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Optimal design of I-section beam-columns with stress, non-linear deflection and stability constraints

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ABSTRACT

The standard hot-rolled sections with various shapes are used to construct the skeletal structural system of the steel civil engineering structures. The conventional design rules direct the engineer to select the smallest section from the manufacturers' catalog that satisfies the considered constraints. However, use of these predesigned sections may result in waste of structural material. This problem can be handled by searching for optimal built-up section designs, which can be manufactured by cutting the plates to the determined dimensions and welding them to each other so as to form the optimized shape. This paper presents the optimal design of prismatic I-section beam-columns under stress, non-linear deflection and global buckling constraints with one of the recent metaheuristic algorithms and discusses the influence of variable grouping on the optimization results. Four optimization types are introduced and the contribution of using optimized shapes instead of hot-rolled sections to the structural material economy is demonstrated over numerical examples. It is shown that optimization may lead up to 23% lighter solutions than the hot-rolled sections and it is possible to obtain adequately efficient doubly-symmetric I-section designs (in terms of material amount used) from an engineering point of view.

1. Introduction

Beams are the structural frame elements that are subjected mostly to bending. On the other hand, columns are predominantly under compression. The members that are subjected to non-negligible compression and bending are called beam-columns. Note that this combined loading case of axial compression and bending may be produced by an eccentrically applied load in the direction of the longitudinal axis or combination of concentrically applied axial load(s) and transversal load (s) and/or concentrated moment(s). The conventional design practice for these members is to use the smallest standard section that meets the structural requirements such as mechanical constraints (stress, deflection, etc.) and geometric suitability. The standard hot-rolled sections can be found in the market in various shapes such as I, T and U with different names in different countries.

The search for the optimal shapes of bars under various loading conditions has a relatively long history compared to many other engineering optimization problems. The works of Keller [1], Taylor [2] and Simitses et al. [3] on columns are the earlier works on the optimization of bars. Concerning beam-columns, Karihaloo and Parbery wrote a set of articles on the optimum design of these members between the years 1979 and 1983 [4–6]. These articles deal with minimizing the transverse deflection of the simply supported [4] and cantilever [5,6] members. In addition, they presented the optimum design of the pin ended members that have to serve as a beam for a part of their life and as a column for the rest [7,8]. In these papers, constraints of the optimization problems are the deflection in beam and the Euler buckling load in column mechanisms. The paper by Kanagasundaram and Karihaloo presents the optimal design of beam-columns under stress constraints [9]. Finally, Karihaloo as sole author wrote two papers on minimum weight design of the beam-columns with deflection constraints [10,11]. In the last decade, several researchers presented optimization procedures for the general thin-walled steel sections [12,13]. A considerable attention has been paid for the optimization of columns. Olhoff and Seyranian formulated the column optimization problems allowing for bimodal optimum buckling loads [14]. Maalawi presented a method to obtain the column designs with maximum possible buckling load [15]. Krużelecki and Stawiarski investigated the optimal design of tubular columns [16]. Novakovic and Atanackovic studied the optimal shape of an elastic column with clamped ends and with/without elastic foundation [17]. Krużelecki and Ortwein investigated the optimization of columns under combined compression and torsion [18]. Novaković determined the optimal shape of a column on Winkler elastic foundation [19]. Zhang et al. presented semi-analytical solutions based on the Hencky bar-chain model for optimal design of columns [20]. Ruocco et al. proposed a method to optimize the Bernoulli columns [21]. In addition, a significant number of works on the optimization of cold-formed columns have been conducted [22–28]. Also,

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studies on composite columns exist in the literature [29]. The number of the recent studies on the optimization of beams is non-negligible. Optimal shapes of a cantilever H-beam with a reduced section subjected to cyclic displacements are found by Ohsaki et al. [30]. Banichuk et al. investigated the optimal design of flexible cantilever beams that are loaded from their free ends [31]. The shape optimization of a slender cantilever beam for lateral buckling is investigated by Drazumeric and Kosel [32]. There is another study concerning the optimization of slender cantilever beams in which they partnered with Polajnar [33]. There are works on the optimization of beams made of high strength steel [34] and resting on the Winkler foundation [35]. The shape optimization of tapered I-beams are studied by Ozbasaran and Yilmaz [36]. Numerous researchers presented studies on the optimization of beams with web openings [37–41]. Similar to columns, there is an "optimization of cold-formed steel beams" section in the literature [42–44]. As for the works conducted on beam-columns, Gil-Martín et al. presented the proportioning of steel beam-columns based on the Reinforcement Sizing Diagrams (RSD) optimization methodology with code-based constraints [45]. It is assumed that the section is compact and singly-symmetric, the external loading produces in-plane bending moment about the strong axis of the section, shear force acting in the plane of the bending moment and axial force. Cheng et al. studied the optimum design of clamped beam-columns under thermal loads that maximize the buckling temperature and the fundamental natural frequency of transverse vibrations [46]. Finally, Wang et al. investigated the shape optimization of simply supported singly-symmetric cold-formed beams and beam-columns [47].

Most of the engineering design problems are not sufficiently constrained to have a single solution; an infinite number of theoretical solutions exist where the number of unknowns is greater than the number of equations. The modern design procedures seek the best solution(s) utilizing various optimization algorithms. This is one of the most important differences between modern and conventional design procedures. The structural optimization can be classified into three categories as 'size', 'shape' and 'topology' optimization. The size optimization process searches for the optimal design by taking the 'size' of the structural components as design variables, while topology optimization deals with the connection information of the members. One of the best definitions for the "shape optimization" concept is looking for the best node positions of the finite element mesh of a structure without changing the connectivity properties. For example if joint 1 is connected to joint 2 and joint 3 is not connected to joint 5, they should stay so during the optimization process.

