Thin-Walled Structures 81 (2014) 50–66

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

On the behaviour, failure and direct strength design of thin-walled steel structural systems

Dinar Camotim [a,*], Cilmar Basaglia [b]

[a] Department of Civil Engineering and Architecture, ICIST, Instituto Superior Técnico, University of Lisbon, Av. Rovisco Pais, 1049-001 Lisboa, Portugal
[b] Department of Structural Engineering, School of Civil Engineering, Architecture and Urban Design, University of Campinas, Av. Albert Einsten, 951, 13083-852 Campinas, SP, Brazil

ARTICLE INFO

Available online 22 December 2013

Keywords:
Cold-formed steel continuous beams
Thin-walled steel frames
Buckling behaviour
Post-Buckling behaviour
Design approach
Direct Strength Method (DSM)

ABSTRACT

This paper reports the main results of an ongoing numerical investigation aimed at (i) assessing the buckling, post-buckling, strength and collapse behaviour of thin-walled steel structural systems and (ii) developing an efficient direct approach to estimate the ultimate loading of such structural systems, which may fail in complex modes that combine local, distortional and global features. The results currently available, obtained from Generalised Beam Theory and Ansys shell finite element analyses, concern continuous beams and simple frames subjected to various transverse loadings applied at/along the shear centre axis and causing non-uniform bending. The possibility of developing a design approach, based on the application of the existing Direct Strength Method (DSM) strength curves, is explored for the structural systems under consideration. The quality of the corresponding failure loading estimates is assessed through the comparison with the values yielded by shell finite element simulations.

1. Introduction

The extensive use of thin-walled steel structural systems, namely continuous beams and frames, in the construction industry stems mostly from their high structural efficiency (large strength-to-weight ratio) and remarkable fabrication versatility. However, since these structural systems are usually built from open-section members (*e.g.*, cold-formed steel profiles), which are highly prone to local, distortional and global instability phenomena, the direct assessment of their structural response and ultimate strength constitutes a rather complex task [1].

In the last few years, a fair amount of research work has been devoted to the development of efficient design rules for isolated (single-span) thin-walled steel members, mostly subjected to uniform internal force and moment diagrams. The most successful end product of this research activity was the increasingly popular "Direct Strength Method" (DSM) [2], applicable to members subjected to uniform compression (columns) or major/minor-axis bending (beams) and already included in the current Australian/New Zealand [3], North American [4] and Brazilian [5] specifications for cold-formed steel structures. However, it seems fair to say that the amount of research work on the buckling, post-buckling, strength and design of thin-walled steel beams subjected to non-uniform bending, namely continuous beams, is still rather scarce. In this context, it is worth noting the recent works of (i) Yu and Schafer [6], who used shell finite element models to investigate the influence of linear bending moments on the distortional buckling and post-buckling behaviour of single-span steel beams, and employed their findings to examine and extend the DSM design procedure to such members, (ii) Camotim et al. [7], who used Generalised Beam Theory (GBT) to analyse the buckling behaviour of steel beams with several loadings and support conditions (including intermediate supports), (iii) Pham and Hancock [8], who proposed a DSM-based design criterion for purlin-sheeting systems using elastic lateral–torsional buckling moments evaluated through either the so-called "C_b-factor approach" or finite element analyses and (iv) Dubina and Ungureanu [9], who studied the semi-continuous behaviour of multi-span cold-formed Z-purlins with bolted lapped connections.

Thin-walled steel frames are currently designed by means of an indirect approach, basically consisting of (i) performing a frame analysis that incorporates only global geometrical non-linear effects, (ii) "extracting" the various members from the frame (more or less adequately) and (iii) safety checking them individually as "isolated members" (accounting for the local and/or distortional geometrical non-linear effects in an indirect/approximate fashion). Although obviously advantageous, mainly due to its simplicity, this approach has major shortcomings (sources of error/approximation), namely the fact that it does not take into account adequately (i) the interaction between the various geometrical non-linear effects and (ii) the "real

* Corresponding author. Tel.: +351 21 8418403; fax: +351 21 849 7650.
E-mail address: dcamotim@civil.ist.utl.pt (D. Camotim).

0263-8231/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.tws.2013.11.013

behaviour" of the frame joints – indeed, the "extracted" members are almost always safety checked under the assumption of standard support conditions (pinned or fixed end sections) and the only "link" to the original frame is the member "effective/buckling length", a concept initially devised in the context of the in-plane flexural buckling of isolated members and later extended to handle the frame in-plane global geometrically non-linear behaviour. In particular, no attention is paid to several important frame joint behavioural features, such as those associated with (i) warping torsion transmission (*e.g.*, [10]), (ii) localised displacement restraints, due to bracing systems or connecting devices (*e.g.*, [11]), or (iii) local/global displacement compatibility (*e.g.*, [12]). In order to provide a first contribution towards overcoming the above shortcomings, Part 1-1 of Eurocode 3 [13] proposes (allows for) the use of a so-called "General Method" to estimate the out-of-plane global (lateral or lateral–torsional) ultimate strength of isolated members and plane frames subjected to in-plane loading, even if, up to now, validation results and/or application guidelines were provided exclusively for beams and simple portal frames failing in lateral–torsional modes (*e.g.*, [14–16]).

