Engineering Structures 158 (2018) 28–42

Contents lists available at ScienceDirect

Engineering Structures

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

Finite element modelling of composite cold-formed steel flooring systems

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ARTICLE INFO

Keywords:
Cold-formed steel
Composite action
Finite element modelling
Numerical modelling
Partial shear connection
Wood-based particle boards

ABSTRACT

The findings from a numerical investigation into the degree of composite action that may be mobilised within floor systems comprising cold-formed steel joists and wood-based particle boards are presented herein. Finite element models have been developed, simulating all the components of the examined systems, as well as the interaction between them. The models include initial geometric imperfections, the load-slip response of the fasteners employed to achieve the shear connection as well as both geometric and material nonlinearities. The developed models were first validated against 12 physical tests reported in the literature, which showed them to be capable of accurately capturing the load-deformation curves and failure modes exhibited by the tested specimens. Parametric studies were then performed to examine the influence of key parameters on the structural behaviour of these systems, including the depth and thickness of the cold-formed steel section, as well as the spacing of the employed fasteners; in total, about 100 systems have been examined. Significant benefits in terms of structural response have been identified from the presented numerical study as a result of the mobilisation of composite action; for the systems investigated, which were of typical, practical proportions, up to 140% increases in moment capacity and 40% increases in stiffness were found. The presented research reveals the substantial gains in structural performance and the influence of the key governing parameters for this novel form of composite construction.

1. Introduction

The use of cold-formed steel beams in conjunction with wood-based flooring panels for the construction of lightweight and economical flooring systems is widespread. Cold-formed steel joists are often preferred over other structural members (e.g. timber joists) due to their high strength-to-weight ratio which results in easy and fast erection, reduction in transportation and handling costs and, ultimately, in economical and durable solutions for floors. An experimental programme described in [1–3] concluded that it is feasible for composite action to develop within flooring systems comprising cold-formed steel beams and wood-based particle boards, leading to substantial improvements in structural performance and load carrying capacity, while previously conducted laboratory tests had shown that the serviceability performance of these floors can be further improved by enhancing end fixity and considering interaction with the flooring boards [4,5].

Although the findings of these experimental investigations are promising, further research is required to explore the key features of the structural behaviour, to expand the existing pool of data and, hence, to quantify more accurately the benefits derived due to the development of composite action within cold-formed steel flooring systems. However, laboratory tests, which constitute the traditional method of data generation, are costly and time consuming. The need for a finite element investigation, replicating the complex geometry and nature of cold-formed steel flooring systems, is therefore evident.

In this paper, finite element models of composite flooring systems comprising cold-formed steel beams and wood-based particle boards are presented and validated against data from physical tests reported in the literature. The validated numerical models are then employed for numerical simulations investigating the influence of key parameters on the performance of these composite flooring systems; the results are then reported and analysed.

2. Development of finite element models

The finite element software package ABAQUS [6], which has been widely used in the past for the analysis of cold-formed steel members [7–11], was chosen for the performed numerical investigation. The developed finite element models were initially used for the simulation of the physical beam tests reported in [1–3], utilising the relevant material and push-out test results as inputs. The main features of the developed finite element models are presented herein while their validation, as well as the conducted parametric studies, are presented in Sections 3 and 4 of this paper, respectively.

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https://doi.org/10.1016/j.engstruct.2017.12.024
Received 12 May 2017; Received in revised form 10 October 2017; Accepted 12 December 2017

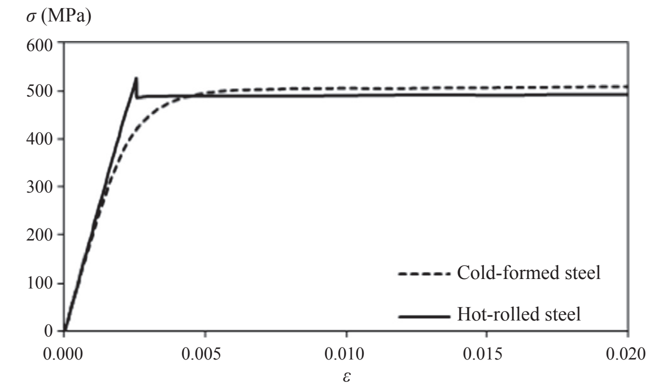

Fig. 1. Initial part of material stress-strain curves for typical cold-formed and hot-rolled steels.

2.1. Material modelling

In order to accurately capture the response of a structural system, the material characteristics of all its members must be precisely determined and incorporated into the numerical simulations.

2.1.1. Cold-formed steel

Unlike hot-rolled steel, cold-formed steel exhibits a gradually yielding response followed by a significant period of strain hardening, apparent even at low levels of strain – see Fig. 1. A constitutive model initially proposed by Ramberg and Osgood [12] for aluminium and modified by several researchers [13–17] for application to other nonlinear metallic materials, has been employed herein. Specifically, the two-stage Ramberg-Osgood model presented in Eqs. (1) and (2), proposed by Gardner and Ashraf [18], has been chosen for the material modelling of the cold-formed steel.

