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On the mechanics of local-distortional interaction in thin-walled lipped channel columns

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ABSTRACT

The objective of this paper is to present and discuss numerical results concerning the geometrically non-linear behaviour of thin-walled lipped channel columns experiencing local-distortional (L-D) interaction that will shed fresh light on the mechanics underlying this coupling phenomenon. These results, obtained through Generalised Beam Theory (GBT) elastic post-buckling analyses, provide the evolution, along given equilibrium paths, of the column (i) deformed configuration, expressed in modal form, (ii) relevant displacement profiles, and (iii) modal participation diagrams. Taking full advantage of the GBT modal features, it becomes possible to unveil the most relevant behavioural/mechanical aspects associated with the occurrence of L-D interaction. Particular attention is devoted to the structural interpretation and explanation of the quantitative and qualitative differences exhibited by the column post-buckling behaviours associated with (i) "pure"/individual local and distortional behaviours and (ii) the occurrence of L-D interaction stemming from either the closeness between the local and distortional critical buckling loads ("true L-D interaction") or from a secondary bifurcation phenomenon ("secondary distortional or local bifurcation L-D interaction"). The columns analysed exhibit (i) the aforementioned different types of L-D interaction, (ii) two support conditions, namely fixed (mostly) or pinned end cross-sections, and (iii) several critical-mode initial geometrical imperfection shapes.

1. Introduction

Commonly used cold-formed steel structural systems are very often formed by slender open-section thin-walled members, which means that their structural behaviour and ultimate strength are frequently governed by instability phenomena that may involve cross-section deformation, namely local (L), distortional (D) and/or global (G) buckling. However, in order to assess the structural efficiency of slender thin-walled members it is not enough obtain in-depth information about their "pure"/individual (L, D, G) buckling and post-buckling behaviours, since any interaction involving these three instability phenomena may occur, namely L-G, L-D, D-G or L-D-G interaction. Therefore, it is indispensable to have also in-depth information about the mechanics of these interactive behaviours − this work deals specifically with L-D interaction in columns.[1] The main challenge facing the technical/scientific community is to assess the relevance of the effects due to the various interactions, *i.e.*, to know when they are relevant and to quantify such relevance. In fact, it is well known that neglecting any of the above interaction phenomena may lead to unacceptably low reliability levels, *i.e.*, to a high likelihood of reaching unsafe designs.

Traditionally, the non-linear behaviour of thin-walled members could only be rigorously assessed by resorting (i) to shell finite element simulations (*e.g.*, [2]), which are computationally costly and time-consuming, or, to a smaller extent, (ii) to spline finite strip analyses (*e.g.*, [3]), both providing outputs that are not easy to apprehend/interpret. However, this situation has been altered in the last decade, due to the formulation of an elastic geometrically non-linear Generalised Beam Theory (GBT) [4], which emerged as a very promising alternative to obtain similarly accurate results in a much more efficient (drastic reduction of the number of d.o.f. required) and clarifying (structurally meaningful modal d.o.f.) manner. Indeed, performing GBT-based geometrically non-linear imperfect analyses (GNIA) of prismatic thin-walled members, instead of shell finite element ones, corresponds to adopting a *modal approach* (not a *nodal* one) to obtain the member structural response under consideration. The GBT approach makes it possible to identify and quantify the various behavioural aspects

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[1] Although this work deals exclusively with L-D interaction in cold-formed steel columns, this interaction phenomenon is not restricted to steel members. For instance, results reported by Silvestre et al. [1] showed both experimental and numerical evidence of L-D interaction in CFRP ("Carbon-Fibre-Reinforced Polymer")-strengthened cold-formed steel lipped channel columns (although, it wasn't the aim of that investigation).

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contributing to such member response, since they are clearly reflected by the evolution, as loading progresses, of the participations of the various deformation modes in the member deformed configuration. This modal nature/feature provides the means to acquire a much more in-depth understanding of the member behaviour, thus ensuring a deeper and more illuminating understanding of the mechanical aspects involved, as well as leading to considerable computational savings (without loss of accuracy). Regarding the use of elastic non-linear GBT formulations to investigate the post-buckling behaviour of cold-formed steel (isotropic materials) members, it is worth noting the works of (i) Silvestre and Camotim [4,5], on the local and distortional post-buckling behaviour of uniformly compressed columns with lipped channel, zed and web-flange stiffened lipped channel sections, (ii) Silvestre and Camotim [6], on the distortional post-buckling behaviour of zed-section beams, (iii) Silvestre et al. [7], who reported an investigation on the distortional post-buckling behaviour of cold-formed steel lipped channel columns with several intermediate and/or end stiffeners, and, recently, (iv) Basaglia et al. [8], who studied the influence of the cross-section geometry on the distortional post-buckling behaviour of lipped channel, hat-section and zed-section simply supported columns.[2] Still regarding the use of GBT to assess the non-linear response of cold-formed steel structures, Basaglia et al. [10,11] (i) reported an investigation on the effect of non-standard support conditions on the post-buckling behaviour of columns and beams, and (ii) extended the GBT formulation to the analysis of thin-walled frames, by developing a "joint element" that guarantees the displacement compatibility between the connected members. Recently, Silva [12] and Silva et al. [13] developed and implemented a GBT-based beam finite element to analyse the post-buckling behaviour of laminated FRP (Fibre Reinforced Polymers) composite thin-walled members with arbitrary cross-section shapes, based on a beam finite element implementation of a geometrically non-linear GBT formulation derived a few years earlier [14]. As far as isotropic thin-walled members affected by coupling phenomena are concerned, GBT post-buckling results are only available for thin-walled (mostly) lipped channel and zed-section (i) columns experiencing either L-D interaction due to very close local and distortional critical buckling loads [15] or D-G interaction [16], and (ii) uniformly bent beams affected by either by L-D [17] or D-G interaction [18].

