Thin-Walled Structures 96 (2015) 29–38

Contents lists available at ScienceDirect

Thin-Walled Structures

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

Multiobjective optimization of cold-formed steel columns

J.F.A. Madeira [a,b], Joaquim Dias [c], Nuno Silvestre [a,*]

[a] IDMEC, LAETA, Department of Mechanical Engineering, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisboa, Portugal
[b] ADM-ISEL, Department of Mathematic, Instituto Superior de Engenharia de Lisboa, Instituto Politécnico de Lisboa, 1959-007 Lisboa, Portugal
[c] CERis-ICIST, Department of Civil Engineering, Architecture and Georesources, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisboa, Portugal

ARTICLE INFO

Article history:
Received 5 June 2015
Received in revised form
28 July 2015
Accepted 29 July 2015
Available online 7 August 2015

Keywords:
Multiobjective optimization
Cold-formed steel
Maximum strength
Local buckling
Global (flexural) buckling
Distortional buckling

ABSTRACT

The optimal design of cold-formed steel columns is addressed in this paper, with two objectives: maximize the local-global buckling strength and maximize the distortional buckling strength. The design variables of the problem are the angles of orientation of cross-section wall elements—the thickness and width of the steel sheet that forms the cross-section are fixed. The elastic local, distortional and global buckling loads are determined using Finite Strip Method (CUFSM) and the strength of cold-formed steel columns (with given length) is calculated using the Direct Strength Method (DSM). The bi-objective optimization problem is solved using the Direct MultiSearch (DMS) method, which does not use any derivatives of the objective functions. Trade-off Pareto optimal fronts are obtained separately for symmetric and anti-symmetric cross-section shapes. The results are analyzed and further discussed, and some interesting conclusions about the individual strengths (local-global and distortional) are found.

1. Introduction

Cold-formed steel sections have been used extensively in buildings as structural members. Despite having a thickness of approximately 1–2 mm and typical section depths between 75–300 mm, cold-formed steel sections have considerable strength. One of the most convenient features of cold-formed steel sections is that they may be fabricated from plane steel sheets to nearly any shape of open cross-section. Therefore, the finding of optimal shapes for cold-formed steel sections is a problem of great interest, by getting the minimization of weight while satisfying strength (safety) constraints. Since cold-formed steel members are usually thin-walled, they are subject to different buckling phenomena, including local buckling, distortional buckling, and global buckling. The goal of this work is to identify the cross-sections that maximize capacity of a member with a given length, cross-section perimeter and sheet thickness. Instead of trying to find the minimum weight for a given cross-section shape, this work explores the topology more freely and tries to answer the manufacturer's question: what is the most effective (maximum strength) cross-section shape for a given amount of steel?

A key and challenging task in the optimization process is to compute the buckling strength of candidate designs with complex cross-sections. Using the Direct Strength Method (DSM [1]), adopted by AISI [2], the nominal strength P_n of cold-formed steel columns is given by the minimum between three strengths (global—P_{ne}, local-global—P_{nle}; distortional—P_{nd}), which are calculated using the elastic critical loads (local—P_{crl}; distortional—P_{crd}; global—P_{cre}) and the yielding load (P_y). The computation of these critical loads for an arbitrary cross-section can be made using the finite strip software CUFSM [3]. This DSM/CUFSM procedure led several authors to study the optimization of cold-formed steel sections under compression [4–8].

Liu et al. [4] used a "knowledge-based global optimization" process and a gradient-based local optimization process to maximize the strength of cold-formed steel sections, which were limited to eight folds and disregarded both edge and intermediate stiffeners. They explained that optimized cold-formed steel shapes have much higher strength than commonly used shapes (up to 300% improvement over the common C-shape). Leng et al. [5] used three different algorithms to optimize the cross-section shape of cold-formed steel columns. They explored the steepest descent method, genetic algorithms, and simulated annealing method. The steepest descent is a gradient-based method that provides an efficient local search, while genetic algorithms and simulated annealing are stochastic search methods that provide a more general search and generally provide multiple local maxima (minima). They studied cross-section with thickness of 1 mm and a perimeter of 280 mm divided into 21 strips of 13.33 mm each, and obtained optimum "open circular" and "S-shaped" cross-sections. More recently, Leng et al. [6] used a simulated annealing algorithm

* Corresponding author.
E-mail address: nsilvestre@ist.utl.pt (N. Silvestre).

http://dx.doi.org/10.1016/j.tws.2015.07.025
0263-8231/

for cross-section shape optimization of cold-formed steel columns and considered end-use and manufacturing constraints, including limits on number and spacing of roll stands where the section may be folded (i.e. the number of rollers). These end constraints included (i) symmetry and anti-symmetry, (ii) a requirement for parallel flanges for board attachments, (iii) minimum and maximum dimensions on web, flange, and lip dimensions, and (iv) depth and clearance requirements. Their design objective was to seek cross-section shapes that maximize the nominal axial strength P_n evaluated using the Direct Strength Method and employing finite strip method (CUFSM) for the calculation of critical buckling loads. Gilbert et al. [7] presented and applied a self-shape optimization method to strength maximization of singly-symmetric open cold-formed steel columns. The columns had a wall thickness of 1.2 mm and lengths varying from 1000 to 2500 mm. The cross-section shapes converged to “bean”, “oval” or rounded “Σ” shape types, in a relatively low number of generations (around 70). Moharrami et al. [8] extended the work by Leng et al. [5] by investigating the effect of different boundary conditions on the optimal geometry of the cold-formed steel columns. The design space was searched via a hybrid strategy composed of a stochastic search algorithm, used to arrive at near-optimal designs, and gradient descent, used to fine-tune the near optimal designs. They imposed geometrical constraints (symmetry and anti-symmetry) and found that (i) the strength of optimal cross-sections more than double that of the original (standard) shapes and (ii) the shape of the optimal cross-sections is greatly influenced by the column boundary conditions.

