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Post-buckling behaviour and strength of cold-formed steel lipped channel columns experiencing distortional/global interaction

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ABSTRACT

This paper reports the results of a numerical investigation concerning the elastic and elastic–plastic post-buckling behaviour of cold-formed steel lipped channel columns affected by distortional/global (flexural–torsional) buckling mode interaction. The results presented and discussed were obtained by means of analyses performed using the finite element code Abaqus and adopting column discretisations into fine 4-node isoparametric shell element meshes. The columns analysed (i) are simply supported (locally/globally pinned end sections that may warp freely), (ii) have cross-section dimensions and lengths that ensure equal distortional and global (flexural–torsional) critical buckling loads, thus maximising the distortional/global mode interaction effects, and (iii) contain critical-mode initial geometrical imperfections exhibiting different configurations, all corresponding to linear combinations of the two "competing" critical buckling modes. After briefly addressing the lipped channel column "pure" distortional and global post-buckling behaviours, one presents and discusses in great detail a fair number of numerical results concerning the post-buckling behaviour and strength of similar columns experiencing strong distortional/global mode interaction effects. These results consist of (i) elastic (mostly) and elastic–plastic non-linear equilibrium paths, (ii) curves or figures providing the evolution of the deformed configurations of several columns (expressed as linear combination of their distortional and global components) and, for the elastic–plastic columns, (iii) figures enabling a clear visualisation of (iii_1) the location and growth of the plastic strains and (iii_2) the characteristics of the failure mechanisms more often detected in the course of this research work.

1. Introduction

Most cold-formed steel members display very slender thin-walled open cross-sections, a feature making them highly susceptible to several instability phenomena, namely *local*, *distortional* and *global* (flexural or flexural–torsional) buckling – see Fig. 1(a)–(d). Moreover, depending on the member length and cross-section shape/dimensions, any of these buckling modes can be critical. However, since several commonly used cold-formed steel member geometries may lead to rather similar distortional and global buckling stresses, the corresponding post-buckling behaviour (elastic or elastic–plastic), ultimate strength and failure mechanism are likely to be strongly affected by the interaction between these two buckling modes.

It has been well known for quite a long time that cold-formed steel members exhibit stable local and global elastic post-buckling behaviours with clearly different post-critical strength reserves: rather high in the first case and quite low in the second. On the other hand, fairly recent studies have shown that (i) the *distortional* post-buckling behaviour fits somewhere in the middle of the two previous ones (in kinematic and strength terms) and (ii) exhibits a non-negligible asymmetry with respect to the sense of the flange-stiffener motion (outward or inward) – *e.g.*, see the works of Kwon and Hancock [1], Prola and Camotim [2], Camotim and Silvestre [3] or Silvestre and Camotim [4].

Concerning the mode interaction phenomena that may affect the column post-buckling behaviour and strength, those stemming from the nearly simultaneous occurrence of local and global buckling are, by far, the better understood – this is attested by the fact that their effects are already taken into account by virtually all current hot-rolled and cold-formed steel design codes, either through the well-known "plate effective width" concept (*e.g.*, [5]) or by means of the much more recent (but increasingly popular) "Direct Strength Method" (*e.g.*, [6,7]). On the other hand, the influence of local/distortional mode interaction effects on the post-buckling behaviour and strength of lipped channel columns has attracted the attention of several researchers in the recent past (*e.g.*, [8–13]) – it is worth noting that some of the investigations carried out have already led to the development and calibration of novel

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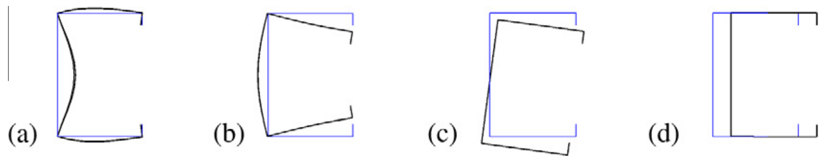
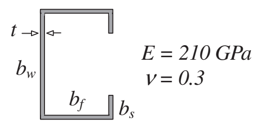
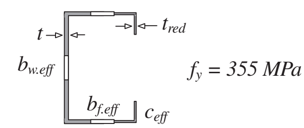


Fig. 1. Lipped-channel column (a) local, (b) distortional, (c) flexural–torsional and (d) flexural buckling mode (cross-section) shapes.



(a)

b_w (mm)	b_f (mm)	b_s (mm)	t (mm)
150	110	17.5	2.4



(b)

$b_{w.eff}$ (mm)	$b_{f.eff}$ (mm)	c_{eff} (mm)	t (mm)	t_{red} (mm)	A_{eff} (mm^2)
92.6	104.1	16.3	2.4	1.29	648.4

Fig. 2. Lipped channel column (a) cross-section dimensions and elastic constants, and (b) effective cross-section geometry and dimensions (according to EC3 and for f_y = 355 MPa).

applications (design curves) of the Direct Strength Method (*e.g.*, [9,12–14]).

