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Topology optimization of double and triple layer grid structures using a modified gravitational harmony search algorithm with efficient member grouping strategy

Mostafa Mashayekhi [a,*], Eysa Salajegheh [b], Milad Dehghani [a]

[a] Department of Civil Engineering, Vali-e-Asr University of Rafsanjan, Rafsanjan, Iran
[b] Department of Civil Engineering, Shahid Bahonar University of Kerman, Kerman, Iran

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ABSTRACT

An efficient modified gravitational harmony search algorithm (MGHSA) for topology optimization of double and triple layer grid structures is presented in the article. In MGHSA, the best agents in each iteration are identified and each of them is considered as a group leader. Other agents are randomly located in these groups. To determine the new agents' positions, only the group leader applies force to the other agents in the group. Also, a novel member grouping strategy is included in the optimization algorithm. Optimization results demonstrate the efficiency of the novel MGHSA algorithm and member grouping strategy developed in this study.

1. Introduction

Structural optimization has become one of the most active branches of structural design in the last decade [1,2]. A usual objective function is the weight of the structure, while the constraints vary from displacements and stress constraints, depending on the considered problem. The optimum design of structures can be usually defined as one or any combination of three main optimization problems, namely sizing, topology and layout optimization. Sizing optimization attempts to find the optimal cross-sectional areas of elements assuming that element connectivity and node coordinates are fixed. Topology optimization deals with element connectivity, i.e. presence or absence of elements between joints. Layout optimization searches for optimal positions of nodal coordinates, assuming that topology is fixed [3].

Advantages entailed by topology optimization are well known since 1904 [4]. In the last decades, different methods have been proposed for optimization of truss structures, most of which are based on the concept of the ground structure approach initiated by Dorn et al. [5]. Combining sizing and topology optimization leads to formulate very complex optimization problems. Since the 1960s, there have been many studies based on the ground structure method [6,7]. For truss topology optimization, Krisch [8] combined explicit optimality criteria with the grillage method. Ohsaki and Katoh [9] formulated the optimization problem with stress constraints as a mixed integer programming (MIP) problem, solved with the branch-and-bound method. Meta-heuristic optimization methods have been extensively used in truss design problems. For example, applications of genetic algorithms (GAs) are reported in [10–12]. Also, Deb and Gulati [13] applied a real-coded GA with a simulated binary crossover to optimize the sizing, layout and topology of trusses. Hasançebi and Erbatur [14] developed a simulated annealing (SA) code for the simultaneous optimum design of truss type structures with respect to size, shape and topology design variables. Luh and Lin [15] used a two-stage ant colony optimization (ACO) algorithm to solve combined topology and sizing optimization problems: topology was first optimized with a conventional ant system and a continuous version of the ant colony algorithm was then utilized for sizing optimization of truss members. Topping et al. utilized simulated annealing [16] while the tabu search method was used by Bennage and Dhingra [17]. An effective method for stress constrained topology optimization problems under load and material uncertainties has been presented by Luo et al. [18], using an enhanced aggregation method. The two-point gradient based approximation was developed by Li and Khandelwal [19] in order to improve the performance of the method of moving asymptotes (MMA) in topology optimization problems. Numerical results demonstrated the validity of the proposed approach which outperformed other approximation methods.

* Corresponding author. Fax: +98 3431312202.
E-mail address: m.mashayekhi@vru.ac.ir (M. Mashayekhi).

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Large-scale spatial skeletal structures belong to a special kind of 3D structures widely used in exhibition centers, supermarkets, sport stadiums, airports, etc., to cover large surfaces without intermediate columns. Space structures are often categorized as grids, domes and barrel vaults [20]. Double layer grid structures are classical instances of prefabricated space structures and also the most popular forms which are frequently used nowadays.

In topology optimization of large-scale skeletal structures with discrete cross-sectional areas, the performance of meta-heuristic optimization algorithms can be increased if they are combined with continuous-based topology optimization methods. For example, Mashayekhi et al. [21] applied a two-stage optimization method for reliability-based topology optimization of double layer grid structures combining MMA and ACO. Also, Mashayekhi et al. [22] combined evolutionary structural optimization (ESO) and ant colony optimization into the ESO-ACO method to minimize weight of double layer grid structures; artificial ground motion was used to calculate the structural dynamic response. The same authors performed reliability-based topology optimization (RBTO) of double layer grid structures with the SIMP-ACO algorithm [23] where structural stiffness is optimized with solid isotropic material with penalization method (SIMP) and the characteristics of the optimized topology are used to enhance ACO. An efficient optimization method was recently proposed by Mashayekhi et al. [24] which was a combination of Imperialist Competitive Algorithm (ICA) and Gravitational Search Algorithm (GSA). The proposed hybrid method was based on ICA but the moving of countries toward their relevant imperialist was done using the law of gravity of GSA.

