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Computationally efficient discrete sizing of steel frames via guided stochastic search heuristic

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ABSTRACT

Recently a design-driven heuristic approach named guided stochastic search (GSS) technique has been developed by the authors as a computationally efficient method for discrete sizing optimization of steel trusses. In this study, an extension and reformulation of the GSS technique are proposed for its application to problems from discrete sizing optimization of steel frames. In the GSS, the well-known principle of virtual work as well as the information attained in the structural analysis and design stages are used together to guide the optimization process. A design wise strategy is employed in the technique where resizing of members is performed with respect to their role in satisfying strength and displacement constraints. The performance of the GSS is investigated through optimum design of four steel frame structures according to AISC-LRFD specifications. The numerical results obtained demonstrate that the GSS can be employed as a computationally efficient design optimization tool for practical sizing optimization of steel frames.

1. Introduction

Generally, the optimum design of a structural system can be defined as seeking the best arrangement of structural members that produces an economical solution while satisfying a set of design constraints imposed by a considered design code. During the past decades many researchers employed numerous optimization methods, such as mathematical programming [1] and optimality criteria [2] techniques, for tackling structural optimization problems including optimization of steel frames. For example Saka [3] considered the optimum design problems of steel frames with stability constraints based on an optimality criteria approach. Chan [4] developed an optimality criteria algorithm for minimum weight design of tall steel buildings and applied the method to optimal design of a 60-story planar frame under multiple inter-story drift constraints. Based on an optimality criteria method, Chan and Grierson [5] proposed a resizing technique for the optimum design of tall steel building frames subject to multiple drift constraints.

In the industrial applications, typically, optimum design of steel frame structures is performed with respect to a predefined list of available sections, resulting in a discrete sizing optimization problem. Indeed, development of optimization algorithms for handling such discrete optimization problems is basically due to the fact that the speed of existing computers is not high enough to facilitate evaluating every possible solution in a timely manner. Hence search techniques capable of generating near optimum solutions without performing an exhaustive search have become popular in the real world applications.

Undoubtedly, most of the recent optimization algorithms developed for discrete sizing of skeletal structures belong to the class of metaheuristic techniques [6–9]. The basic idea in metaheuristic search techniques is to investigate the vicinity of more successful solutions found so far to determine the direction of the search. However, following such a blind search in structural optimization requires an excessive computational effort. In this regard, proposing search strategies that are capable of reducing the computational cost in the metaheuristic based structural optimization algorithms can be useful to some extent [10]. For example Chan and Wong [11] combined the stochastic search capabilities of a genetic algorithm with a design wise optimality criteria technique. They proposed a hybrid optimization method for topology and sizing optimization of steel frameworks in which a local search operator based on a rigorously derived optimality criteria technique is embedded in the framework of a genetic algorithm. In their work after obtaining the optimal stiffness for satisfying the serviceability criteria, the element strength requirements were

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checked by a fully stressed design (FSD) [12] procedure. Recently, Park et al. [13] developed a resizing technique-based hybrid genetic algorithm for the drift design of multistory steel frame buildings. In their study, through comparing the performance of the developed hybrid method to that of a genetic algorithm, improvements in convergence properties using the hybrid technique were reported.

Nevertheless, a design wise search, which takes advantage of available domain knowledge, is unbeatable in terms of convergence speed of the optimization process. In other words, unlike metaheuristics where the search is based on random moves and associated with slow learning, the latter directly uses information collected from the structural analysis and design check stages of the former solutions to make rapid and judicious moves towards conceivably better solutions in the following iterations.

Recently, a guided stochastic search (GSS) technique, as a novel computationally efficient design optimization method, has been proposed by the authors for computationally efficient optimum design of steel trusses in Ref. [14]. The GSS offers a stochastic procedure where the optimization process is guided by the principle of virtual work as well as response computations of the generated designs resulting in an efficient and rapid search in the design space. Indeed the idea of handling the displacement constraints in structural optimization problems using the principle of virtual work is not new, as employed in the following studies as well. In Ref. [15] a drift control method using the displacement participation factors with a variable linking strategy is formulated into an optimization problem to determine the amount of material to be modified. Using the drift control method, a structural design model for a high-rise building is proposed and applied to one verifying truss instance as well as two moment resisting frames. Later, an optimal sizing technique for lateral stiffness design of tall steel and concrete buildings was proposed in Ref. [16]. The practicality of the technique was demonstrated through an actual application to the preliminary design of an 88-story building in Hong Kong. In Ref. [17] an iterative method based on the principle of virtual work was developed for structures with fixed topologies subject to a single deflection constraint and load case. These restrictions are lifted in Ref. [18] where the authors optimized different instances including a planar 60-story, 7-bay frame [4] under both the displacement and strength requirements.

