Thin-Walled Structures 101 (2016) 181–204

Contents lists available at ScienceDirect

Thin-Walled Structures

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

Full length article

On the influence of local-distortional interaction in the behaviour and design of cold-formed steel web-stiffened lipped channel columns

A.D. Martins, P.B. Dinis, D. Camotim *

CEris, ICIST, DECivil, Instituto Superior Técnico, Universidade de Lisboa, Portugal

ARTICLE INFO

Article history:
Received 4 October 2015
Accepted 25 November 2015

Keywords:
Cold-formed steel columns
Web-stiffened lipped channels
Local-distortional interaction
Abaqus SFEA investigation
Post-buckling behaviour
Direct Strength Method (DSM) design

ABSTRACT

This work reports the results of a numerical (Abaqus shell finite element analysis) investigation on the influence of local–distortional (L–D) interaction in the ultimate strength and design of fixed-ended cold-formed steel web-stiffened lipped channel columns, hereafter termed “WSLC columns”. These results concern columns with various geometries and yield stresses, ensuring a wide variety of combined ratios between (i) the distortional and local critical buckling stresses, and (ii) the yield stress and the higher of the above two buckling stresses. The objectives of the work are two-fold: (i) acquire in-depth knowledge on the mechanics underlying the L–D interaction in the WSLC columns analysed, all selected to ensure that local buckling is triggered by the flanges, and also (ii) provide a first contribution towards the efficient Direct Strength Method (DSM) design of these columns. The results presented and discussed concern the (i) post-buckling behaviour (elastic and elastic–plastic), (ii) ultimate strength and (iii) failure mechanisms of WSLC columns undergoing L–D interaction. Special attention is paid to the comparison between the ultimate strength erosion, stemming from L–D interaction, exhibited by web-stiffened and plain lipped channel columns (the latter were studied earlier by the authors). The paper closes with some considerations about the impact of the findings reported in this work on the design of cold-formed steel columns experiencing different levels of L–D interaction.

1. Introduction

Cold-formed steel structural systems commonly used in the construction industry are very often formed by slender open-section thin-walled members, which exhibit a low torsion stiffness and a high susceptibility to instability phenomena involving cross-section deformation, namely local and distortional buckling – Fig. 1(b)–(c) shows buckled WSLC cross-sections associated with local (flange-triggered) and distortional column modes – for comparison purposes, Fig. 1(d)–(e) depict globally buckled cross-sections. Moreover, cold-formed steel members often display geometries (cross-section shape and/or dimensions, and unrestrained length) that lead to fairly close local (L) and distortional (D) critical buckling stresses, which means that their post-buckling behaviour (elastic or elastic–plastic), ultimate strength and failure mode are likely to be affected, to a smaller or larger extent, by interaction effects involving these two instability phenomena, *i.e.*, by local–distortional (L–D) interaction.

A considerable amount of research has been recently devoted to the structural response and load-carrying capacity of cold-formed steel columns affected by L–D interaction, including experimental studies, numerical simulations and design proposals. However, the vast majority of the available results concerns columns with plain lipped channel columns. For instance, while the works of Kwon and Hancock [1], Kwon et al. [2], Loughlan et al. [3] and Young et al. [4] provided experimental evidence of L–D interaction, Dinis et al. [5], Silvestre et al. [6] and Martins et al. [7] obtained numerical evidence of this coupling phenomenon, by resorting to shell finite element analysis (SFEA). Nevertheless, some research work has also been reported for columns with other cross-sections shapes, namely by Dinis et al. [8] (hat-sections), Dinis et al. [9] (rack-sections) and Dinis and Camotim [10] (zed, hat and rack-sections). In all the above cross-section shapes, local buckling is practically always triggered by the web, where most of the L–D interaction takes place. This situation may change when intermediate stiffeners (*e.g.*, “v-shaped” stiffeners) are added to the web (see Fig. 1(a)), since local buckling is bound to be triggered by the flanges, with very little deformation occurring in the web (see Fig. 1(b)). Naturally, this fact may alter considerably the L–D interaction features. However, to the authors best knowledge, this type of L–D interaction has only been addressed, experimentally, by Kwon and Hancock [1], Kwon et al. [2], Yap and Hancock [11] and He et al. [12]. The aim of the present work is to

* Corresponding author.
E-mail addresses: andrerdmartins@ist.utl.pt (A.D. Martins), dinis@civil.ist.utl.pt (P.B. Dinis), dcamotim@civil.ist.utl.pt (D. Camotim).

http://dx.doi.org/10.1016/j.tws.2015.11.021
0263-8231/

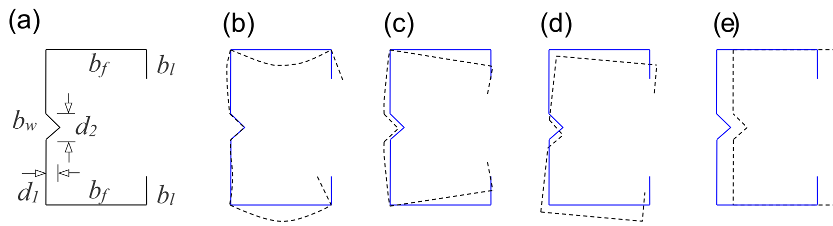

Fig. 1. Web-stiffened lipped channel (a) geometry and buckled shapes associated with column (b) local (flange-triggered), (c) distortional and (d) flexural-torsional and (e) flexural buckling.

present and discuss numerical results concerning the post-buckling and ultimate strength behaviour of WSLC columns undergoing flange-triggered L–D interaction, in order to acquire fresh insight on this coupling phenomenon, which will be subsequently used to contribute towards the development of a design approach for such members based on the Direct Strength Method (DSM).