This article presents an efficient meta-heuristic algorithm (MGHSA) for topology optimization of double and triple layer grid structures. The ground structure approach is utilized. In each iteration, the best agents are identified and each of them is selected as a group leader. Other agents are randomly located in these groups so as to have good and bad agents well distributed in each group. Based on the Newtonian gravity and the laws of motion, only the group leader applies force to the other agents in its group to determine their new positions, and correct positions violating side constraints with HS-based strategy. The member grouping strategy developed by Mashayekhi et al. [21–24] is modified in this study in order to reduce the search space: the achieved profile number of each member group reduces to one or two digits for elements subject to low internal forces. Optimization results generated for double and triple layer grid structures design problems demonstrate the efficiency of the proposed algorithm and member grouping strategy that allowed structural weight to be considerably reduced with respect to literature.

2. Topology optimization of double and triple layer grid structures

In topology optimization of double and triple layer grid structures, the geometry of the structure, support locations and coordinates of nodes are fixed and this structure is assumed as a ground structure. Presence/absence of bottom nodes for double layer grid structures or presence/absence of bottom and middle nodes for triple layer grid structures, and element cross-sectional areas are selected as design variables. The ground structure is assumed to be supported at the perimeter nodes of the bottom grid. Therefore, these supported nodes will not be removed from the ground structure. In topology optimization of the ground structure, tabulating of nodes is carried out based on structural symmetry: this leads to reduce complexity of design space and nodes are removed in groups of 8, 4 or 1 [21]. For example in the double layer grid structure shown in Fig. 1, the number of bottom nodes with similar geometry positions is arranged in Table 1, while in this 6-rows table, there are 1, 4 or 8 nodes in each row (group). Therefore, in this structure, six topology variables ($NTV = 6$) are needed to define the variability of all node groups. The presence or absence of each node group is identified by a variable (topology variable) which takes the value of 1 and 0 for the two cases, respectively. In other words, assigning a zero value to the ith topology variable means that the ith node group, and all of the elements connected to those nodes should be removed from the ground structure.

In topology optimization problem, the number of design variables (NDV) is the summation of the number of compressive and tensile element types and the number of topology variables (NTV) [21]. For example, it is assumed that during the topology optimization procedure of the ground structure shown in Fig. 1, the vector of design variables of a structure is obtained as depicted in Fig. 2. In this figure, it is assumed that the number of tensile and compressive element types is considered as 2 and 4, respectively. Since the 1st and the 4th topology variables have zero values, all of the nodes in the 1st and the 4th rows in Table 1 are deleted from the ground structure. The obtained topology is shown in Fig. 3. The remaining 6 design variables are used to assign the cross-sectional area to the members in any group (type) by referring to a table of available profiles. In other words, the 3rd, the 6th, the 5th and the 2nd profile are allocated to all the compression members of the first through the fourth group (type), respectively, and the 4th and the 3st profile are allocated to all the tension members of the first and the second group (type), respectively.

Discrete variables are used for determining the suitable cross-sectional area of the structural members. These variables are selected from pipe sections with specified thickness and outer diameter. In order to design a practical structure, the existence of nodes in top grid is not considered as a variable. This implies that the load bearing areas of top layer joints remain unchanged [21].

In topology optimization problems of double and triple layer grid structures, the objective is to minimize the weight of the structure (W) under constraints on element stress (g_σ), slenderness ratio (g_λ) and displacement (g_δ) [21]. Design variables can be selected from a discrete set of values. The optimization problem is formulated as follows:

$$\begin{aligned}&\text{Find}: \bar{\mathbf{A}} = [J_1, J_2, \ldots, J_{NTV}, a_1, a_2, \ldots, a_{NMG}]^T\\&\quad J_i \in [0,1],\ i = 1,2,\ldots,NTV\\&\quad a_k \in \tilde{\mathbf{A}},\ k = 1,2,\ldots,NMG\\&\text{to minimize}: W = \rho^e \sum_{k=1}^{NMG} a_k \sum_{i=1}^{N_k} l_i\\&\text{subject to}: g_\sigma,\ g_\lambda,\ g_\delta \leqslant 0\end{aligned} \tag{1}$$

where NMG is the number of member groups, J_i is the ith topology variable, N_k is the number of members in the kth member group, a_k is the discrete cross-sectional area of the kth member group which is selected from steel pipes in a given profile list ($\tilde{\mathbf{A}}$), ρ^e is the material density and l_i is the length of the ith element.

The constrained optimization problem can be converted into an unconstrained one where the modified objective function (Ψ) must be minimized [25]. In the present study, the Ψ function is defined as in [21]:

$$\Psi(\bar{\mathbf{A}}) = W(\bar{\mathbf{A}})(1 + C(\bar{\mathbf{A}}))^2 \tag{2}$$

in which

$$C(\bar{\mathbf{A}}) = \sum_{i=1}^{ne}(g_{\sigma,i}(\bar{\mathbf{A}}) + g_{\lambda,i}(\bar{\mathbf{A}})) + \sum_{j=1}^{nj} g_{\delta,i}(\bar{\mathbf{A}}) \tag{3}$$

where C is the penalty function, ne is the number of elements and nj is the number of joints. It is noted that these penalty terms are