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Local-distortional interaction in cold-formed steel beams: Behaviour, strength and DSM design

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ABSTRACT

This work presents and discusses numerical results concerning cold-formed steel simply supported beams subjected to uniform bending and exhibiting (i) three cross-section shapes (lipped channels, zed-sections and hat-sections), and (ii) two end support conditions (differing in the warping and local displacement/rotation restraints, which are either free or fully prevented). A systematic numerical investigation is carried out, in order to characterise the post-buckling behaviour and ultimate strength of beams experiencing more or less severe L-D interaction effects. 43 geometries and 11 yield stresses are considered for each combination of cross-section shape and support conditions, thus ensuring distinct (i) ratios between the local (M_{crL}) and distortional (M_{crD}) critical buckling moments ($0.50 \leq M_{crD}/M_{crL} \leq 2.00$), and (ii) local or distortional slenderness values, ranging from 0.50 to 3.50. The numerical results are obtained through ABAQUS shell finite element analyses and concern the (i) post-buckling behaviour (elastic and elastic-plastic), ultimate strength and failure mechanisms of beams previously selected to undergo considerable L-D interaction. Based on the acquired information, a first contribution towards the Direct Strength Method (DSM) design of cold-formed steel beams undergoing different "levels" of L-D interaction is presented and discussed.

1. Introduction

Most cold-formed steel members display very slender thin-walled open cross-sections, which makes them highly susceptible to buckling phenomena involving cross-section deformations, namely local (L) buckling (wall bending only – no fold-line motions) or distortional (D) buckling (wall bending and cross-section distortion – fold line motions). In fact, any of these instability phenomena may be critical and govern the structural response of such members for either "short" (L instability) or "intermediate" (D instability) lengths. Moreover, when the critical buckling moments M_{crL} and M_{crD} are close (or, at least, not far apart), the beams experience L-D interaction, generally occurring in beams with short-to-intermediate lengths. Obviously, the behavioural features associated with this coupling phenomenon must be taken into account in the design of such members, since they may cause significant ultimate strength erosion (particularly when $M_{crL} \approx M_{crD}$) – otherwise, unsafe designs might occur. Unfortunately, L-D interaction has been far less studied than its local-global counterpart, particularly in beams (or in beam-columns, for that matter). Indeed, there are only a few investigations dealing with L-D interaction in cold-formed steel beams. However, it is consensual, amongst the technical and scientific communities working with cold-formed steel structures, the need to acquire in-depth knowledge on the structural response/performance of beams affected by these coupling effects. This constitutes a necessary first step in the path towards the development, calibration and validation of design approaches able to handle such effects and to meet the appropriate requirements for the incorporation in cold-formed steel codes/specifications.

Most of the available results concerning numerical/experimental investigations or design proposals dealing with L-D interaction in cold-formed steel members involve fixed-ended columns under uniform compression – e.g., the works of Kwon and Hancock [1], Young et al. [2] and Martins et al. [3–5]. Although research has already been conducted on the behaviour of cold-formed steel beams, the authors are only aware of very few studies addressing the influence of L-D interaction on that same behaviour. They consist of numerical and experimental investigations − the former concern simply supported (i) lipped channel beams exhibiting flange or web-triggered L-D interaction under uniform major-axis bending and with $0.85 \leq M_{crL}/M_{crD} \leq 1.15$ [6] or $M_{crL}/M_{crD} \approx 1.0$ [7,8], and also (ii) zed-section beams with and without intermediate stiffeners subjected to 4-point bending [9–11]. As for the experimental investigations, it is worth noting (i) the tests conducted by Bernard *et al.* [12,13] on simply supported thin-walled profiled steel decks with and without intermediate ("v-shaped" [12] and "flat-hat"

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[13]) stiffeners under minor-axis bending (subsequently, the authors compared their ultimate strength results with the predictions of several design standards [14] and showed evidence of L-D interaction), (ii) most of the tests reported by Wang and Zhang [15] on lipped channels with several lip configurations (upright, inclined and return) involving specimens under uniform or non-uniform bending, which showed clear evidence of L-D interaction, and (iii) the studies carried out by Douty [16] and Serrete and Peköz [17] on simply supported standing seam roof panels with several configurations (these authors reported evidence of L-D interactive failures in most specimens). However, a systematic investigation, aimed at identifying which combinations of the ratios involving M_{crL} or M_{crD} and the yield moment lead to sizeable/relevant L-D interaction effects, is still lacking – the purpose of this work is to provide a first contribution towards filling this gap, based on the knowledge acquired from the recently reported Generalised Beam Theory (GBT) post-buckling results [18], which shed fresh light on the mechanics of lipped channel beams undergoing L-D interaction.

Thus, the main objectives of this work are (i) to present and discuss numerical results obtained for simply supported uniformly bent beams affected by L-D interaction and (ii) to provide a first contribution towards the development of an efficient Direct Strength Method (DSM) design approach for such members. The beams analysed exhibit (i) three cross-section shapes (lipped channels, hats and zeds) and (ii) two end support conditions (addressed in Section 2). A systematic numerical investigation is carried out, in order to characterise the post-buckling behaviour and strength of beams experiencing more or less severe L-D interaction effects. It involves beams (i) with 43 geometries, for each combination of cross-section dimensions and end support conditions, selected to ensure distinct ratios between M_{crD} and M_{crL}, namely $0.50 \leq R_{DL} \leq 2.00$ ($R_{DL} = M_{crD}/M_{crL}$) and (ii) 11 yield stresses, such that a wide slenderness range (0.50–3.50 interval) is covered. The numerical results presented and discussed are obtained from ABAQUS [19] shell finite element analyses and concern the beam (i) post-buckling behaviour, (ii) ultimate strength and (iii) failure mode – special attention is paid to assessing the ultimate strength erosion due to the coupling effects. Finally, the paper closes with some considerations about the impact of the findings reported on the DSM-based design of cold-formed steel beams experiencing different L-D interaction levels, as well as a few comments about the work on this topic planned for the near future.

