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On the direct strength design of cold-formed steel columns failing in local-distortional interactive modes

André Dias Martins, Dinar Camotim*, Pedro Borges Dinis

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

A R T I C L E I N F O

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A B S T R A C T

This paper present and discusses proposals for the codification of efficient design approaches for cold-formed steel columns affected by local-distortional (L-D) interaction. These proposals, based on the Direct Strength Method (DSM), were developed, calibrated and validated on the basis of experimental and numerical (shell finite element) failure load data concerning columns with several cross-section shapes (plain, web-stiffened and web-flange-stiffened lipped channels, hat-sections, zed-sections and rack-sections) and obtained from investigations carried out by various researchers. Three types of L-D interaction are taken into account, namely "true L-D interaction", "secondary-local bifurcation L-D interaction" and "secondary-distortional bifurcation L-D interaction". Moreover, previously available DSM-based design approaches developed to handle column L-D interactive failures are reviewed and their merits are assessed and compared with those exhibited by the present proposals. The paper also presents reliability assessments of the failure load predictions provided by the available and proposed DSM-based design approaches, following the procedure prescribed by the current version of the North American Specification for the Design of Cold-Formed Steel Structural Members.

1. Introduction

Cold-formed steel (CFS) members invariably display very slender thin-walled open cross-sections, a feature responsible for their high susceptibility to several individual (local – L, distortional – D, global – G) or coupled (L-G, L-D, D-G, L-D-G) buckling phenomena. Nowadays, it is consensual amongst the technical and scientific communities working with CFS structures that it is necessary to establish efficient (safe and accurate) design approaches to handle interactive failures, a goal that has long been achieved for L-G interaction, a coupling phenomenon affecting both cold-formed and hot-rolled steel members. In the case of CFS members, design approaches based on the "Effective Width" and "Direct Strength" concepts are currently codified (e.g., [1]). Concerning interactive failures involving distortional buckling, virtually exclusive of CFS members, the situation is completely different and adequate design approaches can only be established after in-depth knowledge about the structural response of members affected by the coupling phenomenon under consideration has been acquired. In the case of CFS columns undergoing L-D interaction, such knowledge already exists, mainly due to the efforts of the authors. Moreover, design approaches based on the Direct Strength Method (DSM – e.g., [2,3]) have been proposed to predict specifically L-D interactive failures in columns exhibiting most of the cross-section shapes of practical interest – the estimates provided by such design approaches were shown to be safe and reliable. Thus, it may be rightfully argued that only the codification of DSM-based design approaches against column L-D interactive failures is missing – indeed, the currently codified DSM column design curves concern only L, D, G and L-G (interactive) failures, i.e., the column nominal strength (P_n) is given by the condition $P_n = min\{P_{nL}, P_{nD}, P_{nG}, P_{nLG}\}$.[1] The aim of this work is to propose additional design approaches covering adequately short-to-intermediate columns, which are often prone to L-D interaction, which means that $P_n = min\{P_{nL}, P_{nD}, P_{nG}, P_{nLG}, P_{nLD}\}$ – P_{nLD} is the column nominal strength against L-D interactive failures.

As mentioned in the previous paragraph, the objective of this paper is to present and discuss proposals for the possible codification of efficient DSM-based design approaches for CFS columns undergoing L-D interaction (the ultimate goal of this research effort). These proposals were developed, calibrated and validated on the basis of (i) experimental failure loads obtained from test campaigns carried out be several researchers (the authors were involved in some of them) and (ii) extensive numerical failure load data obtained by means of shell finite element (SFE) geometrically and materially non-linear imperfect analyses (GMNIA). The above experimental and numerical failure loads

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

[1] The values of P_{nL} and P_{nLG} are obtained from the same set of expressions.

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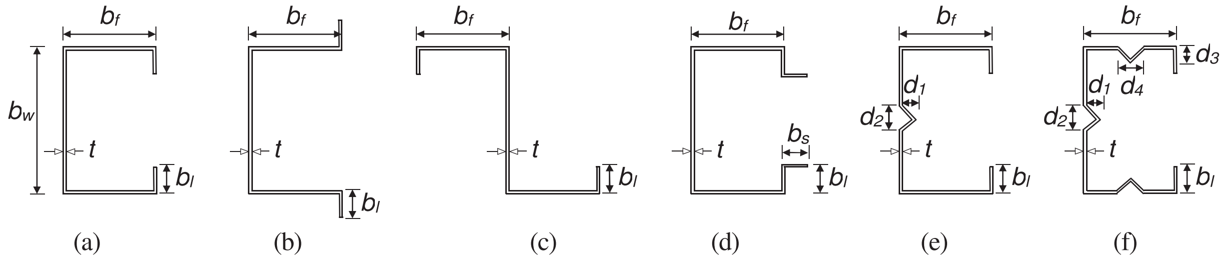

Fig. 1. Cross-section shapes and dimensions of the columns analysed: (a) plain lipped channel, (b) hat-section, (c) zed-section, (d) rack-section, (e) web-stiffened lipped channel and (f) web-flange-stiffened lipped channel.

