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Bat inspired algorithm for discrete size optimization of steel frames

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ABSTRACT

Bat inspired (BI) algorithm is a recently developed metaheuristic optimization technique inspired by echolocation behavior of bats. In this study, the BI algorithm is examined in the context of discrete size optimization of steel frames designed for minimum weight. In the optimum design problem frame members are selected from available set of steel sections for producing practically acceptable designs subject to strength and displacement provisions of American Institute of Steel Construction-Allowable Stress Design (AISC-ASD) specification. The performance of the technique is quantified using three real-size large steel frames under actual load and design considerations. The results obtained provide a sufficient evidence for successful performance of the BI algorithm in comparison to other metaheuristics employed in structural optimization.

1. Introduction

A steel frame refers to a type of structure where vertical steel columns and horizontal beams generally selected from I-shaped steel sections are arranged in the form of a rectangular grid to support lateral and vertical loads acting on a building. The lateral stability of such systems is provided by flexural stiffness of beams and columns if beams are rigidly connected to columns at joints. Alternatively, moment-free connections can be used, in which case the framework must be stiffened with a full-bracing system that behaves like a vertical truss throughout the height of the building to transmit lateral forces to the ground. Different types of floor slabs can be adopted in such systems in composite or non-composite forms. A composite floor consists of a high-strength profiled steel deck with concrete topping cast and is more preferable for multi-story buildings due to high speed of construction.

Both safety and economy have to be considered while designing a steel frame. The common practice followed by a practicing engineer is to observe structural safety always, while an economical design is pursued meanwhile using intuition, experience and a trial-and-error based procedure. However, despite the best effort of the designer, the optimum design, which leads to minimum weight or cost of the structure, can be reached at almost no times. Further, sometimes a design produced this way may lead to very uneconomical solutions especially when the design is governed by displacement constraints. Hence, it is essential that the design process of steel frames be implemented in conjunction of computer-aided numerical algorithms that are automated to achieve optimum design of such structures.

In the past optimum design of structures was overwhelmingly carried out using optimality criteria (OC) and mathematical programming (MP) based methods [1]. Despite strong mathematical backgrounds and remarkable speed of convergence to the optimum, these methods have found scarce applications in discrete size optimization problems of steel frames. In the aforementioned problems, a set of steel sections selected from available section tables are initially collected in a design pool. Each steel section is assigned a sequence number that varies between one to the total number of sections in the list. The selection of steel sections for member groups is carried out using these numbers. This selection should be performed in such a way that a steel frame has the minimum weight or cost while behavior and performance of the structure is within the limitations described according to serviceability and strength requirements of a chosen code of design practice. The need for selecting member sizes from a list of ready sections as well as gradient-based nature of OC and MP algorithms hampers a direct application of these methods to such problems encountered in real life. Fortunately, in the last two decades a number of computational methods, commonly referred to as metaheuristics in the literature, have been developed as powerful tools that can effectively deal with discrete structural optimization problems at the expense of increased computational cost [2–10]. These novel and innovative approaches are derivative-free methods and make use of ideas inspired from the nature. There are a large number of metaheuristic techniques available in the

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literature nowadays. The state-of-the-art review of metaheuristics in structural design optimization is outlined in several excellent review papers, such as Lamberti and Pappalettere [11], Saka [12], and Saka and Dogan [13].

One recent addition to metaheuristic algorithms is the bat-inspired (BI) search. The idea behind this technique is to imitate echolocation behavior of bats. In simple words, echolocation is used to refer to the way bats use to navigate their surroundings. Bats get to find their directions and detect prey and different types of objects around them even in complete darkness. They achieve this by emitting calls out to the environment and listening to the echoes that bounce back from them. The echolocation behavior of bats was turned into a numerical algorithm by Yang [14] for solving optimization problems. A verification of this algorithm was conducted using several standard test functions of unconstrained optimization in Yang [14,15]. Besides, the technique was successfully applied to some benchmark constrained engineering optimization problems in Yang and Gandomi [16] and Gandomi et al. [17].

In Hasançebi et al. [18] a thorough reformulation of the BI algorithm was proposed for sizing optimization of steel trusses. In this study, the BI algorithm was scrutinized in the context of discrete sizing optimization of steel frames. It should be underlined that the latter is seemingly a more challenging optimization problem. The reason is that truss members carry only one type of force (i.e. axial force), and a discrete optimization process can be carried out for these systems using a well-ordered section list generated by sorting steel sections according to their cross-sectional areas. On the other hand, beams and columns in a steel framework are axial–flexural members. The governing behavior of a frame member is determined by relative magnitudes of axial force and bending moment carried by the member at a time. When steel sections are sorted according to a chosen sectional property, i.e. cross-sectional area or moment or inertia, there is no guarantee that the next section in the list is stronger for some frame members. This introduces a great deal of disorder in the list, and makes the search process more complicated for an algorithm. Hence, aside from presenting a new application of the BI algorithm, this study intends to investigate efficiency of this technique in more complicated problems of structural optimization. In the study strength and displacement provisions of steel frames are imposed according to the provisions of AISC-ASD specification [19]. The numerical performance of the BI algorithm is tested and verified using three real-size design examples. The numerical results evince that the BI algorithm performs very efficiently for this class of problems and produces improved results as compared to other techniques of metaheuristics.