The GSS utilizes the information provided through the structural analysis and design check stages for handling strength constraints. On the other side, the well-known principle of virtual work is employed to detect the most effective structural members for satisfying displacement criteria. The GSS is originally applied to optimal sizing problems of steel truss structures under single displacement constraint and single load case and later it is further enhanced in Ref. [19] for a more general class of truss optimization instances subject to multiple displacement constraints and load cases.

Regarding the promising performance of the GSS in sizing optimization of truss structures, in the present study the GSS is extended and reformulated for discrete sizing optimization of steel frames subjected to design provisions according to AISC-LRFD [20]. It is attempted to investigate realistic three dimensional test examples considering both the displacement and strength constraints simultaneously. Furthermore, it is worth mentioning that, different from optimality criteria approaches wherein generally approximate relations are assumed between the area and moment of inertia for each commercial ready section, similar to metaheuristics GSS can be directly applied to the discrete sizing optimization problems without any approximate assumptions. The performance of the proposed technique is numerically evaluated through optimum design of four steel frame structures. The numerical results reveal the success of the GSS in locating promising solutions for this kind of problems through a reasonable computational effort.

The remaining sections of the paper are organized as follows. The second section presents a mathematical statement of the considered sizing optimization problem according to AISC-LRFD [20] specifications. In the third section the concept of sensitivity index is described in details. The formulation of the GSS for discrete sizing optimization of steel frames is outlined in the fourth section. The fifth section touches on local search and move-back mechanisms incorporated into the GSS to accelerate its performance. The sixth section describes the approach employed for handling multiple load cases and displacement criteria in the GSS. Performance evaluation of the GSS through design optimization examples are covered in the seventh section. The last section presents a brief conclusion of the study.

2. Optimum design of steel frames to AISC-LRFD

In practical applications the frame members are typically selected from a set of available steel sections which yields a discrete sizing optimization problem. For a steel frame composed of N_m members grouped into N_d design groups, the optimum design problem, based on AISC-LRFD [20] code, can be stated as follows. 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 structure

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

where A_i and ρ_i are the length and unit weight of the steel section selected 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. Here, the objective of finding the minimum weight structure is subjected to several design constraints, including strength and serviceability requirements. According to AISC-LRFD [20] code of practice, the following design constraints (C^i_{IEL} and C^v_{IEL}) must be satisfied for the strength requirements.

$$C^i_{IEL} = \left[\frac{P_{uJ}}{\phi P_n}\right]_{IEL} + \frac{8}{9}\left(\frac{M_{uxJ}}{\phi_b M_{nx}} + \frac{M_{uyJ}}{\phi_b M_{ny}}\right)_{IEL} - 1 \leqslant 0 \quad \text{for} \left[\frac{P_{uJ}}{\phi P_n}\right]_{IEL} \geqslant 0.2 \tag{3}$$

$$C^i_{IEL} = \left[\frac{P_{uJ}}{2\phi P_n}\right]_{IEL} + \left(\frac{M_{uxJ}}{\phi_b M_{nx}} + \frac{M_{uyJ}}{\phi_b M_{ny}}\right)_{IEL} - 1 \leqslant 0 \quad \text{for} \left[\frac{P_{uJ}}{\phi P_n}\right]_{IEL} < 0.2 \tag{4}$$

$$C^v_{IEL} = \left[\frac{V_{uJ}}{\phi_v V_n}\right]_{IEL} - 1 \leqslant 0 \tag{5}$$

In Eqs. (3)–(5), $IEL = 1, 2, \ldots, NEL$ is the element number, NEL is the total number of elements, $J = 1, 2, \ldots, N$ is the load combination number and N is the total number of design load combinations. P_{uJ} is the required axial (tensile or compressive) strength, under J-th design load combination. M_{uxJ} and M_{uyJ} are the required flexural strengths for bending about x and y, under the J-th design load combination, respectively; where subscripts x and y are the relating symbols for strong and weak axes bending, respectively. On the other hand, P_n, M_{nx} and M_{ny} are the nominal axial (tensile or compressive) and flexural (for bending about x and y axes) strengths of the IEL-th member under consideration. ϕ is the resistance factor for axial strength, which is 0.85 for