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Development of optimum cold-formed steel sections for maximum energy dissipation in uniaxial bending

Jun Ye[a], Jurgen Becque[a,*], Iman Hajirasouliha[a], Seyed Mohammad Mojtabaei[a], James B.P. Lim[b]

[a] Department of Civil and Structural Engineering, The University of Sheffield, Sheffield, UK
[b] Department of Civil and Environmental Engineering, The University of Auckland, New Zealand

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ABSTRACT

Cold-formed steel (CFS) elements are increasingly used as load-bearing members in construction, including in seismic regions. More conventional hot-rolled steel and concrete building structures are typically allowed by the design standards to exceed their elastic limits in severe earthquakes, rendering parameters indicating ductility and energy dissipation of primordial importance. However, insufficient research has yet been conducted on the energy dissipation of CFS structures. In the majority of previous optimization research on CFS sections the ultimate capacity, as typically controlled by local, distortional and/or global buckling modes, is considered to be the sole optimization criterion. This paper aims to improve the seismic performance of CFS elements by optimising their geometric and material highly non-linear post-buckling behaviour to achieve maximum energy dissipation. A novel shape optimisation framework is presented using the Particle Swarm Optimisation (PSO) algorithm, linked to GMNIA ABAQUS finite element analyses. The relative dimensions of the cross-section, the location and number of intermediate stiffeners and the inclination of the lip stiffeners are considered to be the main design variables. All plate slenderness limit values and limits on the relative dimensions of the cross-sectional components as defined by Eurocode 3, as well as a number of practical manufacturing and construction limitations, are taken into account as constraints in the optimisation problem. It is demonstrated that a substantial improvement in energy dissipation capacity and ductility can be achieved through the proposed optimization framework. Optimized cross-sectional shapes are presented which dissipate up to 60% more energy through plastic deformations than a comparable commercially available lipped channel.

1. Introduction

Cold-formed steel (CFS) sections are produced by rolling or brake-pressing relatively thin metal sheets into cross-sectional shapes at ambient temperature. Structural systems composed of CFS members provide a wide range of advantages. They typically offer a high strength-to-weight ratio, making efficient use of the material. Moreover, they are lightweight and consequently easy to handle, transport and install. Practical limitations on the sheet thicknesses, however, result in CFS members being susceptible to instabilities such as local, distortional and global buckling. The large width-to-thickness ratios of CFS members also leave them typically outside the limits prescribed by seismic design codes (e.g. [2,10]) for high seismic regions.

It has been shown that optimisation of CFS elements based on their maximum strength under bending or compression can lead to significant material savings. Relevant work has been carried out by, among others, Liu et al. [16], Tian and Lu [26], Leng et al. [15] and Ma et al. [17].

While research has previously been conducted on the seismic behaviour of CFS stud wall systems ([19]), research into the energy dissipation capacity of individual CFS load-bearing elements is very limited. Calderoni et al. [7] conducted monotonic and cyclic tests to study the seismic behaviour of CFS channel beams. The results of their study showed a substantial ductility and energy dissipation capacity. The cyclic behaviour of typical CFS wall studs was investigated by Padilla-Llano et al. [20]. The experimental results showed that the amount of energy dissipated by the studs varied with the dimensions and the shape of the profile, but typically decreased with increasing cross-sectional slenderness.

Other research on the development of members for CFS moment-resisting frames has shown that the ductility and energy dissipation of the sections can be significantly improved by curving the flanges into a semi-circular shape [23]. However, such curved flanges are difficult to manufacture and provide challenges when connecting them to floor elements. More practical shapes can be developed by taking into account manufacturing and construction constraints, as demonstrated by

* Corresponding author.
E-mail address: j.becque@sheffield.ac.uk (J. Becque).

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Ye et al. [29] and Ye et al. [30].

In other relevant research Pan et al. [21] developed an optimisation method to obtain hot-rolled H-beams with optimal flange shapes which maximize the energy dissipation capacity of the members under monotonic and cyclic loads. To achieve this, they combined a Simulated Annealing optimisation algorithm with detailed nonlinear finite element analyses.

The fact that the production process of CFS members is relatively straightforward and versatile offers great scope for the development of new, innovative and optimized cross-sections. A novel framework is therefore proposed in this paper to optimise CFS sections with respect to their energy dissipation capacity under monotonic loading. The relative dimensions of the cross-sections, the location and the number of intermediate stiffeners and the inclination of the lip stiffeners were thereby considered as the main design variables. To obtain the global optimum solution a Particle Swarm Optimisation (PSO) algorithm was combined with the general purpose finite element program [1], which was used to carry out geometric and material non-linear analyses including the effects of initial imperfections (GMNIA).