In all these works, single-objective optimization procedures were used to maximize the strength of cold-formed steel columns. The objective of this paper is to show the application of a multi-objective optimization tool to maximize the strength of cold-formed steel columns. The procedure presented herein follows that proposed by Leng et al. [5] and the results are also based on the use of (i) the Finite Strip Method (FSM) [3] for elastic buckling analyzes and (ii) the Direct Strength Method (DSM) [1,2] for strength calculations. The space of solutions (cold-formed steel shapes) may be optimized for maximum strength because a steel sheet with given (fixed) width is allowed to be bent transversally at several locations, thus being able to provide many possible cross-section shape. Unlike previous research by Leng et al. [5], the optimization problem proposed in this paper is solved using the Direct MultiSearch (DMS) method for derivative-free multi-objective optimization. DMS is a solver for multiobjective optimization problems developed by the author (Custódio et al. [9]), which does not use any derivatives of the objective functions. It is based on a novel technique developed by extending direct search from single to multiobjective optimization. DMS has recently been used for the design of a viscoelastic laminated sandwich composite panels [10], thus maximizing modal damping and minimum mass and material cost, by choosing the number of layers, the material of the layers, as well as the respective thickness and orientation. Very recently, Yin et al. [11] also used multiobjective optimization to maximize the specific energy absorption and minimize the maximum impact force of foam-filled multi-cell thin-walled structure using nonlinear finite element method and multiobjective particle swarm optimization algorithm. In the present case, DMS adopts the maximization of cold-formed steel column strengths in different failure modes (P_{nle} and P_{nd}) as objectives. Therefore, the main goal of this work is not to maximize the overall strength of a cold-formed steel column, but rather to maximize separately the local-global strength (P_{nle}) and distortional strength (P_{nd}), as well as to conclude how the former affects the latter (and vice-versa).

2. Optimization problem

In the great majority of common problems for structural optimization, the design objective is the cost minimization (roughly proportional to weight of the structure). In the case of optimization of cold-formed steel structures, several works were published in the last decade where the design objective was to maximize the strength P_n of structural members made from a sheet with given width and thickness. Therefore, the width and thickness of steel sheet were not variables of the problem. The problem variables were strictly related with the folding of the steel sheet after the forming process, i.e., the cross-section shape. Usually, the single-objective optimization problem is given by

$$\max P_n(\boldsymbol{\theta}) \tag{1}$$

with some geometric constraints to avoid the intersection between cross-section walls. It is well known that different cross-section shapes lead to dissimilar strengths of compressed members failing in different buckling modes (local, distortional and global). The single objective problem given by Eq. (1) proved to be interesting from the design viewpoint but limited in regard to the identification of the optimal (i.e. less disadvantageous) failure mode. This target can only be achieved using multiobjective optimization procedures.

The calculation of the member strength follows the Direct Strength Method (DSM) adopted by AISI [1,2]. DSM is capable of determining the nominal strength P_n of cold-formed steel columns provided the user specifies the yield load (P_y) and the elastic critical loads in local (P_{crl}), distortional (P_{crd}) and global (P_{cre}) buckling modes. Because the steel sheet width (b) and thickness (t) are fixed in each analysis, the cross-section area ($A = bt$) and the yield load ($P_y = Af_y$) remain unchanged. Like other authors, we use the software CUFSM [3], which employs the finite strip method, to determine the critical load values P_{crl}, P_{crd}, and P_{cre}.

The nominal strength in global buckling (either flexural or flexural-torsional) is given by

$$P_{ne} = \begin{cases} (0.658^{\lambda_c^2})P_y & \text{for} \quad \lambda_c \le 1.5 \\ (0.877/\lambda_c^2)P_y & \text{for} \quad \lambda_c > 1.5 \end{cases} \tag{2}$$

$$\lambda_c = \sqrt{\frac{P_y}{P_{cre}}} \tag{3}$$

where λ_c is the global buckling slenderness. Because the local failure of compressed members might occur in combination with global buckling, DSM prescribes the calculation of the nominal strength of columns failing in local-global modes. The nominal strength for local-global buckling failure is given by

$$P_{nle} = \begin{cases} P_{ne} & \text{for} \quad \lambda_{le} \le 0.776 \\ [1 - 0.15(\frac{P_{crl}}{P_{ne}})^{0.4}](\frac{P_{crl}}{P_{ne}})^{0.4}P_{ne} & \text{for} \quad \lambda_{le} > 0.776 \end{cases} \tag{4}$$

$$\lambda_{le} = \sqrt{\frac{P_{ne}}{P_{crl}}} \tag{5}$$

where λ_{le} is the local-global buckling slenderness. Note that the global strength P_{ne} must always be calculated prior to local-global buckling strength P_{nl}. Additionally, P_{nle} was always considered in these calculations because $P_{nle} \le P_{ne}$. The nominal strength for distortional buckling is given by