Full length article

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

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ARTICLE INFO

Keywords:
Cold-formed steel beams
Local-distortional interaction
Major/minor/skew bending
Shell finite element analysis
Elastic-plastic post-buckling behaviour
Direct Strength Method (DSM)

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_{crit}) and distortional (M_{det}) critical buckling moments (0.50 ≤ M_{det}/M_{crit} ≤ 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_{crit} and M_{det} 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_{crit} ≈ M_{det}) – 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 ≤ M_{det}/M_{crit} ≤ 1.15 [6] or M_{det}/M_{crit} = 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”
by considering three deformation mode sets, namely modes (i) $7\sim17$ (local), (ii) $5\sim6$ (distortional), and (iii) $3\sim4$ (lateral-torsional: minor axis-bending + torsion) – note that the cross-section discretisation involves 9 intermediate nodes (3 in the web and flanges). Since the $7\sim17$ modes yield practically the exact critical local buckling moment and the $5\sim6$ modes lead to an approximate $^1$ critical distortional buckling moment, Fig. 1(a2) 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 $L = L_{\text{fl}} = 50$ 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 XI to X43, where “X” stands for either “C”, “H”, “Hw” 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 $R_{\text{fl}}$ values in the range $0.50 \leq R_{\text{fl}} \leq 2.00$ and (ii) have global buckling moments ($M_{\text{cr}}$) much higher than (iii) the local and distortional ones ($M_{\text{cr}} / M_{\text{cr, max}} \gg 1.0$ – $M_{\text{cr, max}} = \max(M_{\text{cr}}; M_{\text{fl}})$) and (iv) the yield moments ($M_{\text{cr}} / M_{\text{y, max}} \gg 1.0$), 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 (most common situation in practice) and, in order to study the effect of strong L-D interaction, 26 beams were selected in the $0.85 < R_{\text{fl}} < 1.15$ 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” ($^{[23]}$).

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, Hw 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 Hw + SCA 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 $^{[9]}$ shell finite element analysis

\footnote{1 Pure} distortional critical buckling modes often contain small (but not negligible) contributions from local deformation modes.

\footnote{2 The exceptions are some Hw, beams, for which local buckling may be triggered by the lips.}