The DSM (i) has its roots in the work of Hancock et al. [13], (ii) was first proposed by Schafer and Peköz [14], and (iii) is included in the Australian/New Zealand [15] and North American [16] cold-formed steel specifications (amongst others). It has been shown to provide efficient (safe and accurate) estimates of the ultimate strength of cold-formed steel columns (with and without perforations) failing in local (L), distortional (D), global (G) and local-global (L–G) interactive modes. However, the consideration of these limit states is not sufficient for the design of such members, since interaction phenomena involving distortional buckling, namely L–D, D–G and L–D–G interaction, may cause significant erosion of the column ultimate strength – neglecting these coupling phenomena may lead to unacceptably low reliability indices, *i.e.*, to a high likelihood of reaching unsafe designs.

This work deals solely with column L–D interactive failures. Although several attempts have been made to develop a DSM-based design approach to handle such failures, they focused almost exclusively on plain cross-sections, namely lipped channels, zeds, hats and racks – all exhibiting web-triggered local buckling. In this context, a new DSM-based design approach, termed here "MNDL approach", was proposed for lipped channel columns [6] and subsequently extended to cover zed, hat and rack-section columns [10] – note that this approach was validated exclusively against failure loads from columns with fairly close local and distortional critical buckling stresses, *i.e.*, columns affected by "true L–D interaction". Very recently, the authors [7] extended the scope of the previous investigations and assessed the performance of the MNDL design approach for plain lipped channel, hat, zed and rack-section columns affected by L–D interaction caused by a "secondary bifurcation". It was found that good estimates are still provided for a fairly wide range of ratios between the local and distortional critical buckling stresses, which means that, at present, the MNDL approach is the most successful/effective in predicting column L–D interactive failures (for plain cross-section columns). A main purpose of this work is to assess whether this assertion remains valid for WSLC columns, which exhibit flange-triggered local buckling.

This paper (i) presents and discusses numerical results aimed at acquiring in-depth understanding on the mechanics underlying L–D interaction in WSLC columns and (ii) provides a contribution towards the efficient DSM design of such structural elements[1]. A systematic numerical investigation is carried out, by means of Abaqus (Simulia Inc [18]) shell finite element analyses, in order to characterise the post-buckling behaviour and strength of WSLC columns experiencing more or less severe L–D interaction effects. The results obtained concern the (i) post-buckling behaviour (elastic and elastic-plastic), (ii) ultimate strength and (iii) failure mechanisms of WSLC columns selected to undergo considerable L–D interaction. Special attention is devoted to comparing the ultimate strength erosions stemming from L–D interaction in plain and WSLC columns, in order to assess whether the DSM-based design approaches developed for "plain cross-section" columns are also applicable to their WSLC counterparts. Finally, the paper closes with some remarks on the possibility of proposing a DSM-based design approach capable of efficiently predicting the load-carrying capacity of "plain cross-section" and WSLC cold-formed steel columns undergoing various "levels" of L–D interaction.

[1] Note that the authors [17] have recently reported the first results of this investigation, concerning columns with very close local and distortional critical buckling stresses.

2. Buckling analysis – column geometry selection

In order to investigate the ultimate strength of fixed-ended WSLC columns affected by various levels of L–D interaction, the first step consists of selecting column geometries (cross-section dimensions and length) associated with different ratios between their local and distortional critical buckling stresses ($R_{DL}=f_{crD}/f_{crL}$). As done in previous studies, the column geometry selection was made by means of a "trial-and-error" procedure involving the performance of GBT-based buckling analysis sequences using the code GBTul (Bebiano et al. [19]), which makes it possible to determine buckling loads associated with "pure" local, distortional and global buckling modes. Fig. 2(a) shows the GBT discretisation adopted for all the WSLC columns analysed, which (i) comprises 21 (9 natural and 12 intermediate) nodes and (ii) leads to 21 deformation modes (4 global, 5 distortional and 12 local) – Fig. 2 (b) displays the in-plane deformed shapes of all these modes. The "pure" f_{crL}, f_{crD} and f_{crG} are obtained through GBT analyses including the following deformation modes:

(i) f_{crG}: modes **2**+**4**, since the WSLC column critical global mode is flexural-torsional (of course, very long columns will buckle in minor-axis flexural modes, *i.e.*, mode **3**).
(ii) f_{crD}: unlike in plain lipped channel columns [4], for which all (two) distortional modes are considered to determine f_{crD}, only two of the five WSLC column distortional modes are included in the GBT analyses (modes **5** and **6** – see Fig. 2(b)). The remaining three modes (**7**–**9**) are only termed "distortional" because they exhibit natural node in-plane displacements (the natural nodes are identified in Fig. 2(a)). For instance, note that modes **8** and **9** are clearly "disguised local modes" with web single and double curvature, respectively – these deformation modes are the web-stiffened counterparts of the plain modes **7** and **8** [4].
(iii) f_{crL}: in view of the content of the previous item, the GBT buckling analyses include deformation modes **7** to **21**. Due to the very short local half-wave length, the column longitudinal discretisation must be finer than that used to calculate f_{crD} and f_{crG} – 40–60 beam finite elements were considered.