The aim of this paper is to present and discuss the main results of an ongoing numerical investigation aimed at (i) assessing the buckling, post-buckling, strength and collapse behaviour of thin-walled steel structural systems and (ii) exploring the possibility of developing an efficient direct approach, based on DSM strength curves, to estimate the ultimate loading of such structural systems. Concerning the first goal, the results available at this stage concern lipped channel continuous (two and three-span) beams and simple frames subjected to various loadings applied at/along the shear centre axis and causing non-uniform bending – it is worth noting that the determination of most of the numerical results addressed here has been presented and discussed in previous works by the authors [17–19]. These results were obtained through (i) GBT buckling analyses and (ii) elastic and elastic–plastic shell finite element (SFE) non-linear analyses. Regarding the (much more ambitious) second goal, an attempt is made to lay the foundations of the conceptual framework for the development of an efficient direct design approach. Then, as a first exploratory step, the possibility of extending the use of the current DSM strength curves outside their range of validity (isolated columns and beams), namely to predict the ultimate strength of the structural systems under consideration (continuous beams and portal frames), is investigated. In order to assess the quality of the failure loading estimates provided by the above tentative direct design approach, they are compared with numerical values obtained from rigorous ANSYS [20] SFE simulations. Besides highlighting and quantifying the expected limitations of the proposed exploratory design approach (particularly for the frames), these comparisons also (i) provide clear evidence that both the continuous beam and frame ultimate strength ratios are nicely aligned along "design-like" strength curves and (ii) make it possible to draw interesting conclusions concerning the features that must be included in a future DSM-based design approach that can handle efficiently structural systems such as the continuous cold-formed steel beams and simple frames dealt with in this work.

2. GBT and shell finite element modelling

This section addresses a few relevant aspects concerning the performance of (i) GBT buckling analyses and (ii) ANSYS SFE buckling and elastic or elastic–plastic post-buckling analyses of continuous beams and frames. Concerning the GBT buckling analysis, the following modelling issues are worth mentioning:

(i) *Cross-section discretisation*. The cross-section discretisations adopted in the analyses carried out in this work follow the approach developed by Dinis et al. [21].

(ii) *Member discretisation*. The equilibrium equations are solved using the beam finite elements developed by Camotim et al. [7] (for continuous beams) and Basaglia et al. [11] (for frames): 2-node elements and the modal amplitude functions approximated by Hermite cubic polynomials – these finite elements take into account the geometrical effects due to the longitudinal normal stress gradients and also to the ensuing pre-buckling shear stresses, thus enabling a proper capture of possible shear buckling effects.

As far as the ANSYS SFE analyses are concerned, the following modelling issues are relevant:

(i) *Discretisation*. The structural systems are discretised into SHELL181 elements (4-node shear deformable thin-shell elements with six degrees of freedom per node and full integration) – previous convergence studies showed that 25 mm × 25 mm meshes provide quite accurate results, even if at the cost of a fairly high computational effort.

(ii) *Support conditions*. The support conditions are modelled in the "usual fashion": (ii_1) null transverse membrane and flexural displacements imposed at all cross-section nodes associated with the simple/pinned supports (end and intermediate supports of the beams) and (ii_2) null displacements and rotations imposed at all cross-section nodes associated with the fixed supports.

(iii) *Material modelling*. The steel material behaviour is deemed either (iii_1) linear elastic, for the bucking analyses, or (iii_2) linear-elastic/perfectly-plastic following the Prandtl-Reuss plasticity model (von Mises yield criterion and associated flow rule), for the post-buckling (non-linear) analyses. This means that no strain hardening is taken into account and that it is assumed that the ductility available is enough to allow for the stress and moment redistributions occurring prior to the beam/frame collapse.

(iv) *Initial imperfections*. All initial geometrical imperfections exhibit the structural system critical buckling mode shape and amplitude equal to either 10% of the wall thickness t (local or distortional buckling) or L/1000 (global buckling) of the member triggering the instability, which are values often adopted in numerical simulations concerning cold-formed steel structures – a more judicious choice requires the performance of imperfection-sensitivity studies, which fall outside the scope of this paper. Moreover, no residual stresses or corner strength effects are included in the analyses.

At this stage, it is worth mentioning the well known fact that the material nonlinearity and enhanced corner effects often influence significantly the structural response (strength and failure) of thin-walled cold-formed steel members. Therefore, they must necessarily be included in numerical simulations that (i) are carried out in the context of parametric studies intended to investigate their influence on the performance of a structural system or (ii) aim at reproducing the "real structural behaviour" obtained from specimens tested in the course experimental investigations. However, since the objective of the work reported in this paper is none of the above, it was decided to adopt the (simpler) linear-elastic/perfectly-plastic material model and neglect the corner enhanced strength. This option seems perfectly acceptable for this study, since an efficient design approach must be also capable of predicting the ultimate strength of structural systems exhibiting the (simple) constitutive law adopted.

3. Continuous beams: scope and numerical results

The continuous beams analysed (i) are made of structural steel (Young's modulus E=205 GPa and Poisson's ratio ν=0.3),