Thin-Walled Structures 124 (2018) 58–71

Contents lists available at ScienceDirect

Thin-Walled Structures

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

Full length article

Elastic buckling analysis of cold-formed steel built-up sections with discrete fasteners using the compound strip method

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ARTICLE INFO

Keywords:
Compound strip method
Cold-formed steel
Built-up section
Buckling analysis
Discrete fasteners

ABSTRACT

In this paper, the compound strip method is applied to the stability analysis of cold-formed steel built-up sections. A beam element with adjustable stiffness properties is adopted to represent the utilised fastener and the associated stiffnesses of the connection elements are incorporated in the global stiffness matrix of the built-up sections. The presented method allows for modelling arbitrarily-located discrete fasteners in the context of the semi-analytical finite strip method. The proposed numerical technique is verified against finite element solutions through various numerical examples and shown to be both accurate and versatile. Some typical and also complex built-up sections with various fastener configuration and end boundary conditions are analysed to evaluate the influence of fastener spacing. The extent of composite behaviour in built-up sections is determined by investigating the enhancement of buckling capacity and changes in the corresponding buckling modes. The simplicity of the proposed technique expedites extensive parametric studies of cold-formed built-up sections and facilitates the search for optimal placement of fasteners and choice of section geometry.

1. Introduction

Cold-formed steel (CFS) sections are extensively used in the construction industry, from residential houses to industrial buildings. In recent years, the demand for sections with higher capacities has created a new trend in the application of CFS by connecting several single sections to form “built-up” cross-sections. Compound sections are generally connected using typical fasteners such as screws, bolts, and clinches. The presence of discrete fasteners influences the overall behaviour of the members and changes the encountered buckling modes and corresponding loads. A reliable application of these members requires an efficient analysis tool that can accurately incorporate the effects of discrete fasteners. In the last decade, extensive research has been dedicated to provide a better understanding of built-up sections comprising numerical investigations and/or experimental studies.

The early studies on the behaviour of CFS built-up members appear to date back to 1974, when buckling and post-buckling capacities of box and I-section columns made of two channels were investigated experimentally [1]. The double-channel CFS beam was analysed by Ghersi et al. [2] to determine the buckling modes and ultimate behaviour of such beams. Stone and LaBoube [3] studied the behaviour of screw-connected CFS built-up I-sections and determined their ultimate capacity. Young and Chen [4] later carried out an experimental investigation on screw-connected built-up closed sections with the inclusion of longitudinal web stiffeners. Fixed-ended columns were tested at various lengths to provide valuable data for comparison with design strength curves. An extensive experimental study was conducted by Whittle and Ramseyer [5] to evaluate the impacts of member characteristics on the ultimate strength of built-up closed sections made of welded channels. In their study, only the pin-ended boundary condition was considered, but later a series of tests was performed for the same section considering different end boundary conditions, including rigid and flexible supports [6]. The results showed that the ultimate capacity of the considered built-up section was slightly affected by the type of end boundary condition.

Zhou and Shi [7] investigated the flexural behaviour of built-up I-beams, comprising of two spot welded back-to-back lipped channels. The tested beams were subjected to four-point loading and the results were utilised for the development of a design method for built-up beams. In a subsequent experimental study, bending tests were carried out on bolted double-Z sections [8]. Different arrangements of bolt spacing were tested, and it was concluded that the longitudinal slip between profiles is an important factor in the behaviour of such built-up beams. Georgieva et al. [8,9] performed a series of full-scale tests on the behaviour of bolted built-up columns made of two identical lipped Z-sections [9] and combinations of three or four Z, C and sigma sections

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https://doi.org/10.1016/j.tws.2017.11.046
Received 18 July 2017; Received in revised form 21 November 2017; Accepted 26 November 2017
0263-8231/

[8]. Later, Zhang and Young [10] investigated the behaviour of screw-connected built-up I-sections with edge and web stiffeners. The columns varied from 300 to 3200 mm in length and had fixed-end boundary conditions with evenly spaced screws. The obtained strength curves were used to evaluate the appropriateness of the current design equations. Laim et al. [11] experimentally tested series of CFS built-up open (lipped I) and closed (single-loop or double-loop) sections under four-point bending. It was observed that the beams with built-up open sections failed in lateral-torsional buckling, whereas the beams with built-up closed sections generally failed in distortional buckling.

Li et al. [12] tested screw-connected built-up box sections to study the effect of various fastener arrangements on the capacity of built-up columns. They showed that the spacing and arrangement of fasteners significantly affect the failure load and suggested requirements for fastener spacing. Ting [13] performed extensive experimental studies on short, intermediate and slender CFS built-up columns made of two back-to-back lipped channels with various screw spacing. It was concluded that columns with screw spacing beyond the limits of the AISI specification almost displayed the non-composite behaviour. Wang and Young [14,15] studied the behaviour and possible failure modes of built-up box and I-sections with edge and/or intermediate stiffeners [14], and with different sizes of intermediate web perforations [15]. Recently, a series of experimental tests were performed to investigate the composite action in screw-connected back-to-back built-up I-sections [16]. The results showed that end boundary conditions, along with friction and contact, have a significant impact on the composite action of built-up members. Although such experiments provide crucial benchmark data for the stability analysis of built-up sections, their relatively high cost necessitates utilisation of reliable, less expensive, numerical approaches for extensive parametric studies.

