Thin-Walled Structures 105 (2016) 231–247

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Full length article

Numerical investigation and direct strength design of cold-formed steel lipped channel columns experiencing local–distortional–global interaction

D. Cava [a],*, D. Camotim [b], P.B. Dinis [b], A. Madeo [a]

[a] University of Calabria, Arcavacata di Rende, CS, Italy
[b] CEris, ICIST, DECivil, Instituto Superior Técnico, Universidade de Lisboa, Portugal

ARTICLE INFO

Article history:
Received 11 October 2015
Received in revised form
7 February 2016
Accepted 25 March 2016
Available online 13 May 2016

Keywords:
Cold-formed steel columns
Lipped channels
Local–distortional–global (LDG) interaction
Koiter's method
Initial geometrical imperfection
Shell finite element analysis
Ultimate strength
Direct strength method (DSM)

ABSTRACT

This paper reports the results of a numerical investigation concerning the relevance and Direct Strength Method (DSM) prediction of the ultimate strength erosion caused by local-distortional-global (LDG) interaction in cold-formed steel fixed-ended lipped channel columns. The geometries of the columns analysed (cross-section dimensions and lengths) were carefully selected to ensure that the three competing critical buckling loads are not more than 20% apart, thus guaranteeing a fairly high level of LDG coupling, and ordered in all the various possible sequences. In order to cover a wide slenderness range, several yield stresses are considered, falling below, in-between and above the lowest and highest critical buckling stresses. After providing a brief description of the column selection procedure, which is based on buckling analyses performed with Generalised Beam Theory (GBT), the methodology adopted to identify the most detrimental initial geometrical imperfection shape (in the sense it minimises the column strength) is addressed – it employs Koiter's asymptotic method along with a Monte Carlo simulation. Then, columns containing those initial geometrical imperfections are compressed up to failure, by means of ABAQUS shell finite element analyses (SFEA), making it possible to acquire in-depth knowledge on the behaviour of lipped channel columns undergoing LDG interaction and gather considerable failure load data. Finally, the last part of the paper is devoted to the DSM prediction of those failure loads and uses the obtained "data bank" to assess whether the available design approaches are able to handle adequately the ultimate strength erosion caused by the triple interaction phenomenon under investigation – if this is not the case, new design curves must be developed.

1. Introduction

Most cold-formed steel columns are known to be susceptible to instability phenomena, namely local (L), distortional (D) or global (G, flexural or flexural-torsional) buckling – Fig. 1(a)-(d) depict the corresponding lipped channel column cross-sections. Depending on the column geometry (cross-section shape and dimensions and member length), either of the above buckling behaviours may be critical. Moreover, for some commonly used column geometries, two or three of these buckling behaviours may be associated with relatively close buckling loads, which implies that the corresponding structural response and ultimate strength are bound to be significantly influenced/eroded by the occurrence of mode interaction.

Local-global (LG) interaction has been thoroughly investigated in the past and, therefore, all the current design specifications contain provisions against the corresponding failures, based on either the Effective Width Method or the DSM [1], even if the latter has been shown to provide high-quality estimates with relatively little effort [2]. In the last few years, a considerable amount of research work has been directed towards investigating columns undergoing local-distortional (LD) interaction [3–12], comprising numerical and experimental studies, as well as the proposal of design approaches, and involving lipped channel (mostly), hat-section, zed-section and rack-section columns practically always with fixed-ended support conditions. As far as the interaction between distortional and global buckling (DG interaction), the available literature is extremely scarce. To the author's best knowledge there are only two unrelated works, both involving lipped channel columns: a numerical investigation on simply supported structural steel columns [13] and an experimental study on fixed-ended stainless steel columns [14].

The situation concerning local-distortional-global (LDG) interaction is slightly different, since there exists already a fair amount of numerical and experimental work on fixed-ended lipped channel columns (i) with very close (less than 10% apart) critical

---

* Corresponding author.

http://dx.doi.org/10.1016/j.tws.2016.03.025
0263-8231/© 2016 Elsevier Ltd All rights reserved.

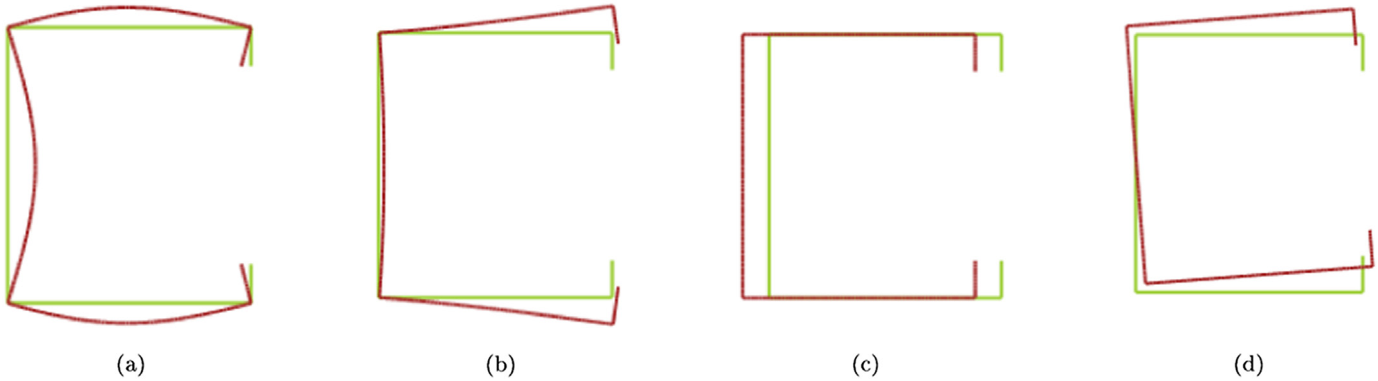

Fig. 1. Lipped channel buckled shapes associated with column (a) local, (b) distortional, (c) flexural and (d) flexural–torsional buckling.

