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Performance-based seismic design of steel frames utilizing charged system search optimization

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ABSTRACT

In this paper, a performance-based optimal seismic design of steel frames is presented utilizing Charged System Search (CSS) optimization. This meta-heuristic optimization algorithm has been recently developed and employed in many optimization problems showing a high capability in structural optimization. Here, a pushover analysis method based on semi-rigid connection concept is employed as analysis and design method. Two numerical examples which have been previously considered in literature are studied and the results illustrate significant improvement in structural weight compared to the conventional design methods. The capabilities of the CSS are compared to those of the ACO and GA.

1. Introduction

In engineering projects, it is desirable to reduce the project costs to a possible minimum amount. In structural engineering, this goal can be achieved in various stages, for example when the structure is being designed, fabricated, erected, etc. Optimal design of structure is an effort to reduce the project cost at the stage of designing the structure. Therefore, there have been great efforts for optimal design of different kinds of engineering problems, and various approaches were developed. In this way, using meta-heuristic algorithms based on natural events and physical laws are being extended in engineering optimization problems. *Particle Swarm Optimization* (PSO) was proposed by Eberhart and Kennedy, and it has been applied to various optimization problems [1]. El-Maleh et al. proposed a binary PSO and applied it in state assignment for area minimization of sequential circuits [2]. Moreover, several hybrid metaheuristic algorithms have been presented thus far some of which can be found in refs. [3–6]. On the other hand, some new algorithms based on swarm intelligence concept have been proposed. One of these algorithms is known as the *Charged System Search* (CSS) optimization which was developed by Kaveh and Talatahari [7]. This algorithm is based on the Coulomb and Gauss electrical and the Newtonian laws of mechanics. This method was extensively and successfully applied to structural optimization problems by Kaveh et al. [8–12].

Another important point in optimal design is the method of analysis and design. Since seismic loads have unpredictable nature, if a structure is designed such that it remains elastic under a tolerate earthquake effects, weight of the structure resulted from such a design will increase to an uneconomic value. Thus, building codes and design methods consider inelastic behavior of structures in a safe manner. A robust approach for seismic design of structures considering inelastic behavior of structures is the performance-based design of structures which is a multi-level approach to structural design in various seismic levels, and in each level the designer must control appropriate constraints correspond to that level. Nonlinear static analysis, *Pushover analysis*, is a method for performance-based design of structures. Based on this method, earthquake effects, including displacements or forces, are applied to structure statically in some stages from zero to a proposed value, and in each stage the nonlinear internal forces and nodal displacements are calculated and used for the next stage.

Also, another important issue in the structural analysis is the order of the analysis. For example in first order analysis of structures, deflections of members and the geometrical stiffness do not take part in structural analysis, while in the second order they do. A computer-based second order analysis of members including geometrical stiffness and sensitivity matrices for optimization using semi-rigid steel framework concept has been presented by Xu [13]. Hassan et al. applied this method to the pushover analysis for performance based seismic design [14]. Kaveh et al. have implemented

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performance based seismic design of steel frames using ant colony optimization (ACO) and genetic algorithm (GA) and have compared these two methods of optimization reaching a lower weight [15].

In this paper, a method for performance-based optimal seismic design of steel frames utilizing CSS is developed. Results illustrates significant improvement in structural weight compared to the conventional design method and the higher capability of the CSS compared to ACO and GA.

2. Statement of optimal performance-based seismic design of buildings

In structural design, it is desirable to reach a proposed serviceability level with the least usage of the material. Performance level is the required behavior of a structure in different situations. In this study, four performance levels are considered which are defined as follows:

(a) Operational: In earthquake situation with probability of exceeding equal to 50% in 50 years structure life, the structure must maintain elastic and lateral drift in center of gravity at roof level must be lesser than allowable value:

$$\Delta^{OP} \le \overline{\Delta}^{OP} \tag{1}$$

where Δ^{OP} is the lateral drift in center of gravity at roof level and $\overline{\Delta}OP$ is the allowable lateral drift in center of gravity at roof level both in operational level.

(b) Immediate occupancy: In earthquake situation with probability of exceeding equal to 20% in 50 years structure life, lateral drift in center of gravity at roof level must be lesser than allowable value:

$$\Delta^{IO} \le \overline{\Delta}^{IO} \tag{2}$$

where Δ^{IO} is the lateral drift in center of gravity at roof level and $\overline{\Delta}^{IO}$ is the allowable lateral drift in center of gravity at roof level both in immediate occupancy level.