The most widely used numerical methods for the buckling analysis of CFS members are the finite element (FE) and finite strip (FS) methods. Two types of finite element analyses have been conducted for CFS members; (*i*) the linear elastic buckling analysis to estimate the critical buckling loads and corresponding modes, and (*ii*) the nonlinear analysis to capture the post-buckling response. Xu et al. [17] performed parametric studies using ANSYS software to identify the influencing parameters on the flexural strength of CFS built-up boxes. The effect of screws was taken into account by coupling corresponding degrees of freedom (DOF) of the constituent profiles at fastener locations, and it was concluded that decreasing fastener spacing resulted in at most 6 percent increase in flexural capacity. A subsequent parametric study [18] was carried out on CFS built-up double-Z members in which the slip and bearing of the bolts were represented by sets of springs that connected nodes of the component profiles at bolt locations. The study revealed the importance of modelling fasteners as discrete constraints. Li et al. [12] investigated the impact of installation errors and fastener spacing on the ultimate strength of built-up box and I-columns via extensive parametric studies in ANSYS and concluded that the fastener spacing and arrangement can affect the failure load. Laim et al. [11] conducted parametric studies in ABAQUS to determine the influence of cross-sectional dimensions on the flexural behaviour of CFS built-up open- and closed-section beams. They modelled the self-drilling screws with 3D solid elements, and the numerical results suggested a reduction in the strength-to-weight ratio as the considered span increased. In addition, Wang and Young [19] studied the effect of both cross-sectional dimensions and fastener spacing on the ultimate strength of built-up box and I-beams with intermediate fasteners. Later, the effect of edge and web stiffeners on the behaviour of built-up I-columns was investigated via extensive parametric studies [20].

The FSM has been widely used for the elastic buckling analysis of CFS members due to its numerically efficient features including narrow bandwidth of stiffness matrices, low computational cost, and easy implementation for prismatic members. However, its range of application is mostly limited to simple geometries and simple end boundary conditions. These limitations have been the motivation for introducing variants or enrichment of the FSM, e.g. [21–23]. Some attempts have been made to extend the application range of conventional FSM to built-up sections by applying nodal multi-point constraints that tie any desired DOF from the adjacent plate components continuously along the length of the member [24] or by modelling fasteners as continuous longitudinal solid stiffeners [20]. However, these assumptions may not represent the actual effect of discrete fasteners and may fail to capture the level of composite action accurately.

Puckett and Gutkowski [25] developed the compound strip method (CSM) by including the stiffness of elastic supporting elements such as columns, longitudinal and transverse beams in a direct formulation and significantly enhanced the versatility and capability of the FSM. In this method, the strain energy of the supporting elements is added to the strain energy of the component plate strips and then the stiffness matrix is obtained by minimising the total energy with respect to displacements. The CSM was employed for the linear flexural [26] and buckling [27] analyses of straight continuous flat plates over flexible supports. Borković et al. [28] studied the linear transient vibration of stiffened plates using the CSM where the strain and the kinetic energy of stiffeners were added to those of finite strips. Maleki [29] further extended the application of the CSM to the analysis of folded plates and box girders with intermediate non-rigid supports. Borković et al. [30] utilised the CSM for geometric nonlinear static analysis of prismatic shells with internal supports and stiffeners. For the analysis of folded plates, Puckett and Wiseman [31,32] developed a technique for the inclusion of bracing elements. The spline compound strip method [33,34] was introduced as a more versatile extension of the conventional CSM and was utilised in the analysis of stiffened plates and braced thin-walled structures.

In this study, the compound strip method is employed for the buckling analysis of built-up CFS members. The discrete fasteners are modelled as connecting elements with adjustable stiffness properties. A simple yet accurate framework is presented for the reliable analysis of built-up sections with any desired cross-sectional composition and fastener configuration. The framework provides an effective numerical tool that expedites extensive parametric studies and can be used for the structural design of built-up sections. In Section 2, the semi-analytical finite strip method is briefly reviewed, then the formulation of connection element with the required procedure for its inclusion in the finite strip formulation is illustrated in detail. A series of numerical examples are presented in Section 3 to show the accuracy and versatility of the CSM for the elastic buckling analysis of various built-up CFS sections. Section 4 summarises the outcomes of this study and concludes the paper.

2. Numerical method and formulation

2.1. General

In this section, the basic concept and methodology of the utilised technique for the modelling of discrete fasteners are briefly outlined. The numerical method employed in this study is based on the compound strip method for plates [25] which is an extension of the semi-analytical FSM (S-a FSM) and was developed to model structures with support and connecting elements [31,35]. In the following, the basics of S-a FSM is briefly reviewed and subsequently the assembly process that incorporates the fastener elements in the finite strip formulation is explained in detail. In this technique, a connection element with adjustable translational and rotational stiffness is utilised to represent the fasteners. The end displacements and rotations of these connecting elements are chosen such that they are compatible with the displacements of the corresponding finite strip plate elements. To achieve the required compatibility for displacements, the total strain energy of the finite strips and connecting elements are derived in terms of global nodal displacement of the strips. To this end, first the local displacements of the connecting elements are transformed to the adopted global