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Unconstrained shape optimisation of singly-symmetric and open cold-formed steel beams and beam-columns

Bin Wang [a,*], Guillaume L. Bosco [a], Benoit P. Gilbert [a], Hong Guan [a], Lip H. Teh [b]

[a] Griffith School of Engineering, Gold Coast Campus, Griffith University, QLD 4222, Australia
[b] School of Civil, Mining and Environmental Engineering, University of Wollongong, NSW 2522, Australia

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ABSTRACT

This study aims to optimise the cross-sectional shape of singly-symmetric, open-section and simply-supported cold-formed steel (CFS) beams and beam-columns. No manufacturing or assembly constraints are considered. The previously developed augmented Lagrangian Genetic Algorithm (GA), referred to as the “self-shape” optimisation algorithm, is used herein. Fully restrained and unrestrained beams against lateral deflection and twist, as well as unrestrained beam-columns are optimised. Various combinations of axial compressive load and bending moment are analysed for the beam-columns. The Direct Strength Method (DSM) is used to evaluate the nominal member compressive and bending capacities. The accuracy of the automated rules, developed in the literature to determine the elastic local and distortional axial buckling stresses from Finite Strip signature curves, is verified herein to estimate the elastic bending buckling stresses. The optimised cross-sectional shapes are presented for all cases and the evolution of the unrestrained shapes from pure axial compression to pure bending is discussed.

1. Introduction

Cold-formed steel (CFS) members are intensively used in the construction industry due to their ease of erection and low weight-to-capacity ratio [1]. Their structural efficiency lies in the versatility of the cross-sectional shapes that enhances the strength by controlling the three fundamental buckling modes, i.e. local, distortional and global. Local buckling is enhanced in practice by adding wall stiffeners, while lip stiffeners and rear flanges greatly influence distortional buckling [2].

Improving the overall cross-sectional shape of CFS members through shape optimisation algorithms is currently gaining significant interest. The ultimate objective is to discover new and innovative optimum cross-sections that can be manufactured and practicably used onsite.

Nevertheless, research on shape optimisation of CFS members has been solely restricted to columns with unconstrained (where the algorithm is free to converge to any cross-sectional shapes) [3–7] and constrained (where sections are able to be manufactured and/or practicably assembled onsite) [8–12] problems. Shape optimisation of CFS beams has been seldom investigated and the optimisation of CFS beams has been primarily performed so far by algorithms that aimed at optimising the dimensions of a given cross-section rather than optimising the cross-sectional shape itself, see [13–17] for instance. Shape optimisation of thin-walled beams has been performed to a certain extent [18,19], but only to maximise the second moments of area and minimise the cross-sectional area.

This paper aims at shape optimising the cross-sections of unconstrained (no manufacturing and assembly constraints) CFS beams and beam-columns by minimising their cross-sectional area for various combinations of axial compressive load and bending moment. Unconstrained optimisation problems allow the “absolute” optimised cross-sectional shape to be discovered. This outcome provides a reference shape to be compared to when manufacturing and assembly constraints are later introduced into the algorithm. The present work is therefore an important step in shape optimisation of practical CFS sections. An existing shape optimisation algorithm [4,18] is used for this purpose.

The Direct Strength Method (DSM) [20] is used to calculate the nominal axial compressive and bending capacities of the cross-sections. Rules to automatically estimate the elastic bending local and distortional buckling stresses to be used in the DSM are given and verified against 64 cross-sections. The algorithm is applied to beams that are either restrained (braced) or not against lateral deflection and twist, and unrestrained (unbraced) beam-columns. The optimised cross-sectional shapes are presented and the evolution of the unrestrained shapes from pure axial compression to pure bending is discussed.

* Corresponding author.
E-mail address: b.wang@griffith.edu.au (B. Wang).

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2. The shape-optimisation algorithm

In this study, the "self-shape" optimisation algorithm for CFS members, for which the principles are published in [18] and its applications to singly-symmetric cross-sections are presented in [4], is used. Genetic Algorithm (GA) [21] is used as the search algorithm. The GA is combined with the Augmented Lagrangian (AL) method [22] to avoid ill-conditioned processes by ensuring finite values of the penalty factors.

Initial cross-sections are drawn using self-avoiding random walks. Cross-over and mutation operators are performed on a design space [4,18]. The algorithm has the advantages of (i) being verified against a known optimisation problem for which an analytical solution exists [18] and (ii) allowing arbitrary cross-sections to be initially created with no presumption of the optimised shape. Examples of arbitrary drawn singly-symmetric and open cross-sections in the initial population can be found in [4].

More information and full details of the algorithm are available elsewhere [4, 18]. The calibration of the factors used in the AL method is given in [18].

3. The optimisation problem

The "self-shape" optimisation algorithm is used herein to optimise simply-supported, free-to-warp, singly-symmetric and open-section beams and beam-columns. The three fundamental buckling modes, i.e. local, distortional and global, are incorporated through the use of the DSM, as described in Section 4. The yield stress f_y of the steel is 450 MPa, the Young's modulus E is 200 GPa and the shear modulus G is 80 GPa. The wall thickness t is taken as 1.2 mm. The member is subjected to a uniform bending moment M^* about its axis of symmetry (x-axis) and a compressive axial load N^*. The optimisation problem is illustrated in Fig. 1.

