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Guided stochastic search technique for discrete sizing optimization of steel trusses: A design-driven heuristic approach

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ABSTRACT

This study presents a design-driven heuristic approach named guided stochastic search (GSS) technique for discrete sizing optimization of steel trusses. The method works on the basis of guiding the optimization process using the well-known principle of virtual work as well as the information collected during the structural analysis and design stages. The performance of the proposed technique is investigated through a benchmark truss instance as well as four real-size trusses sized for minimum weight according to AISC-LRFD specifications. A comparison of the numerical results obtained using the GSS with those of other available algorithms indicates that the proposed technique is capable of locating promising solutions using lesser computational effort.

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1. Introduction

In general, the optimum design of a steel truss structure is an attempt to find the best set of steel profiles for its members that results in a minimum weight or cost design of the structure. Meanwhile, for practical applications the optimum design should satisfy a set of predefined constraints stipulated by a given design code. Generally, the optimum design of truss structures can be divided into three main categories as sizing, shape, and topology optimization. In sizing optimization the cross-sectional areas of members are considered as design variables. This can further be divided into two subcategories as continuous and discrete sizing optimization in terms of the nature of the design variables employed. In continuous sizing optimization any positive value can be assigned to cross-sectional areas of the members. However, this is usually not the case in practical applications, where structural members should be selected from a set of available sections. The latter is referred to as discrete sizing optimization. In shape optimization the best nodal coordinates (positions) of a selected group of joints in a structure are investigated. The third category, namely topology optimization interrogates the presence or absence of structural components, such as elements and nodes for optimum layout design of a structure. The present study covers discrete sizing optimization of steel trusses, which is the most common case in practical applications.

In the recent decades, the drawbacks of traditional structural optimization methods namely mathematical programming [1] and optimality criteria [2,3] techniques (such as their gradient based formulations and inefficiency in handling discrete design variables) have led to an increasing tendency towards non-traditional stochastic search techniques or the so-called metaheuristics. These techniques such as genetic algorithms (GAs) [4], simulated annealing (SA) [5], particle swarm optimization (PSO) [6], ant colony optimization (ACO) [7,8], harmony search method (HS) [9], etc., have been widely employed for tackling structural design optimization problems so far [10–18]. However, the slow rate of convergence towards the optimum and the need for a high number of structural analyses are still conceived as the main shortcomings of these techniques. It is known that response computations of designs sampled during a search process mostly occupies 85-95% workload of a stochastic technique [18], and thus large number of structural analyses substantially increases the total computing time. Here, one solution to this is to lessen the total computational time by taking advantage of high performance computing methods, such as parallel or distributed computing techniques. The idea behind these approaches is to distribute the total workload of the optimization algorithm amongst multiprocessors of a single computer or within a cluster of computers connected to each other through local area network. In Hasançebi et al. [18] it is demonstrated using three design examples of large-scale steel structures that a maximum speedup ratio between 12.2 and 16.8 can be achieved by a cluster computing system composed of 32 processors. Another approach, which is more straightforward and easier to apply, is to develop efficient structural design optimization

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techniques for reducing the total number of structural analyses required in the course of optimization. The latter, can be performed by proposing enhanced optimization techniques which are able to locate optimum solutions using fewer structural analyses, i.e., less computational effort.

In general stochastic search techniques perform random moves in the design space using strategies borrowed from nature to locate the optimum solution using a single or a population of candidate designs. The basic difference between these techniques lies in the way that they decide on the next move in the design space. This can significantly affect both the quality of final solution as well as the computational time of the optimization process. Therefore, it becomes vital to make an effective search in a timely manner by developing some robust strategies as a guide to stochastic moves in the design space. Since response computations are performed for generated designs at each iteration of a stochastic optimization algorithm, it is possible to utilize such valuable information collected during response computations to guide the optimization process.