Previous work by the authors [19–21], based on shell finite element results, showed that cold-formed steel columns may be affected by two types of L-D interaction, namely (i) one due to the closeness between local and distortional critical buckling loads, denoted as "true L-D interaction",[3] and (ii) the other caused by a secondary (local or distortional) bifurcation, termed "secondary local or distortional-bifurcation L-D interaction", which occurs when the local and distortional critical buckling loads are not so close and stems from the high (local) or moderate (distortional) post-critical strength – the latter are particularly relevant when the yield stress is much higher than the critical local and distortional buckling stresses (*e.g.*, in thin-walled systems made of high-strength steels − but not limited to them), thus leaving enough "room" for the emergence and development of L-D interaction.

The objective of this paper is to present and discuss numerical (GBT-based) results concerning the geometrically non-linear response of thin-walled lipped channel columns experiencing L-D interaction, which shed fresh light on the mechanics underlying this coupling phenomenon. The geometries of the columns analysed, discussed in Section 2, are associated with fixed-ended (mostly) and pin-ended (also termed simply supported) columns exhibiting true or secondary bifurcation L-D interaction and containing several critical-mode initial geometrical imperfection shapes. The aforementioned numerical results, presented and discussed in Section 3, were obtained through GBT elastic post-buckling analyses and provide the evolution, along given equilibrium paths, of the column (i) deformed configuration, expressed in modal form, (ii) relevant displacement profiles, and (iii) modal participations diagrams – for validation purposes the GBT-based results are compared with values yielded by shell finite element analyses carried out in the code Abaqus [22]. Taking full advantage of the GBT modal nature, it becomes possible to unveil the most relevant behavioural/mechanical features associated with the occurrence of L-D interaction. Special attention is devoted to the structural interpretation/explanation of the quantitative and qualitative differences exhibited by the column post-buckling behaviours associated with (i) "pure" (individual) local and distortional behaviours, and (ii) either "true L-D interaction" or "secondary (local or distortional) bifurcation L-D interaction". Finally, it is also expected that the outcome of this study will have impact on the improvement/development of existing/new design approaches, based on the Direct Strength Method (DSM), against column failures stemming from the above two types of L-D interaction.

2. GBT buckling behaviour − column geometry selection

In order to investigate the mechanics underlying the geometrically non-linear response of thin-walled columns experiencing L-D interaction, it is indispensable to begin by selecting column geometries (cross-section dimensions and lengths) with "appropriate" local and distortional critical buckling loads (P_{crL} and P_{crD}). Initially, four different columns geometries were selected, namely (i) two experiencing "true L-D interaction" ($R_{DL} = P_{crD}/P_{crL} \approx 1.00$), the first associated with fixed end supports (including full warping restraint) and the second associated with pinned end supports (end cross-sections locally/globally pinned and free to warp), and (ii) two concerning fixed-ended columns affected by "secondary bifurcation L-D interaction", one with $R_{DL} \approx 0.60 < 1.00$ (secondary-local bifurcation) and the other with $R_{DL} \approx 1.60 > 1.00$ (secondary-distortional bifurcation) – these columns are hereafter termed "C_F1", "C_P1", "C_F2" and "C_F3", respectively. As done in previous studies, the column geometry selection was made by means of a "trial-and-error" procedure involving GBT buckling analysis sequences performed with code gbtul [23].

Fig. 1 shows the GBT nodal discretisation[4] adopted in all the columns analysed in this work, involving 15 nodes: 6 natural and 9 intermediate (3 in the web and flanges).[5] This discretisation leads to (i) 17 conventional modes (4 global, 2 distortional and 11 local) − modes **1–17** (see Fig. 1(a)), (ii) 14 shear modes (5 global and 9 local) − modes **18–31** (see Fig. 1(b)), (iii) 14 linear transverse extension modes (1 global isotropic, 4 global deviatoric and 9 local) − modes **32–45** (see Fig. 1(c)) and (iv) 14 quadratic transverse extension modes (modes **46–59** − see Fig. 1(c)), totalling 59 (sequentially numbered) deformation modes. In the buckling analysis it suffices to consider only the conventional deformation modes. Fig. 2(a_1)-(a_4) and Table 1 show the output of this effort, *i.e.*, the cross-section dimensions (b_w, b_f, b_l, t − web-flange-lip widths and wall thickness) and lengths (L) of the four columns ($E = 210$ GPa, $\nu = 0.3$) selected to ensure the desired interaction "levels" (*i.e.*, R_{DL} values): Fig. 2(a_1) to (a_4) show curves providing the variation of P_{cr} (critical buckling load) with the column length L (logarithmic scale) concerning the C_F1, C_P1, C_F2 and C_F3, respectively – naturally, all the columns belong to short-to-intermediate length range where the L-D phenomenon is relevant. On the other hand, Fig. 2(b_1)-(b_4) display (i) the critical mode shapes (local and/or distortional) that correspond to all initial geometrical imperfections adopted/employed in the GBT-based GNIA, about to be discussed in Section 3, and (ii) the corresponding GBT modal amplitude functions – these one-dimensional functions, which are the problem unknows, provide the

[2] Aside from the pioneering work due to Miosga [9], nowadays only of historical interest.

[3] The columns analysed by Silvestre and Camotim [15] fall into this category.

[4] The GBT cross-section analysis involves a lengthy set of fairly complex operations which has been reported in the literature − the interested reader can find detailed accounts in the works of Gonçalves et al. [24] and Bebiano et al. [25].

[5] An attempt to reduce the number of intermediate nodes in the flanges (from 3 to 1) in the GNIA based analysis led to inaccurate results.