In reference to Fig. 1, the member length L is fixed throughout this paper at 1.5 m. Five load cases (LC) are considered to investigate the optimum cross-sectional shapes of simply supported beams, columns and beam-columns:

- LC1: Pure bending ($N^*=0$ and $M^*=2.5$ kN m) for a fully restrained beam, (i.e. $L_{ey}=L_{ez}=0$ m, where L_{ey} and L_{ez} are the effective buckling lengths for bending about the y-axis and for twisting about the longitudinal z-axis, respectively).
- LC2: Same moment as LC1 but for an unrestrained beam (i.e. $L_{ey}=L_{ez}=L=1.5$ m).
- LC3: Pure axial compression ($N^*=75$ kN and $M^*=0$) for an unrestrained column (i.e. $L_{ex}=L_{ey}=L_{ez}=L=1.5$ m, where L_{ex} is the effective buckling length for bending about the axis of symmetry). This case has already been investigated in [12] and the previously obtained results are used in this study.
- LC4: Combined actions for an unrestrained beam-column with dominant bending. N^* is taken as $^1/_3$ of the axial compressive load in LC3 and M^* as $^2/_3$ of the bending moment in LC2 ($N^*=25$ kN and $M^*=1.67$ kN m).
- LC5: Combined actions for an unrestrained beam-column with dominant axial compression. N^* is taken as $^2/_3$ of the axial compressive load in LC3 and M^* as $^1/_3$ of the bending moment in LC2 ($N^*=50$ kN and $M^*=0.83$ kN m).

As cold-rolled steel coil can usually be ordered in any width, the approach is to mimic a CFS manufacturer who wants to optimise the cross-sectional shape against a given design loading combination. The unconstrained problem in the GA consists of minimising the cross-sectional area A_s subject to an inequality penalty function on N^* and M^*. The interaction equation described in Clause 3.5 of the Australian cold-formed steel design

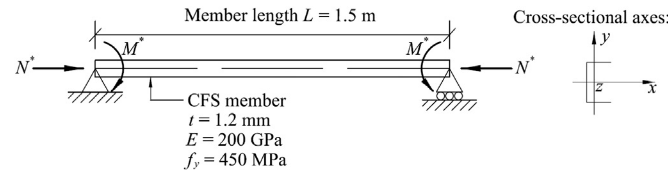

Fig. 1. Optimisation problem.

specification AS/NZS 4600 [23] is used as the penalty function,

$$\frac{N^*}{\varphi_c N_c} + \frac{M^*}{\varphi_b M_b} \le 1 \tag{1}$$

where ϕ_c and ϕ_b are capacity reduction factors, taken as 1.0 in this study. N_c and M_b are the nominal member compressive and bending capacities of the cross-section, respectively. The general form of the fitness function f suitable for GA is then expressed as,

$$f = \frac{A_s}{A_{ref}} + \alpha\left\{\max\left[0, \left(\frac{N^*}{N_c} + \frac{M^*}{M_b} - 1\right)\right]\right\} \tag{2}$$

where A_{ref} is the reference area of similar value to the optimised cross-sectional area. A_{ref} is estimated herein with preliminary runs and is taken as 190 mm^2 for LC1, 292 mm^2 for LC3 [12], and 260 mm^2 for other cases. α is a penalty factor [21].

To avoid ill-conditioning problem, the AL constraint-handling method developed in [22] for the GA is used. The actual form of the fitness function f used in the algorithm then becomes,

$$f = \frac{A_s}{A_{ref}} + \frac{1}{2}\left\{\gamma\left[\max\left(0, \left(\frac{N^*}{N_c} + \frac{M^*}{M_b} - 1\right) + \mu\right)\right]^2\right\} \tag{3}$$

where γ is the penalty function coefficient, and μ is the real parameter associated with the penalty function. Initial values of $\gamma=2.0$ and $\mu=0$ found in [18] are used. Similar to [18], the AL penalty increasing constant β and convergence rate ρ are set to 1.05 and 1.5, respectively.

Detailed parameters of the GA used in this paper are given in [4,18]. In this study, 500 cross-sections are analysed per generation and the algorithm converges in less than 60 generations (see Section 5.1). Therefore, a maximum of 30,000 solutions in total are analysed per run, this is similar to the 40,000 solutions analysed per run in [7]. 10 runs are performed for each load case to verify the robustness of the algorithm. The design space is set to 100 mm × 100 mm. The cross-sections are composed of consecutive elements having nominal length of 4 mm. The probabilities of cross-over and mutation operators are equal to 80% and 1%, respectively.

4. Nominal member compressive and moment capacities

4.1. The Direct Strength Method (DSM)

The DSM [20] allows designing CFS members for local, distortional and global buckling simultaneously. The method presents the same degree of complexity for any cross-sectional shapes and therefore is well suited for shape optimisation problems. The DSM as published in Clauses 7.2.1 and 7.2.2 of the AS/NZS 4600 [23] is used in this study to calculate the nominal member compressive and moment capacities N_c and M_b, respectively. N_c is expressed as,

$$N_c = \min(N_{ce}, N_{cl}, N_{cd}) \tag{4}$$

where N_{ce}, N_{cl} and N_{cd} are the nominal member capacities in compression for global, local and distortional buckling, respectively. Similarly, M_b is expressed as,