2. Optimum design of steel frames as to AISC-ASD

For a steel structure consisting of N_m members that are collected in N_d design groups (variables), the optimum design problem according to AISC-ASD [19] code yields the following discrete programming problem, if the design groups are selected from steel sections in a given profile list.

The objective is to find a vector of integer values $\mathbf{I}$ (Eq. (1)) representing the sequence numbers of steel sections assigned to N_d member groups

$$\mathbf{I}^T = [I_1, I_2, \ldots, I_{N_d}] \tag{1}$$

to minimize the weight (W) of the frame

$$W = \sum_{i=1}^{N_d} \rho_i A_i \sum_{j=1}^{N_t} L_j \tag{2}$$

where A_i and ρ_i are the length and unit weight of the steel section adopted for member group i, respectively, N_t is the total number of members in group i, and L_j is the length of the member j which belongs to group i.

The members subjected to a combination of axial compression and flexural stress must be sized to meet the following stress constraints:

$$if\ \frac{f_a}{F_a} > 0.15; \quad \left[\frac{f_a}{F_a} + \frac{C_{mx} f_{bx}}{\left(1 - \frac{f_a}{F'_{ex}}\right) F_{bx}} + \frac{C_{my} f_{by}}{\left(1 - \frac{f_a}{F'_{ey}}\right) F_{by}}\right] - 1.0 \leqslant 0 \tag{3}$$

$$\left[\frac{f_a}{0.60 F_y} + \frac{f_{bx}}{F_{bx}} + \frac{f_{by}}{F_{by}}\right] - 1.0 \leqslant 0 \tag{4}$$

$$if\ \frac{f_a}{F_a} \leqslant 0.15; \quad \left[\frac{f_a}{F_a} + \frac{f_{bx}}{F_{bx}} + \frac{f_{by}}{F_{by}}\right] - 1.0 \leqslant 0 \tag{5}$$

If the flexural member is under tension, then the following formula is used instead:

$$\left[\frac{f_a}{0.60 F_y} + \frac{f_{bx}}{F_{bx}} + \frac{f_{by}}{F_{by}}\right] - 1.0 \leqslant 0 \tag{6}$$

In Eqs. (3)–(6), F_y is the material yield stress, and $f_a = (P/A)$ represents the computed axial stress, where A is the cross-sectional area of the member. The computed flexural stresses due to bending of the member about its major (x) and minor (y) principal axes are denoted by f_{bx} and f_{by}, respectively. F'_{ex} and F'_{ey} denote the Euler stresses about principal axes of the member that are divided by a safety factor of 23/12. F_a stands for the allowable axial stress under axial compression force alone, and is calculated depending on elastic or inelastic bucking failure mode of the member using Formulas 1.5-1 and 1.5-2 given in AISC-ASD [19]. The allowable bending compressive stresses about major and minor axes are designated by F_{bx} and F_{by}, which are computed using the Formulas 1.5-6a or 1.5-6b and 1.5-7 given in AISC-ASD [19]. It is important to note that while calculating allowable bending stresses, a newer formulation (Eq. (7)) of moment gradient coefficient c_b given in ANSI/AISC 360-05 [20] is employed in the study to account for the effect of moment gradient on lateral torsional buckling resistance of the elements,

$$c_b = \frac{12.5 M_{\max}}{2.5 M_{\max} + 3 M_A + 4 M_B + 3 M_C} R_m \leqslant 3.0 \tag{7}$$

where $M_{\max}$, M_A, M_B and M_C are the absolute values of maximum, quarter-point, midpoint, and three-quarter point moments along the unbraced length of the member, respectively, and R_m is a coefficient which is equal to 1.0 for doubly symmetric sections. C_{mx} and C_{my} are the reduction factors, introduced to counterbalance overestimation of the second-order moments by the amplification factor $(1 - f_a/F'_e)$. For unbraced frame members, they are taken as 0.85. For braced frame members without transverse loading between their ends, they are calculated from $C_m = 0.6 - 0.4(M_1/M_2)$, where M_1/M_2 is the ratio of smaller end moment to the larger end moment. For braced frame members having transverse loading between their ends, they are determined from the formula $C_m = 1 + \psi(f_a/F'_e)$ based on a rational approximate analysis outlined in AISC-ASD [19] Commentary-H1, where ψ is a parameter that considers maximum deflection and maximum moment in the member.

For the computation of allowable compression and Euler stresses, the effective length factors (K) are required. For beam and bracing members, K is taken equal to unity. For column members, alignment charts furnished in AISC-ASD [19] can be utilized. In this study, however, the effective length factors of columns in braced and unbraced steel frames are calculated from the following approximate formulas developed by Dumonteil [21], which are accurate to within about −1.0% and +2.0% of the exact results [22]:

For unbraced members:

$$K = \sqrt{\frac{1.6 G_A G_B + 4(G_A + G_B) + 7.5}{G_A + G_B + 7.5}} \tag{8}$$