stress-true plastic strain. The stress-strain curves were directly obtained from the tensile tests and converted into true stress- true plastic strain curves, as specified in the ABAQUS manual (2013) [10].

3.3 Element type and mesh sensitivity

Figure 5 and Figure 6 show details of a typical finite element mesh of the channel section, the bearing plate and load transfer block. A mesh sensitivity analysis was used to investigate the effect of different element sizes in the cross-section of the channel sections. Finite element mesh sizes were 5 mm × 5 mm for the cold-formed steel channel sections and 8 mm × 8 mm for the bearing plates and load transfer block. From the mesh sensitivity analysis, due to the contact between the load transfer block and inside round corners that form the bend between the flange and web, it was found that at least fifteen elements were required for the corners between the flange and web. On the other hand, for the corners between the flange and lip of the section, only three elements were required. Cold-formed steel channel sections with and without web holes were modelled using S4R shell element. The bearing plates and load transfer block were modelled using analytical rigid plates and C3D8R element.



a) One-half FEA Model (Type 1 holes) b) One-half FEA Model (Type 2 holes)
Figure 5: Interior-one-flange (IOF) loading condition

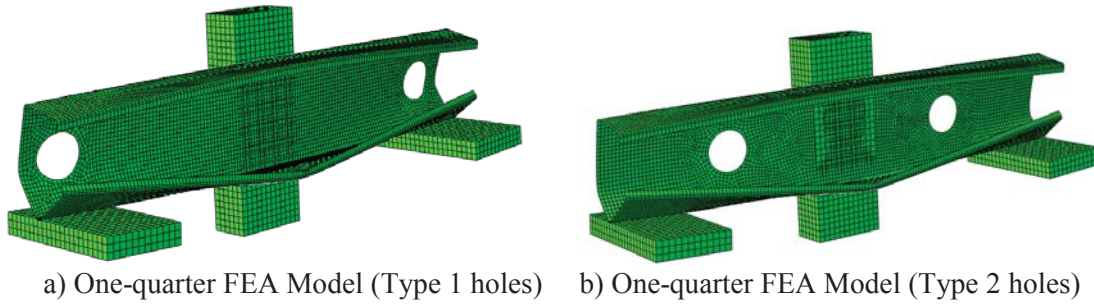


Figure 6: End-one-flange (EOF) loading condition

3.4 Loading and boundary conditions

The vertical load applied to the channel sections through the load transfer block in the laboratory tests was modelled using displacement control. In the finite element model, a displacement in the vertical y direction was applied to the nodes located on the top of the load transfer block. The channel section specimens were tested in pairs, which were bolted to a load transfer block at the central loading point through the web by a vertical row of M16 high tensile bolts. In the shell element idealisation, cartesian connectors were used to simulate the bolts instead of physically modelling bolts and holes. “CONN3D2” connector elements were used to model the in-plane translational stiffness i.e. y - and z -directions. The stiffness of the connectors element was 10 kN/mm, which Lim *et al.* [16-17] suggestion would be suitable. In the x direction, the nodes were prevented from translating. Contact between the bearing plate and the cold-formed steel section was modelled in ABAQUS using the contact pair option. The two contact surfaces were not allowed to penetrate each other. No friction was modelled between the surfaces. In the flanges fastened case, in addition to the contact modelled between the bearing plate and the cold-formed steel-sections, a connector between the flanges and the bearing plate was modelled at the position of the bolt.

3.5 Verification of finite element model

In order to validate the finite element model, the experimental failure loads were compared against the failure load predicted by the finite element analysis. The main objective of this comparison was to verify and check the accuracy of the finite element model. A comparison of the test results with the numerical results of web crippling strengths per web is detailed shown in Lian *et al.* [12-15]. It can be seen that good agreement has been achieved between both results for all specimens. The web crippling failure mode observed from the tests has also been verified by the finite element model for the IOF and EOF loading conditions considering both type of web holes with flanges unfastened and fastened conditions. Typical load-deflection curves comparing the experimental results and the finite element results are shown in figure 7 and figure 8 covering the cases of both with and without the web holes. It is shown that good agreement is achieved between the experimental and finite element results for both the web crippling strength and the failure mode.