2. Scope and range of prototype sections

In the design of hot-rolled steel members for high seismic regions, the width-to-thickness ratios of compressive elements are limited by codes of practice ([2,10]) to allow for the development of sufficient plastic deformations. As expected, CFS members generally do not satisfy these limits. However, unlike hot-rolled steel members, intermediate stiffeners and lips can be rolled into CFS members to suppress cross-sectional instabilities (Fig. 1). Adding a lip stiffener is a very effective way to stabilize the top flange of cross-sections subjected to bending (Fig. 1(a)), while an additional intermediate stiffener in the flange (Fig. 1(b)) is useful for wide flanges. For slender webs with high width-to-thickness ratios local buckling may be initiated in the web and an intermediate web stiffener may therefore increase the flexural performance (Fig. 1(c)).

In addition to sections (a)-(c) in Fig. 1, the 'folded flange' section pictured in Fig. 1(d) was also considered as a prototype in the proposed optimization procedure. This cross-section was previously developed and studied by Ye et al. [30] and originated from a practical approximation of a curved flange section. The study provided additional design guidance to determine the bending capacity of this section to [9], accounting for the possible occurrence of multiple distortional buckling modes. Furthermore, the paper reports on an optimization study where the Particle Swarm Optimisation (PSO) algorithm was employed to maximize the flexural strength of various prototypes, including the sections shown in Fig. 1(a)–(c), as well as the folded flange section. The results showed that, for the same amount of material, the folded flange section provided a bending capacity which was up to 57% higher than other optimized shapes, as illustrated in Fig. 2. Consequently, it is an obvious candidate to be considered in the current optimization study.

3. FE analyses of CFS beams

Previous research studies have shown that finite element (FE) models can be used to accurately predict the load carrying capacity and post-buckling behaviour of CFS sections, provided that the appropriate element type, material parameters and imperfection profiles are selected [12,31,5,6]). In this paper, the general purpose FE package [1] was used, after validation, to predict the deformation behaviour of the prototype beams and to search for the optimum cross-sectional shapes which maximize the energy dissipation.

3.1. FE model and validation

The modelling techniques used in the FE models were first verified against a series of tests on CFS back-to-back channels described by Ye [28]. Six specimens were tested in four-point bending and failed by interaction of local and distortional buckling in the constant moment region. The specimens were laterally supported near the loading points to prevent global instability due to lateral-torsional buckling. The test set-up is schematically shown in Fig. 3. All specimens had a span length of 3100 mm, while the constant moment span was 1200 mm long. Three different cross-sections were considered (Fig. 4) and two specimens of each cross-section were tested. The wall thickness of all specimens was 1.5 mm. The channels were connected above the end supports and under the loading points by M12 bolts, but the constant moment span did not feature any connectors. The material properties and the specimen imperfections were accurately measured and details of the measuring procedure, as well as full results, can be found in Ye [28]. The average measured yield stress was 422 MPa.

The FE models of the CFS beams were developed using 8-node quadrilateral shear-flexible shell elements with reduced integration and five nodal degrees of freedom (S8R5). Fig. 5 illustrates the features of the FE model. Rigid cross-sections were defined over the end supports and under the loading points to simulate the wooden blocking used in the test to prevent localized failure by web crippling. The out-of-plane deformations of the beam were restrained at the supports and at the loading points. Surface-to-surface contact was modelled between the webs of the channels. The bolts were modelled using rigid BEAM connector elements. The measured imperfection profile was transferred into the model by adjusting the initial nodal coordinates. The material was modelled using the measured stress-strain curve, converted from engineering stress and strain to true stress and strain, as shown in Fig. 6. The measured material properties were: elastic modulus E = 200 GPa, yield stress f_y = 427 MPa and tensile strength f_u = 593 MPa. A geometrically non-linear 'static general' analysis was carried out.

Residual stresses and the effects of work hardening as a result of the rolling process were not included in the model, based on the observation that they have to some extent opposite effects and based on the recommendation by Schafer et al. [24] that both phenomena are not independent and that they should therefore either be modelled together or ignored together. Moreover, all sections considered in the study were open sections, in which residual stresses are typically limited.

A mesh sensitivity study was performed using the 180 mm deep

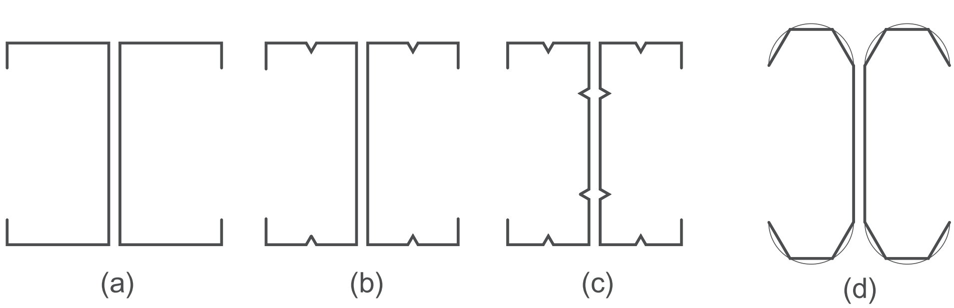

Fig. 1. Cross-section prototypes.