It is worth mentioning that compared to metaheuristics, which provide general frameworks for developing multi-purpose search strategies, heuristic methods can be considered as more problem specific techniques designed to solve particular types of optimization problems. In the present paper a heuristic sizing optimization method named guided stochastic search (GSS) technique is proposed for code based design optimization of steel trusses. The GSS offers a design-driven procedure where the optimization process is guided by the principle of virtual work and response computations of the generated designs, resulting in an efficient and rapid search. In this method, the information provided through the structural analysis and design check stages are utilized for handling strength constraints. Besides, the well-known principle of virtual work is employed to detect the most effective structural members for satisfying displacement constraints. The weight minimization of a structure is then performed using an integrated approach wherein both strength and displacement criteria are taken into account for reduction of the member sizes along the way the aforementioned constraints are handled. The performance of the proposed method is investigated using the standard 10-bar truss example as well as four real-size steel truss structures with 25, 130, 392 and 354 sizing variables designed for minimum weight according to AISC-LRFD [19] specifications. The comparison of numerical results obtained using the GSS to those of different metaheuristic algorithms indicates that the proposed technique is able to locate promising solutions using lesser computational effort. The outline of the paper is as follows. The second section covers a mathematical statement of the considered truss optimization problem according to AISC-LRFD [19] specifications. In the third section the principle of virtual work is outlined. The proposed GSS technique is described in the fourth section. The fifth section includes the performance evaluation of the proposed technique through design optimization of truss instances. The last section provides a brief conclusion of the paper.

2. Optimum design of steel trusses to AISC-LRFD

The discrete sizing optimization problem of a steel truss structure, according to AISC-LRFD [19] code, can be stated as follows.

$$\text{Find} \quad \mathbf{I}^T = [I_1, I_2, \ldots, I_{N_m}] \tag{1}$$

$$\text{to generate} \quad \mathbf{A}^T = [A_1, A_2, \ldots, A_{N_m}] \tag{2}$$

$$\text{which minimizes} \quad W = \sum_{i=1}^{N_m} \rho_i L_i A_i \tag{3}$$

$$\text{subject to} \quad \left[\frac{P_u}{\phi P_n}\right]_i - 1 \le 0; \quad i = 1, \ldots, N_m \tag{4}$$

$$\frac{d_{j,k}}{(d_{j,k})_{all}} - 1 \le 0, \quad j = 1, \ldots, N_j \tag{5}$$

where in the above equations, **I** is a vector of integer values, representing the sequence numbers of standard sections in a given section table, to generate a vector of cross-sectional areas **A** (Eq. (2)) for N_m members of the structure. In Eq. (3) W is the weight of the structure, ρ_i, L_i, A_i are unit weight, length, and cross-sectional area of the ith member, respectively. Here, the objective of finding the minimum weight structure is subjected to design constraints including strength and displacement requirements (Eqs. (4) and (5)). According to AISC-LRFD [19] code, for each member, i, Eq. (4) must be satisfied for the strength requirement where P_u and P_n are the required and nominal axial (tensile or compressive) strengths of the ith member under consideration, respectively. Here, ϕ is the resistance factor for axial strength, which is 0.85 for compression and 0.9 for tension. In addition to the strength requirements, the displacement criterion is formulated in Eq. (5) where j is the joint number, N_j is the total number of joints, $d_{j,k}$, and $(d_{j,k})_{all}$, are the displacements computed in the kth direction of the jth joint and its allowable value, respectively.

According to the AISC-LRFD [19] specifications, the nominal tensile strength of a member, based on yielding in the gross cross section, is equal to:

$$P_n = F_y A_g \tag{6}$$

where F_y is the member's specified yield stress and A_g is the gross cross section of the member. The nominal compressive strength of members with compact and/or non-compact elements, for the limit state of flexural buckling is as follows:

$$P_n = F_{cr} A_g \tag{7}$$

where F_{cr} is the critical stress based on flexural buckling of the member, computed as:

$$\text{for} \quad \lambda_c = \frac{Kl}{r\pi}\sqrt{\frac{F_y}{E}} \le 1.5, \quad F_{cr} = (0.658^{\lambda_c^2})F_y \tag{8}$$

$$\text{for} \quad \lambda_c = \frac{Kl}{r\pi}\sqrt{\frac{F_y}{E}} > 1.5, \quad F_{cr} = \left[\frac{0.877}{\lambda_c^2}\right]F_y \tag{9}$$

In the above equations, l is the laterally unbraced length of the member, K is the effective length factor, r is the governing radius of gyration about the axis of buckling and E is the modulus of elasticity.

3. Application of the principle of virtual work

In order to guide the design optimization process, member wise information should be computed and utilized for determining a useful direction of search. In the case of strength criteria this information can be provided from the load capacity of members that are easily obtained through Eq. (4). However, in the case of displacement criteria one requires a measure to identify contribution of each structural member to the total displacement for each considered direction, referred to as displacement participation factor (DPF). In the present study a procedure based on the principle of virtual work is used to determine the DPF of each member in a truss structure [20]. In order to compute the DPF of a truss member in the kth direction of the jth joint, in addition to a common structural analysis performed under the applied real loads, the truss structure should be analyzed under a unit load (virtual load) applied at the same joint and in the same direction as well. Next,

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