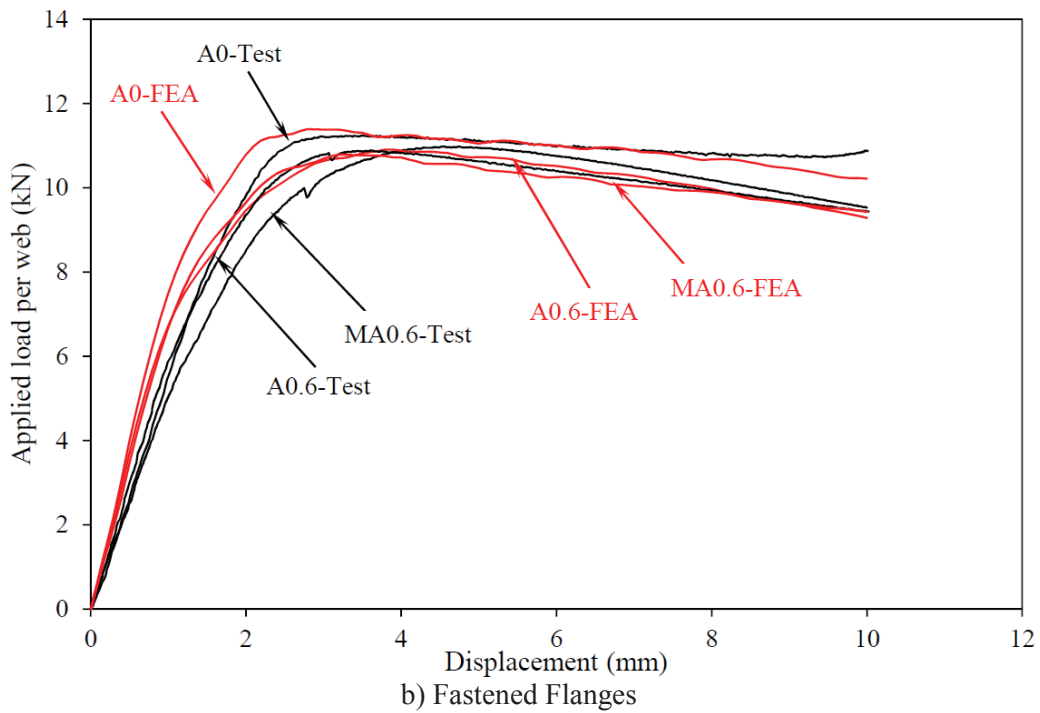
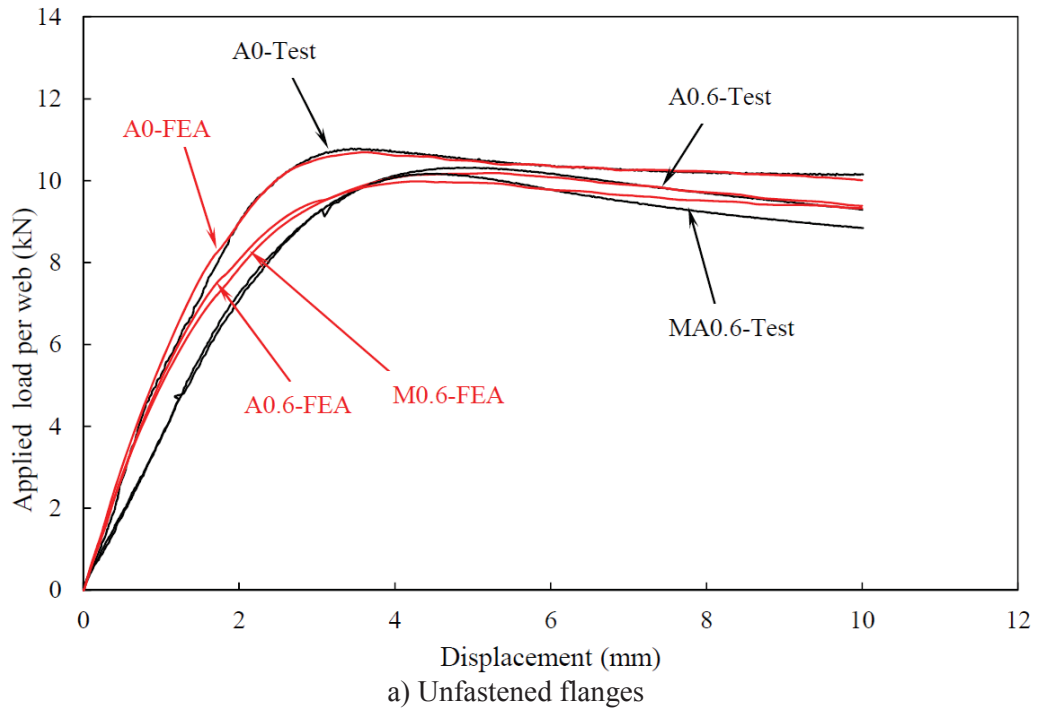