2. Buckling analysis – beam geometry selection

The identification/selection of uniformly bent beam geometries prone to L-D interaction is quite straightforward, since short-to-intermediate beams have similar local and distortional buckling moments (or, at least, not far apart). As done in similar studies, such geometries were selected by means of sequences of GBT buckling analysis using code GBTUL (Bebiano et al. [20]). Seven types of beams ($E = 210$ GPa, $\nu = 0.30$) are considered, combining (i) three cross-section shapes, namely (i_1) lipped channels (C) bent about the major-axis, (i_2) hats bent about the major-axis (H_M) or minor-axis (H_m – lips under compression), and (i_3) zeds (Z) under skew bending causing uniform flange compression (the worst case), (ii) two support conditions (termed here SCA and SCB – the exception are the H_m-beams, for which only SCB are considered): while the SCA beams are simply supported with respect to major and minor-axis bending and have the end cross-section torsional rotations prevented, the SCB beams differ in the fact that the end cross-section warping and local displacements/rotations are also prevented – physically, preventing these displacements/rotations corresponds to rigidly attaching thick end plates to the beam end cross-sections.

In order to confirm/illustrate the assertion that short-to-intermediate beams are prone to L-D interaction, Fig. 1(a_1) shows, for the C+SCA beam with $b_w = 100$, $b_f = 65$, $b_l = 12.5$ and $t = 1.0$ mm, the variation, with the length L (logarithmic scale), of the single half-wave ($M_{b.1}$) and critical (M_{cr}) buckling moments. On the other hand, Fig. 1(a_2) provides GBT-based "approximate" buckling curves obtained by considering three deformation mode sets, namely modes (i) **7–17** (local), (ii) **5+6** (distortional), and (iii) **3+4** (lateral-torsional: minor axis-bending + torsion) – note that the cross-section discretisation involves 9 intermediate nodes (3 in the web and flanges). Since the **7–17** modes yield practically the exact critical local buckling moment and the **5+6** modes lead to an approximate[1] critical distortional buckling moment, Fig. 1(a_2) makes it possible to conclude that beams with lengths $45 < L < 250$ cm are highly prone to L-D interaction – this fairly large length interval evidences the relevance of this coupling phenomenon. Obviously, when global buckling is critical the solution obtained with deformation modes **3+4** only is the exact lateral-torsional buckling moment – note that there is a gap in the transition between the "exact" and **3+4** curves, which corresponds to lengths of beams prone to D-G or L-D-G interaction (coupling phenomena outside the scope of this work – see, for instance, the works of the authors [21,22] on lipped channel beams affected by D-G interaction). Finally, Fig. 1(b) shows the local and distortional critical buckling modes of the $L = L_{DL} = 50$ cm beam, associated with practically coincident local and distortional buckling moments – they exhibit 8 (local) and one (distortional) half-waves. Naturally, the post-buckling behaviour (either elastic or elastic-plastic) of such beam is bound to be strongly affected by L-D interaction.

The output of this selection are 43 beam geometries (labelled X1 to X43, where "X" stands for either "C", "H_M", "H_m" or "Z") for each combination of cross-section shape and end support conditions – they can be found in Annex A (Tables A1–A7). All these beams (i) exhibit R_{DL} values in the range $0.50 \leq R_{DL} \leq 2.00$ and (ii) have global buckling moments (M_{crG}) much higher than (ii_1) the local and distortional ones ($M_{crG} / M_{cr.\,Max} \gg 1.0$ – $M_{cr.\,Max} = max\{M_{crD}; M_{crL}\}$) and ($ii_2$) the yield moments ($M_{crG} / M_{y.\,Max} \gg 1.0$), thus ensuring that no interaction with global (lateral-torsional) buckling occurs – the values of the above two moment ratios are also given in Annex A. Local buckling is almost always triggered by the compressed flange[2] (most common situation in practice) and, in order to study the effect of strong L-D interaction, 26 beams were selected in the $0.85 < R_{DL} < 1.15$ range – the other 17 beams are obtained by varying this ratio in 0.10/0.05 steps until 2.00 and 0.50, respectively, making it possible to investigate "secondary (local or distortional) bifurcation interactions" (Martins *et al.* [23]).

3. Post-buckling behaviour under local-distortional interaction

This section addresses the post-buckling behaviour of uniformly bent beams affected by L-D interaction. Initially, brief descriptions of (i) the shell finite element model adopted (Section 3.1) and (ii) the worst initial imperfection shape considered, for each combination of cross-section and support conditions (Section 3.2), are provided. Then, attention is turned to the discussion of the post-buckling behaviour of cold-formed beams under L-D interaction (Section 3.3). In particular, three types of L-D interaction are addressed (for all the SCA and SCB C, H_M and Z-beams): (i) "true interaction" (Section 3.3.1), (ii) "secondary local bifurcation interaction" (Section 3.3.2) and (iii) "secondary distortional bifurcation interaction" (Section 3.3.3). Finally, the H_m+SCB beams are dealt with separately, since they have been much less studied than the other ones in the past (Section 3.3.4).

3.1. Shell finite element analysis

The beam elastic and elastic-plastic post-buckling analysis were determined by means of ABAQUS [19] shell finite element analysis

[1] "Pure" distortional critical buckling modes often contain small (but not negligible) contributions from local deformation modes.

[2] The exceptions are some H_m beams, for which local buckling may be triggered by the lips.