$$\varepsilon = \frac{\sigma}{E} + 0.002\left(\frac{\sigma}{\sigma_{0.2}}\right)^{n} \quad \text{for } \sigma \leqslant \sigma_{0.2} \tag{1}$$

$$\varepsilon = \frac{\sigma - \sigma_{0.2}}{E_{0.2}} + \left(\varepsilon_{1.0} - \varepsilon_{0.2} - \frac{\sigma_{1.0} - \sigma_{0.2}}{E_{0.2}}\right)\left(\frac{\sigma - \sigma_{0.2}}{\sigma_{1.0} - \sigma_{0.2}}\right)^{n'_{0.2,1.0}} + \varepsilon_{0.2} \quad \text{for } \sigma_{0.2} < \sigma \leqslant \sigma_{u} \tag{2}$$

where σ and ε are the engineering stress and strain respectively, E is the Young's modulus of the material, $\sigma_{0.2}$ and $\sigma_{1.0}$ are the 0.2% and 1% proof stresses respectively, $E_{0.2}$ is the tangent modulus of the stress-strain curve at $\sigma_{0.2}$, $\varepsilon_{0.2}$ and $\varepsilon_{1.0}$ are the total strains corresponding to the 0.2% and 1.0% proof stresses while n and $n'_{0.2,1.0}$ are strain hardening exponents determining the degree of roundedness of the stress-strain curve. The two-stage Ramberg-Osgood model was fitted to the measured stress-strain curves reported in [1,2] and assigned to the flat portions of the modelled cold-formed steel sections.

Coupon tests conducted by several researchers [19–21] have shown that the cold-rolling process can have a significant influence on the material behaviour of the resulting cross-sections due to the accumulation of permanent plastic deformations, particularly in the corner regions, which exhibit higher yield (0.2% proof) strengths compared to the flat portions of the same cross-sections, though with reduced ductility. Corner coupon tests were carried out as part of the research of Kyvelou et al. [1,2] revealing, on average, a 17% higher yield strength in the corners than in the flat portions of the tested sections. Therefore, allowance was made in the developed finite element models for strength enhancements in the corner regions by assigning different material properties, in accordance with the conducted tests, to these parts of the sections. Note that the corresponding through-thickness residual stresses were not incorporated in the numerical simulations since their effect is approximately included in the stress-strain curves obtained from tensile coupon tests extracted from cold-formed sections [22].

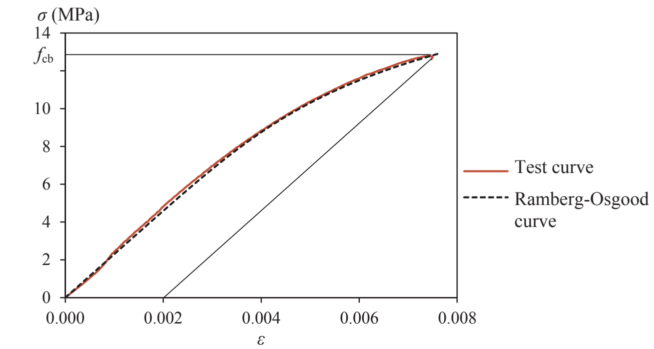

Fig. 2. Comparison between the measured stress-strain curve of the floorboard material and the Ramberg-Osgood material model.

For input into the developed ABAQUS shell finite element models, the nominal stresses and strains, derived by fitting Eqs. (1) and (2) to the measured stress-strain data, have been converted into true stresses and strains. The equations used for the determination of the true (Cauchy) stresses σ_{true} and the true plastic strains $\varepsilon_{true}{}^{pl}$ are presented in Eqs. (3) and (4), respectively.

$$\sigma_{true} = \sigma(1 + \varepsilon) \tag{3}$$

$$\varepsilon_{true}^{pl} = \ln(1 + \varepsilon) - \frac{\sigma_{true}}{E} \tag{4}$$

2.1.2. Wood-based particle board

The results of tests carried out on the floorboard material employed in the beam tests [2,3], were used to define the material stress-strain characteristics of the flooring panels in the present numerical models. The measured material properties lay within the expected range in relation to similar existing experimental results [23,24], and the stress-strain response could be accurately represented by the Ramberg-Osgood curve, as shown in Fig. 2. Hence the material behaviour assigned to the flooring panels in the finite element simulations was determined according to Eq. (1), where E and $\sigma_{0.2}$ were taken as the values of Young's modulus in compression E_b and the compressive strength of the board f_{cb}, respectively – see Fig. 2 – while the value of the strain hardening exponent n was taken as 6, based on a fit to the experimental data. The value of the Poisson's ratio for the boards v_b was taken as 0.2, based on previous physical tests [25,26]. Failure of the floorboards was deemed to occur when the stress reached the ultimate compressive or tensile stress of the board material (f_{cb} and f_{tb} respectively).

2.2. Element types

Shell elements are typically employed for modelling structures in which one dimension, usually the thickness, is significantly smaller than the other two dimensions; these elements are able to accurately capture local instabilities, such as local and distortional buckling, rendering them an ideal choice for modelling thin-walled sections. The general purpose 4-noded three-dimensional S4R [6] shell elements with reduced integration and hourglass control were chosen for the modelling of the cold-formed steel beams examined herein. Several researchers have used these elements in the past for modelling cold-formed steel structures under bending, obtaining accurate replication of the observed physical behaviour [21,27–29].

The 8-noded three-dimensional C3D8R [6] solid elements with reduced integration and hourglass control were chosen for the modelling of the wood-based flooring panels. Numerical investigations on composite systems described in the literature have employed this type of element to model the concrete slab in composite beams, yielding accurate results when compared against physical tests [30,31,32–34].