However, there are very few studies addressing the influence of the distortional/global buckling mode interaction on the post-buckling behaviour and ultimate strength of cold-formed steel columns (or any other members, for that matter). Indeed, besides a preliminary version of the current paper [15], the authors are only aware of a very recent publication that reports an experimental study on fixed-ended cold-formed stainless steel lipped channel columns [16]. Nevertheless, one should mention that (i) Eurocode 3 (Part 1–3) includes a procedure to jointly account for global, local (through an "effective width" approach) and distortional (through a "reduced thickness" approach) buckling, mainly based on work done by Thomasson [17] and Höglund [18], and that (ii) the North-American and Australian/New Zealander Specifications adopt an "effective width" approach to handle distortional/global interactive buckling, based on experimental work carried out by Desmond et al. [19]. However, none of the above studies addresses explicitly the mechanics of the mode interaction phenomenon dealt with in this paper – this is probably the reason why those design approaches are extremely conservative.

Therefore, the aim of this work is to present and discuss a set of numerical results concerning the (i) post-buckling behaviour (elastic and elastic–plastic), (ii) ultimate strength and (iii) failure mode nature of cold-formed steel lipped channel simply supported columns affected by distortional/global (flexural–torsional) mode interaction. In order to enable a thorough assessment of all possible mode interaction effects, one analyses columns with (i) the cross-section dimensions and material properties given in Fig. 2(a), leading to a distortional buckling load meaningfully (about 20%) lower than its local counterpart, thus ensuring that local/distortional interaction effects are not relevant, and (ii) a length selected to guarantee the coincidence between the distortional (*D* – multiple half-waves) and global (*G* – single half-wave) buckling loads, thus maximising the distortional/global interaction effects.[1] In order to provide an idea of how the Eurocode 3 design approach handles a column with this cross-section, Fig. 2(b) shows the associated "effective area", which has been calculated for a yield stress f_y = 355 MPa and must be considered in the safety checking against global (flexural–torsional) buckling – it corresponds to a 33% cross-section area reduction (A_{eff}/A = 0.67).

A fairly large number of columns are analysed and they only differ in the initial geometrical imperfection configuration. The various configurations consist of linear combinations of the competing distortional and global buckling mode shapes with amplitudes (mid-span flange-lip corner vertical displacements) of (i) 10% of the wall thickness t (distortional mode) and (ii) L/1000 (global mode), values that are often adopted for cold-formed steel members and fall below the typical allowable geometrical tolerances, namely (i) b/500, prescribed by ECCS [20] for plates, and (ii) L/750, global tolerance recently stipulated in Europe. Although investigating the influence of the initial imperfection amplitudes on the column post-buckling behaviour and strength is outside of the aim and scope of this work, a very limited imperfection-sensitivity study is included in the paper – for further insight on this topic, the interested reader is referred to investigations carried out (i) by Schafer and Peköz [21] and Dubina and Ungureanu [22], in the context of cold-formed steel members, and (ii) by Maiorana et al. [23], concerning steel girder webs. All numerical results presented were yielded by finite element analyses carried out in the code Abaqus [24] that (i) adopt member discretisations into fine 4-node isoparametric shell element meshes (preliminary convergence/accuracy studies showed that it suffices to discretise the cross-section mid-line into 24 finite elements – 10 in the web, 6 in each flange and 1 in each stiffener – Fig. 4(b) illustrates the meshes adopted, which correspond to an element width approximately equal to 15 mm and a length/width ratio roughly equal to 1), (ii) model the simply supported conditions by imposing null transverse displacements at all end section nodes, as illustrated in Fig. 3(a) (note also that, to preclude a spurious longitudinal rigid-body motion, the axial displacement was also prevented at the mid-span mid-web node) and (iii) simulate the axial compression loading through compressive forces p, uniformly distributed along both column end-section mid-lines, as depicted in Fig. 3(b) (the load parameter is $P = pA/t$, where A and t are the column cross-section area and wall thickness). Detailed accounts of all the relevant modelling issues can be found in previous works by Dinis et al. [11] and Dinis and Camotim [25].

Column buckling analyses are performed at the outset, in order (i) to select the column length that maximised the *D*/*G* interaction, and also (ii) to obtain the associated buckling mode shapes, required to define the initial geometrical imperfections. Next, one addresses

[1] Moreover, the selection of the column cross-section dimensions, obtained through "trial-and-error" buckling analyses, also satisfies two additional conditions: (i) competing ("pure") buckling modes with odd half-wave numbers, so that the maximum deformation occurs at mid-span (although this feature is by no means essential, it renders the presentation of the results much easier) and (ii) no higher-order distortional buckling mode "close" to the distortional and global modes under consideration – this last condition was not easy to enforce (for the cross-section dimensions chosen, there is a 12% buckling load gap).