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Distortional-global interaction in lipped channel and zed-section beams: Strength, relevance and DSM design

André Dias Martins, Dinar Camotim*, Pedro Borges Dinis

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

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ABSTRACT

This work aims at presenting and discussing numerical results concerning the post-buckling behaviour, strength and design of cold-formed steel simply supported lipped channel and zed-section beams under uniform bending and undergoing distortional-global (D-G) interaction – two different support conditions are considered in the lipped channel beams. The relevance of the interaction effects is assessed by identifying the beams whose ultimate strength and/or failure mode are visibly affected by them. Distinct (i) global-to-distortional critical buckling moment ratios (R_{GD}) and (ii) yield-to-non-critical buckling (distortional or global) moment ratios (R_y) are considered, which are expected to lead to different failure mode natures (global, distortional or interactive). For each beam type, combinations of 41 geometries and 11 yield stresses are considered, in order (i) to characterise the beams experiencing "true D-G interaction" ($R_{GD} \approx 1.0$) and "secondary global-bifurcation D-G interaction" ($R_{GD} > 1.0$ and high R_y) and (ii) to investigate the possible occurrence of "secondary distortional-bifurcation D-G interaction" ($R_{GD} < 1.0$ and high R_y). Moreover, an in-depth investigation on the elastic post-buckling behaviour is carried out, to assess how the initial geometrical imperfection shape/configuration influences the behaviour and strength of beams prone to D-G interaction. The results presented consist of (i) relevant non-linear equilibrium paths, (ii) deformed configuration evolutions along those paths and (iii) figures providing the failure mode characterisation. Then, the numerical failure moments obtained are compared with their predictions by means of (i) the currently available Direct Strength Method (DSM) beam distortional and global strength curves, and also (if necessary) (ii) proposed DSM-based design approaches, specifically developed to handle beam D-G interactive failures.

1. Introduction

The slender open thin-walled cross-sections commonly exhibited by cold-formed steel (CFS) members, such as the lipped channel (LC) and zed-section (Z) beams considered in this work, make them highly prone to several instability phenomena, involving individual (local, distortional, global – L, D, G) and/or coupled (L-D, L-G, D-G and/or L-D-G) buckling behaviours. In the latter case, the efficient design of the members (columns, beams and/or beam-columns) is far from well established, particularly when distortional buckling is present. This is a complex task, particularly because interactive buckling may occur even when the corresponding critical buckling loads/moments are reasonably apart, which means that assessing the structural behaviour of such members requires in-depth knowledge on the mechanics underlying the possible couplings between the three above buckling modes (an intrinsic geometrically non-linear feature). Since the development of buckling interaction may erode, to a smaller or larger extent, the member ultimate strength, unveiling the conditions that lead to the emergence and development of such phenomena is an essential step towards proposing simple design rules that are able to handle the associated interactive failures. Although such knowledge is already available for CFS (i) columns [1–5] and beams [6,7] experiencing L-D interaction and (ii) columns undergoing D-G interaction [8,9], it is still lacking for beams affected by D-G interaction, a coupling phenomenon that is highly relevant in "intermediate-to-long" beams. Indeed, this topic has received very little attention from researchers in the past, even if the beam individual (i) distortional (e.g., [10,11]) and (ii) global (e.g., [12–15]) behaviours have been studied, both numerically and experimentally, in the past. To the authors' best knowledge, the only existing studies on D-G interaction beams concern the (i) experimental ("4-point bending") [16] and numerical [17] investigations on stainless steel lipped channel beams and (ii) the Generalised Beam Theory (GBT)-based assessment of the mechanics of D-G interaction in lipped channel beams subjected to uniform major-axis bending [18]. Therefore, a significant research effort, both experimental and numerical, is still needed before efficient design rules against beam D-G interactive

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

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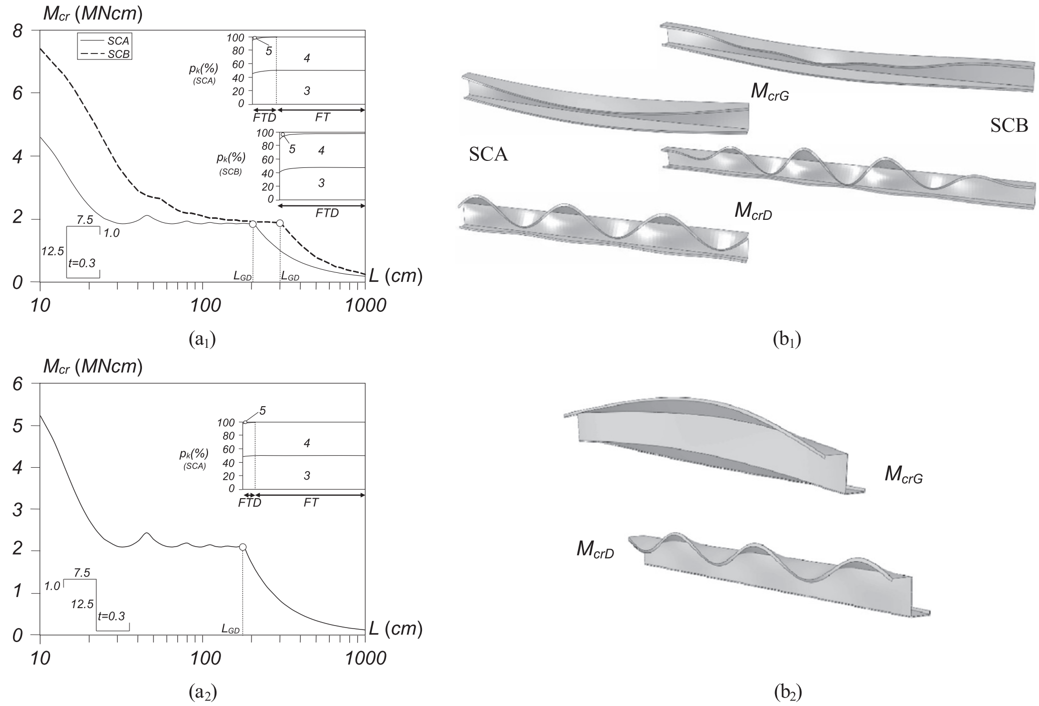