Table 1
Available experimental test results concerning CFS columns experiencing L-D interaction.

	SLI	TI	SDI
PCS	Kwon and Hancock [4] – (1)	Kwon and Hancock [4] – (4) Kwon et al. [9] – (5)	Young et al. [8] – (16) Loughlan et al. [7] – (20) Young and Rasmussen [5] – (3) Kwon et al. [6] – (5) Dinis et al. [10] – (10)
WSLC	Kwon and Hancock [4] – (3) Yap and Hancock [11] – (5)	Kwon and Hancock [4] – (3) Kwon et al. [6] – (7) He et al. [12] – (14) Yap and Hancock [11] – (6)	Kwon et al. [6] – (3) He et al. [12] – (3)
WFSLC		Yang and Hancock [13] – (8)	Yang and Hancock [13] – (4)
	9	47	64

concern columns with various cross-section shapes, namely plain, web-stiffened and web-flange-stiffened lipped channels, hat-sections, zed-sections and rack-sections – hereafter termed “C”, “WSLC”, “WFSLC”, “H”, “Z”, “R” – i.e., those displayed in Fig. 1(a)–(f). Moreover, three types of L-D interaction are taken into account, namely (i) “true L-D interaction” (TI), occurring in columns with close local and distortional critical buckling loads (strongest L-D interaction effects), (ii) “secondary-local bifurcation L-D interaction” (SLI) and (iii) “secondary-distortional bifurcation L-D interaction” (SDI) – the last two occur in columns with the non-critical buckling load visibly above the critical one but significantly below the squash load. Since SLI was found to cause only negligible failure load erosion (with respect to the distortional ultimate strength), the corresponding column failures can be deemed adequately covered by the currently codified DSM column distortional design curve. However, the remaining two L-D interaction types must be addressed, i.e., specific design approaches have to be established to handle the corresponding column interactive failures. While the authors believe that, on the basis of the existing knowledge, the codification of an efficient design approach for columns undergoing TI constitutes a relatively easy task, attaining the same goal for columns experiencing SDI still poses a few challenging problems, namely those dealing with the identification of a “border” beyond which L-D interaction is no longer relevant. Moreover, some available DSM-based design approaches for columns failing in L-D interactive modes are reviewed, and their merits are assessed and compared with those exhibited by the proposed ones.[2] Finally, the paper also presents reliability assessments of the failure load predictions provided by the proposed DSM-based design approaches, following the procedure adopted in the North American Specification for the Design of Cold-Formed Steel Structural Members [1].

2. Available failure loads of CFS columns experiencing L-D interaction

2.1. Experimental failure loads

Although there exist a few test campaigns reported in the literature that were carried out with the specific aim of investigating L-D interaction in fixed-ended CFS columns, exhibiting both plain and stiffened lipped cross-sections, the specimens providing clear experimental evidence of this coupling phenomenon and ensuing failure load erosion are relatively scarce – certainly, much less than those collected to propose/calibrate the existing L, D, G and L-G DSM design curves/expressions [2]. Indeed, the available experimental results evidencing the occurrence of L-D interaction in fixed-ended CFS columns are due to (i) Kwon and Hancock [4], Young and Rasmussen [5], Kwon et al. [6], Loughlan et al. [7] and Young et al. [8], for C columns, (ii) Kwon et al. [9], for C and H columns, (iii) Dinis et al. [10], for R columns, (iv) Kwon and Hancock [4], Kwon et al. [6], Yap and Hancock [11] and He et al. [12], for WSLC columns, (v) Yang and Hancock [13], for WFSLC columns, and (vi) Yap and Hancock [14], for columns with complex-stiffened cross-sections[3] – no Z column test results were found in the literature.

Table 1 summarises the available test results concerning fixed-ended CFS experiencing L-D interaction.[4] The reported/measured geometrical and material properties were used to evaluate the column squash and critical local/distortional/global buckling loads (the latter by means of the GBTul code [16], based on Generalised Beam Theory – GBT) – in some cases (e.g., [11,12]) discrepancies were found between the values obtained and those reported (specially the distortional buckling loads). Based on the values evaluated in this work, the above

[2] Due to space limitations, not all the available DSM-based design approaches are reviewed here.

[3] Due to the unusual cross-section shapes, and also the small number of tests reported in [14], it was decided to exclude them from this study.

[4] Note that another test campaign involving CFS lipped channel columns was recently reported by Dinis et al. [15]. However, these results were excluded from this study due to the fact that no clear L-D failures were observed. Indeed, the specimens tested, which were originally designed to fail in D-G interactive modes, exhibited only either D or L-D-G interactive failures (due to poor manufacture).

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