(c) Life safety: In earthquake situation with probability of exceeding equal to 10% in 50 years structure life, lateral drift in center of gravity at roof level must be lesser than allowable value:

$$\Delta^{LS} \le \overline{\Delta}^{LS} \tag{3}$$

where Δ^{LS} is the lateral drift in center of gravity at roof level and $\overline{\Delta}^{LS}$ is the allowable lateral drift in center of gravity at roof level both in life safety level.

(d) Collapse prevention: In earthquake situation with probability of exceeding equal to 2% in 50 years structure life, the structure must remain stable and lateral drift in center of gravity at roof level must be lesser than allowable value:

$$\Delta^{CP} \le \overline{\Delta}^{CP} \tag{4}$$

where Δ^{CP} is the lateral drift in center of gravity at roof level and $\overline{\Delta}^{CP}$ is the allowable lateral drift in center of gravity at roof level both in immediate occupancy level.

Roof drift of 0.4%, 0.7%, 2.5% and 5% of the height of structure are taken as allowable roof drifts for OP, IO, LS, and CP performance levels in design optimization process, respectively [16,17].

Most of the studies in optimization have considered the weight of frame as the cost function since accurate cost data requires information from many factors that are unpredictable and not precisely defined:

$$W(X) = \sum_{j=1}^{ne} \rho \cdot A_j \cdot L_j \tag{5}$$

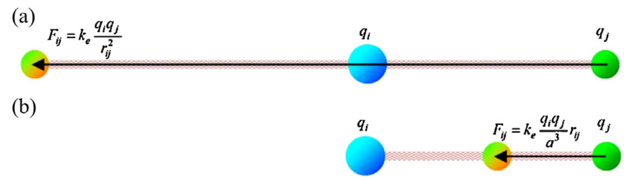

Fig. 1. The forces due to charged particles: (a) for $r > a$, and (b) for $r < a$, Ref. [1].

where $W(X)$ is the weight of frame; X is the vector of design variables taken from W-shaped sections found in AISC design manual [18]; ne is number of elements; ρ is the material mass density; and L_j and A_j are the length and cross sectional area of the member j, respectively.

3. Charged System Search Optimization

Charged System Search (CSS) optimization is an optimizer algorithm based on Coulomb and Gauss electrical and Newtonian laws of Mechanics [7]. An explanation of the CSS for discrete optimization is as follows [7,8]:

In physics, the space surrounding an electric charge has a property known as the electric field. This field exerts a force on other electrically charged objects. The electric field surrounding a point charge is given by Coulomb's law. Coulomb has confirmed that the electric force between two small charged spheres is proportional to the inverse square of their separation distance r_{ij}. The forces due to charged particles are schematically illustrated in Fig. 1.

This algorithm can be considered as a multi-agent approach, where each agent is a Charged Particle (CP), considered as a charged sphere with radius a, having a uniform volume charge density and is equal to:

$$q_i = \frac{fit(i) - fitworst}{fitbest - fitworst}, \quad i = 1, 2, \ldots, N \tag{6}$$

where *fitbest* and *fitworst* are the best and the worst fitness of all the particles respectively; *fit*(i) represents the fitness of the agent i, and N is the total number of CPs.

CPs can impose electric forces on the others. The kind of the forces is attractive and can be repulsive, and its magnitude for the CP located in the inside of the sphere is proportional to the separation distance between the CPs, and for a CP located outside the sphere it is inversely proportional to the square of the separation distance between the particles. In continuous problems it is enough to consider all the forces positive but in discrete problems similar to this study repulsive forces are also considered with the probability of k_t in order to maintain exploration rate. Therefore, the forces can be obtained as:

$$F_j = q_j \sum_{i, i \ne j} \left(\frac{q_i}{a^3} r_{ij} \cdot i_1 + \frac{q_i}{r_{ij}^2} \cdot i_2 \right) \cdot ar_{ij} \cdot p_{ij}(X_i - X_j) \tag{7}$$

where q_j is the volume charge density of the jth particle's defined by Eq. (6), and it has a value between 0 and 1; F_j is the resultant force acting on the jth CP; r_{ij} is the separation distance between two charged particles which is defined as follows:

$$r_{ij} = \frac{||X_i - X_j||}{||(X_i + X_j)/2 - X_{best}|| + \varepsilon} \tag{8}$$

where X_i and X_j are the positions of the ith and jth CPs, respectively; X_{best} is the position of best current CP, and ε is a small positive number that prevents the fraction to become infinity. The initial positions of CPs are determined randomly in the search space and the initial velocities for charged particles are assumed to be zero.