Fig. 1. (a) M_{cr} vs. L curves and modal participation diagrams, and (b) critical "global" and distortional modes for ($_1$) LC (SCA and SCB) and ($_2$) Z SCA beams with $R_{GD} = 1.0$.

failures can be developed and consensually established – naturally, this investigation aims at contributing towards achieving this goal.

The objective of this work is to report the available results of an ongoing numerical (shell finite element) investigation on the post-buckling behaviour, strength and design of cold-formed steel simply supported LC and Z beams experiencing D-G interaction under uniform major-axis bending and skew bending (causing uniform flange compression), respectively – two different support conditions are considered for the LC beams (they are discussed in Section 2). Initially, the relevance of D-G interaction is discussed, in Section 3, by assessing when the beam ultimate strength and/or failure mode are visibly affected by its presence – the ranges of the (i) global-to-distortional critical buckling moment ratio (R_{GD}) and (ii) yield-to-non-critical (distortional or global) buckling moment ratio (R_y) that lead to a non-negligible ultimate strength erosion are investigated. This study involves beams with (i) $R_{GD} \approx 1.0$ (experiencing "true D-G interaction"), (ii) $R_{GD} > 1.0$ (undergoing "secondary global-bifurcation D-G interaction") and (iii) $R_{GD} < 1.0$ (to investigate the possible occurrence of "secondary distortional-bifurcation D-G interaction"). In each case, the elastic-plastic post-buckling behaviours of beams undergoing several types and/or levels of D-G interaction are discussed and compared – their elastic post-buckling behaviours are also investigated, in order to assess the influence of different initial geometrical imperfection shapes/configurations. The results presented consist of (i) relevant non-linear equilibrium paths, (ii) deformed configuration evolutions along those paths, evidencing D-G interactive effects, and (iii) figures providing the failure mode characterisation. Finally, Section 4 begins by assessing the performance (safety and accuracy) of the codified Direct Strength Method (DSM) beam global strength curve, taking into special account the influence of the cross-section dimensions. Then, attention is turned to the comparison between the numerical failure moment data obtained and their predictions by means of (i) the available DSM beam distortional and global and strength curves, and also (if necessary) (ii) proposed DSM-based design approaches, specifically developed to handle beam D-G interactive failures.

2. Buckling analysis – beam geometry selection

The selection of uniformly bent beam geometries prone to strong D-G interaction (practically coincident distortional and global critical buckling moments – $R_{GD} = M_{crG}/M_{crD} \approx 1.0$) is a straightforward task, since they are easily identified on the beam "signature curves": their lengths are close to the transition between distortional and global critical buckling (of course, local buckling must be sufficiently high to preclude the occurrence of local-distortional-global interaction). As done previously, such geometries are selected by means of sequences of GBT buckling analysis using the code GBTUL [19]. The simply supported LC beams under uniform major-axis bending considered exhibit two distinct end support conditions, referred to as SCA and SCB (designations also adopted in previous work by the authors [6]): both beam families are simply supported with respect to major and minor-axis bending and have the end cross-section torsional rotations prevented – they differ in the fact that the end cross-section warping and local displacements/rotations are either free (SCA beams) or fully prevented (SCB beams). Zed-section SCA beams are also considered in this work,[1] subjected to skew bending causing uniform flange compression (the worst scenario, as far as distortional buckling is concerned).

The output of above selection procedure are 41 beam geometries for each family of LC and Z beams, whose characterisation can be found in Annex A – Tables A1–A3 concern the LC + SCA, LC + SCB and Z + SCA beams, respectively. Note that 40 out of these 41 beams (i) exhibit $0.50 \le R_{GD} \le 2.00$ and (ii) have critical local buckling moments (M_{crL}) much higher than M_{crG} and M_{crD}, thus ensuring that no L-D-G interaction occurs. Most of these beams undergo strong D-G interaction ($0.90 < R_{GD} < 1.10$ – 21 out of 40 beams), while the remaining ones exhibit R_{GD} values varying in 0.10 intervals for $R_{GD} > 1.10$ and in 0.05 intervals for $R_{GD} < 0.50$, making it possible to investigate "secondary (global or distortional) bifurcation D-G interaction". The "singular beam" has $R_{GD} \cong 15.0$ and knowing its behaviour is essential to interpret the results concerning the beams with $R_{GD} >> 1.0$. In order to

[1] Since the results concerning the SCA and SCB LC beams were found to be qualitatively similar, it was decided to analyse only SCA Z beams.