This study presents the optimization of built-up I-section beam-columns by seeking the best flange and web plate dimensions. Four constraints are considered as stress, deflection, buckling and geometry. Since mathematical models of the constraints are too complex to implement a mathematical optimization algorithm, a recently introduced modern metaheuristic (Crow Search Algorithm [48]) is used. Four optimization types, which are determined in terms of variable grouping configurations, are introduced and optimal shapes for ten cases consisting of five simply-supported and five cantilever members are found. Then, the smallest predesigned hot-rolled sections that satisfy the structural constraints are determined, and finally, the optimized shapes and hot-rolled sections are compared in terms of structural material economy.

2. Problem statement

The objective in structural optimization is to ensure the safety of structures and find a design with the maximum gain. In the mathematical model, safety measures are defined as design constraints. The first constraint of the study (stress constraint) prevents the yielding of the structural material. The von Mises yield criterion is considered to determine the full elastic capacity of the bars. It is assumed that the stress constraint is violated when the maximum absolute stress occurred on the members exceeds the allowed value. The flanges carry most of the bending moment, whereas the web resists the bulk of the shear force in I-sections. Transversal loads produce normal and shear stresses distributed over the cross-section. However, influence of the shear stress is relatively small on the critical von Mises stress of the I-section members with large spans. An important note at this point is that this study assumes that the parts of the built-up members are rigidly connected. With these simplifications, it becomes easy to determine the maximum von Mises stress produced on the member.

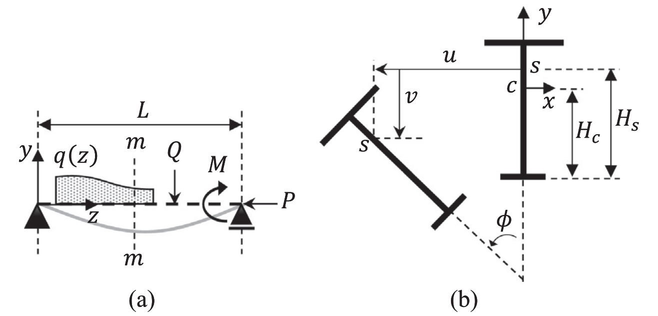

Fig. 2.1. A buckled beam-column under uniaxial bending and uniform compression. (a) Side view, (b) $m-m$ section.

The second constraint limits the maximum absolute deflection. The deflection curve of a member that is subjected to axial load(s) in addition to transverse bending cannot be determined by simple superposition because the axial load causes a feedback-type interaction between the bending moment and the deflection (Fig. 2.1).

In Fig. 2.1, s is the shear center and c is the center of gravity. The author finds it practical to utilize energy methods to obtain the approximate deflection curve of a member due to simple mathematical modelling. The total potential for the in-plane deflection of the beam-column given in Fig. 2.1 can be written as follows considering the second order effects:

$$\Pi_p = \frac{1}{2}\int_0^L EI_x v_{,zz}^2 dz + Qv_Q + Mv_{M,z} + \int qvdz - \frac{P}{2}\int_0^L v_{,z}^2 dz \tag{2.1}$$

where E is the Young's modulus, I_x is the moment of inertia about x axis, v is the displacement in the $-y$ direction, v_Q and v_M are the vertical displacements of the concentrated load (Q) and the concentrated moment (M), respectively. The deflection curve of the beam-column can be obtained by choosing an appropriate trial function for v and substituting it into the total potential equation.

The third constraint is to keep the member stable. Bars may experience a variety of global buckling modes depending on the structural material, section properties and loading case. Flexural, torsional and flexural-torsional buckling are the global buckling modes of the compression members. On the other hand, lateral-torsional buckling applies to beams and beam-columns. In this study, the extensive energy equation provided by Pi and Trahair [49,50], which considers prebuckling deflections (Eq. (2.2)), is used to determine the non-linear global buckling eigenvalues.

$$\begin{aligned}\Pi_b = &\tfrac{1}{2}\int_0^L [EI_y(u_{,zz} + v_{,zz}\phi)^2 + GI_t(\phi_{,z} + \tfrac{v_{,z}u_{,zz} - v_{,zz}u_{,z}}{2})^2 \\ &+ EI_w(\phi_{,zz} + \tfrac{v_{,z}u_{,zzz} - v_{,zzz}u_{,z}}{2})^2]dz \\ &+ \tfrac{1}{2}\int_0^L \lambda P\left[u_{,z}^2 + 2y_0(u_{,z}\phi_{,z} + v_{,z}\phi\phi_{,z}) + \left(\frac{I_x + I_y}{A} + y_0^2\right)\phi_{,z}^2\right]dz \\ &+ \tfrac{1}{2}\int_0^L \lambda M_x(2u_{,zz}\phi + \beta_x\phi_{,z}^2 + v_{,zz}\phi^2)dz + \tfrac{1}{2}\int^{\lambda} q(H_q - H_s)(\phi^2 \\ &- v_{,z}u_{,z}\phi)dz \\ &+ \tfrac{1}{2}\lambda Q(H_Q - H_s)(\phi_Q^2 - v_{Q,z}u_{Q,z}\phi_Q)\end{aligned} \tag{2.2}$$

In Eq. (2.2), I_y is the moment of inertia about weak axis, u is the lateral displacement, ϕ is the torsional rotation, G is the shear modulus, I_t is the torsional constant and I_w is the warping coefficient. λ is the