Engineering Structures 177 (2018) 641–654

Contents lists available at ScienceDirect

Engineering Structures

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

Strength and deflection behaviour of cold-formed steel back-to-back channels

Jun Ye[a,c,*], Seyed Mohammad Mojtabaei[b], Iman Hajirasouliha[b], Paul Shepherd[a], Kypros Pilakoutas[b]

[a] Department of Architecture and Civil Engineering, University of Bath, Bath BA2 7AY, UK
[b] Department of Civil Engineering and Structural Engineering, The University of Sheffield, Sheffield S1 3JD, UK
[c] Faculty of Engineering & Technology, Division of Civil and Engineering, University of West of England, Bristol, BS16 1QY, UK

ARTICLE INFO

Keywords:
Cold-formed steel
Beam
Finite element study
Strength
Deflection

ABSTRACT

Cold-formed steel (CFS) construction can lead to more efficient designs compared to hot-rolled steel members as a consequence of its high strength, light weight, ease of fabrication, and flexibility in their cross-section profiles. However, CFS members are vulnerable to local, distortional and overall buckling modes. This paper develops a numerical model to investigate the flexural strength and failure modes of CFS back-to-back channel beams and verifies the efficiency of an optimisation framework previously proposed. The model incorporates non-linear stress-strain behaviour and enhanced corner properties obtained from coupon tests, as well as initial geometric imperfections measured in physical specimens. To simulate the behaviour of a bolt bearing against a steel plate in the back-to-back section, a connector model is used that takes into account both slippage and bearing deformations. The developed Finite Element (FE) models are verified against six four-point bending tests on CFS back-to-back channel beams, where excellent agreement is found between the experimental results and the FE predictions. The validated FE models are then used to assess the adequacy of the effective width method in EC3 and the Direct Strength Method (DSM) in estimating the design capacity of conventional and optimum design CFS channel beam sections. The results indicate that both EC3 and DSM provide accurate predictions for the bending capacity of lipped channel beam sections. A comparison between FE predictions and tested results show that, the geometric imperfections can change the FE predictions of ultimate capacity by 7%, while the strain-hardening of CFS material at the round corners has negligible effects. It is also shown that EC3 uses a reduced cross-sectional property to calculate deflections, which can reasonably predict deflections with a slight over-estimation (6%) at the serviceability load level.

1. Introduction

Cold-formed steel (CFS) members have traditionally been employed as load-carrying members in a wide range of applications, such as roof purlins and structural envelopes. In recent years, however, CFS members have become increasingly popular in low- to mid-rise multi-storey buildings [1] and CFS portal frames with short to intermediate spans [2,3], as shown in Fig. 1(a) and (b). CFS sections are increasingly being offered as an alternative to hot-rolled steel elements since they provide greater flexibility in terms of cross-sectional profiles and sizes, which can lead to more efficient design solutions with less redundant material. CFS sections are also light-weight, easy to handle on site, and easier to connect. However, CFS components are made of thin plates, which have inherently low buckling resistance. This results in reduced strength for CFS elements, which limits their performance in multi-storey applications. CFS components are usually susceptible to local, distortional and global buckling (and their interactions) as shown in Fig. 2.

Although the accurate prediction of the behaviour of CFS elements is difficult due to their complex failure modes, Finite Element Analysis (FEA) is widely used to predict the flexural behaviour of CFS beams [4]. Previously, a series of physical experiments on hat and back-to-back lipped beams have been conducted by Peköz et al. [5,6] to investigate the capacity of edge stiffeners in CFS sections. Compared to physical experiments, FEA is relatively inexpensive and time efficient, especially when a parametric study of cross-section geometry is involved. In addition, FEA can be efficiently used for investigations considering geometric imperfections and material nonlinearity of structural members, which could be difficult to achieve through physical tests.

* Corresponding author.
E-mail addresses: j.ye@bath.ac.uk, zjuyejun@gmail.com (J. Ye).

https://doi.org/10.1016/j.engstruct.2018.09.064
Received 15 December 2017; Received in revised form 19 July 2018; Accepted 21 September 2018

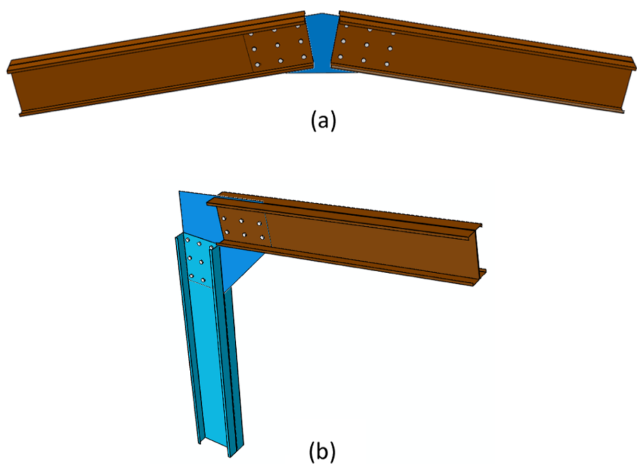

Fig. 1. CFS (a) apex and (b) eaves connections with back-to-back beam sections used in typical portal frames.