Figure 7: Comparison web deformation curves for a specimen subjected to IOF loading condition

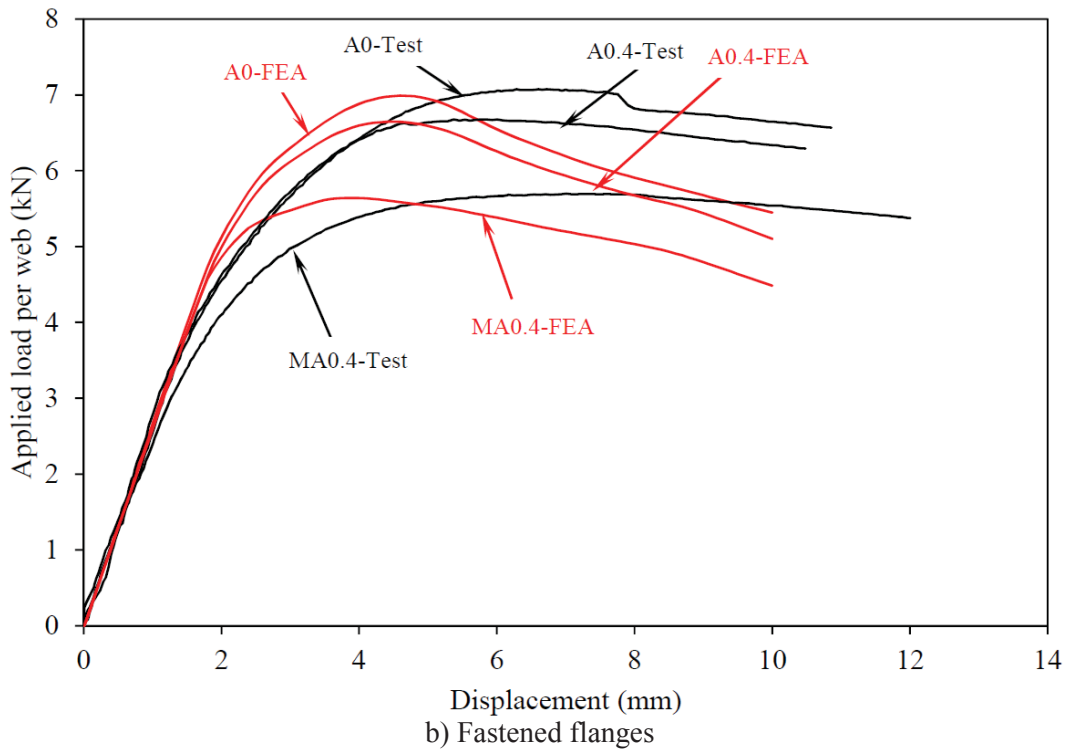
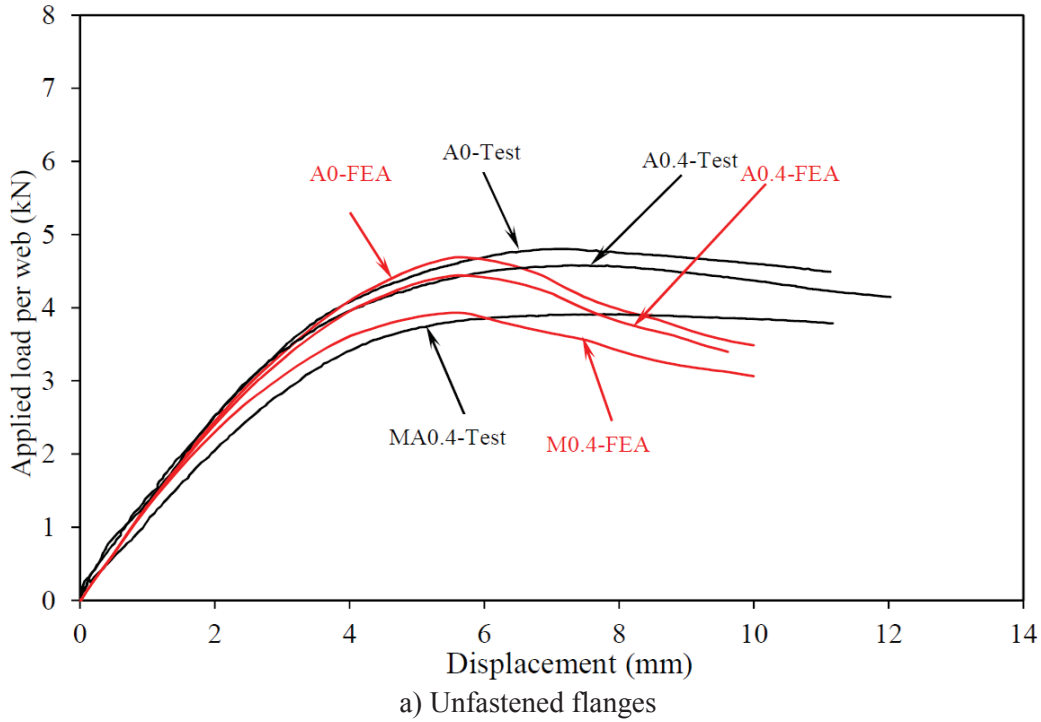


Figure 8: Comparison web deformation curves for a specimen subjected to EOF loading condition

4 CONCLUSIONS

The main conclusions are:

1. An experimental and numerical investigation of lipped channel sections with and without circular web holes subjected to web crippling have been presented;
2. A series of tests was conducted on lipped channel sections with web holes subjected to the interior-one-flange (IOF) and end-one-flange (EOF) loading conditions. The diameter of the web holes was varied in order to investigate the influence of the web holes on

the web crippling strength. The cases of the flanges of the channel sections being fastened and unfastened to the bearing plates also considered.

3. A finite element model that incorporated the geometric and the material nonlinearities has been developed and verified against the experimental results. The finite element model was shown to be able to closely predict the web crippling behaviour of the channel sections, both with and without circular web hole.
4. The new web crippling test data presented in this paper can be used to develop design rules for cold-formed steel sections.

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NOTATION

A	Web holes ratio (a/h)
a	Diameter of circular web holes
b_f	Overall flange width of section
b_l	Overall lip width of section
d	Overall web depth of section
FEA	Finite element analysis
h	Depth of the flat portion of web
L	Length of the specimen
N	Length of the bearing plate
r_i	Inside corner radius of section
t	Thickness of section

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