local, distortional and global buckling loads [15–17] and (ii) exhibiting critical local buckling and higher (between 10% and 30%) close distortional and global critical buckling loads [18,19]. The experimental and numerical failure loads obtained were compared with various DSM-based predictions and led to the preliminary conclusion that the currently codified design curve against local-global interactive failures generally provides efficient (safe and accurate) estimates for the whole set of column failure loads.[1] The objective of this work is to present a numerical (SFEA) investigation aimed at assessing whether the above preliminary conclusion can be extended to a wider range of fixed-ended lipped channel columns experiencing strong LDG interaction.

The set of columns analysed was carefully selected to exhibit (i) critical local, distortional and global buckling loads (P_{crL}, P_{crD}, P_{crG}) not more than 20% apart and ordered in all the various possible sequences, i.e., values of the ratios $R_{DL} = P_{crD}/P_{crL}$ (distortional-to-local), $R_{GD} = P_{crgG}/P_{crD}$ (global-to-distortional) and $R_{GL} = P_{crG}/P_{crL}$ (global-to-local) comprised between 0.8 and 1.2 and ordered differently. The paper begins by illustrating the methodologies adopted (i) to select the column geometries associated with strong LDG interaction, by means of sequences of buckling analyses performed in the code GBTUL [21,22] (based on Generalised Beam Theory – GBT), and (ii) to identify the most detrimental initial geometrical imperfection shape, by means of elastic post-buckling SFEA – this initial imperfection shape is obtained as a linear combination of the column buckling modes and a technique based on Koiter's asymptotic method [23] along with Monte Carlo simulations. Then, the columns selected (i) containing the most detrimental initial geometrical imperfections identified and (ii) exhibiting various yield stresses, in order to cover a wide slenderness range, are analysed up to failure through ABAQUS [24] elastic–plastic post-buckling SFEA, in order to acquire in depth knowledge on the behaviour of lipped channel columns undergoing LDG interaction and gather considerable failure load data. Finally, the failure loads obtained from the above fairly extensive parametric study are compared with the corresponding estimates provided by a few available DSM-based design approaches against interactive failures, making it possible to draw further conclusions about their adequacy to predict the ultimate strength of fixed-ended lipped channel columns affected by strong LDG interaction.

2. Buckling behaviour – column geometry selection

To obtain cold-formed steel (E=210 GPa and $\nu = 0.3$) lipped channel column geometries (web, flange and stiffener width – b_w, b_f, b_s –, wall thickness t and length L) ensuring strong LDG interaction, “educated” trial-and-error GBTUL [21,22] buckling analyses were performed. Fig. 2(a) illustrates the output of a buckling analysis sequence, leading to the identification of the CS2 column geometry defined in Table 1 – note that the column with length L=2650 mm (i) exhibits close local, distortional and global critical buckling loads ($P_{crL} = 58.2$ kN, $P_{crD} = 53.6$ kN, $P_{crG} = 53.5$ kN), (ii) corresponds to the intersection between (ii$_1$) an almost horizontal “plateau” of the P_{cr} vs. L curve, associated with local buckling (short columns) or local–distortional interactive buckling (intermediate columns) and (ii$_2$) a sharply descending branch, associated with global (flexural–torsional) buckling (long columns).

In view of the aim of this work, the selection strategy adopted consisted of (i) determining cross-section dimensions associated with several R_{DL} ratio values comprised between 0.8 and 1.2, and, for each of those cross-sections, (ii) choose a length range that ensures that the R_{GD} and R_{GL} ratios also fall within the above interval. The “trial and error” analysis sequences led to the identification of the 10 cross-section geometries given in Table 1, together with the shortest and longest lengths considered (L_s, L_l) and the associated variation of the R_{DL}, R_{GD} and R_{GL} ratios – all column lengths and critical buckling stresses (f_{crL}, f_{crD}, f_{crG} – obtained by dividing P_{crL}, P_{crD}, P_{crG} by the cross-sectional area) are presented in Tables A1–A10, included in Annex A. It is worth noting that each of these 10 tables corresponds to one row of Table 1, which provides column cross-section dimensions and minimum and maximum lengths – the R_{DL}, R_{DG}, R_{GL} value pairs concern the columns with the minimum and maximum lengths, respectively.

3. Numerical model

This section addresses a number of finite element modelling issues relevant for the performance of the elastic and elastic-plastic analyses whose results are presented in this work, namely (i) to identify and quantify the most detrimental initial geometrical imperfections and (ii) to obtain the column elastic–plastic failure loads. In particular, issues related to (i) the column discretisation and (ii) the modelling of the end support conditions, applied loading and material behaviour are addressed.

(i) *Discretisation*: In the asymptotic analysis performed to identify the most detrimental initial geometrical imperfections, the column mid-surface is discretised into a fine mesh of mixed 4-node 3D plate finite elements [25,26], which makes it possible to avoid extrapolation locking phenomena [27]. In the parametric study carried out in ABAQUS to obtain the failure load data code, the column mid-surface is discretised into S4 finite elements (ABAQUS nomenclature: isoparametric 4-node shell elements with the shear stiffness yielded by a full integration rule). The mesh

---

[1] There is also a numerical investigation on simply supported lipped channel columns [20] – however, it did not include design considerations.