Although FEA is a useful and powerful tool for the analysis of CFS structures, it is important to obtain accurate and reliable finite element models (FEM) prior to any analytical investigations. For example, Yu and Schafer [7] used nonlinear finite element models of CFS beams to develop the Direct Strength Method (DSM) design recommendations. Haidarali and Nethercot [8] then developed a simplified numerical model that could significantly increase the computational efficiency of the non-linear analyses. In their study, the geometrical imperfection of CFS profiles was determined by using the constrained finite strip software CUFSM [9], while the imperfection amplitudes were based on the statistic results presented by Schafer and Peköz [10].

In another study, Kankanamge and Mahen [11] investigated the behaviour of CFS beams subjected to lateral-torsional buckling. A detailed parametric study was conducted to simulate the lateral–torsional buckling behaviour using four-node shell elements with five degrees of freedom per node and reduced integration (S4R) in ABAQUS [12]. The results of their study were used to verify the design guidelines for the lateral-torsional buckling of CFS beams in AS/NZS 4600 [13], DSM [14] and EC3 [15]. Poologanathan and Mahen [16] developed a numerical model in ABAQUS using the S4R5 element. The numerical model was used to investigate the shear buckling and post-buckling characteristics of an innovative LiteSteel Beam. Ayhan and Schafer [17] used an experimentally verified numerical model in ABAQUS [12] to obtain a simplified method for predicting the bending stiffness of CFS members. Based on both experimental and numerical results, new local/distortional slenderness-based design equations were proposed. Similarly, Dubina et al. [18] developed an FE model to investigate the behaviour of CFS beams with corrugated web and discrete web-to-flange fasteners. They used four-node shell elements to model the CFS components, while the connector element CONN3D2 with six degrees of freedom per node was employed in ABAQUS [12] to simulate the behaviour of self-tapping screws and bolts according to single-lap tests [19]. In a more recent study, Wang and Young [20,21] proposed a numerical model to investigate the flexural behaviour of CFS built-up sections with intermediate stiffeners subjected to bending. The S4R shell element and C3D8R solid elements in ABAQUS [12] were used to model the CFS sections and screws, respectively. The surfaces of the solid screws were tied to the drilled hole edges of the beam specimens, while surface interactions between the overlapped elements of the built-up sections were modelled using contact elements.

This paper aims to develop an advanced numerical model to predict the flexural behaviour and bending strength of CFS beam sections CFS back-to-back channel beams and to verify an optimisation framework previously proposed. An experimental investigation, including six physical tests on CFS back-to-back channel beams, which failed by local/distortional buckling about the major axis, is used to verify the FE models in ABAQUS [12]. The advantage of the developed models over the previous studies is that it incorporates non-linear stress-strain behaviour and enhanced material properties based on coupon tests, measured initial imperfections and an effective connector element to model the bolt behaviour. The models are then used to assess the adequacy of both the EC3 design guides [15,22,23] and the Direct Strength Method (DSM) to design a range of conventional and optimum designed CFS beams considering local/distortional buckling modes. The deflection of CFS beams incorporating the effects of the material non-linearity, effective cross-sections and the change of Young's modulus along the distribution of bending moment in the beams, is also investigated.

2. Eurocode 3 design formulation

Prior to the description of the numerical study, a brief introduction is presented to show how the Eurocode 3 design guidelines consider local and distortional buckling modes and their interaction on CFS beam sections.

2.1. Local buckling

In Eurocode 3, the effect of local buckling is considered through the effective width concept. It is based on the observation that local buckling causes a loss of compressive stiffness in the centre of a plate supported along two longitudinal edges ('internal' plate element), or along the free edge of a plate supported along one longitudinal edge ('outstand' plate element) as a result of non-linear effects. The corner

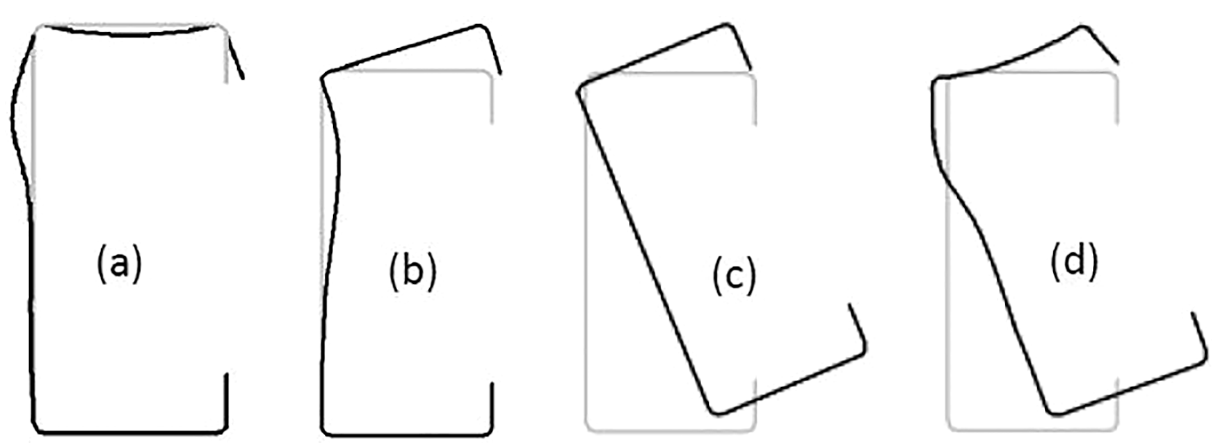

Fig. 2. Buckling of a lipped channel beam: (a) local, (b) distortional, (c) lateral-torsional and (d) local-global interactive modes.