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A robust method for optimization of semi-rigid steel frames subject to seismic loading

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ABSTRACT

In this study, we develop a seismic optimization method to minimize the semi-rigid steel frame cost. In the proposed method, cross-sections of columns and beams and types of beam-to-column and base restraint semi-rigid joints are considered as the design variables of the optimization. The nonlinear seismic behaviors of the structure are carried out by using plastic-hinge beam-column elements for beams and columns, zero-length elements for semi-rigid connections, and time-history dynamic analysis. An effective implementation of harmony search technique (HS) is presented to find the global optimal solution of the optimization. In order to improve HS, a multi-comparison technique (MCT) is proposed that significantly reduces the useless time-consuming evaluations in the optimization. The robustness and efficiency of the proposed method are demonstrated through three optimization problems of semi-rigid steel frames. Compared with particle swarm optimization (PSO), micro-genetic algorithm (micro-GA), and genetic algorithm (GA), the proposed method is found to significantly reduce the number of structural analyses required and yield the better optimum frame designs.

1. Introduction

In conventional steel frame design approaches, the connections of beam-to-column and base restraint are usually simulated as pinned or rigid joints. In fact, many experiments of steel frame connections have been conducted in the literature and they show that their actual behaviors are semi-rigid [1–4]. Hence, semi-rigid connections have been allowed to consider in the analysis of steel frames in steel design specifications (e.g. Eurocode 3 [5], AISC LRFD [6], etc.). Several models have been proposed to show the nonlinear relationship of the rotation and the moment in a semi-rigid joint such as three-parameter power model [7], Frye-Morris polynomial model [8], and four-node joint element approach [9], among others. A semi-rigid steel frame, therefore, has considerable nonlinear behavior that comes from material and geometrical nonlinearities, nonlinear semi-rigid connections, etc. Furthermore, it is possible that the structural nonlinear behavior under complicated dynamic loading such as earthquakes is more complex than under static monotonic loadings. As a consequence, a significant effort has been dedicated to studying practical advanced analysis methods (PAAs) using time-history dynamic analysis for design of semi-rigid steel frames subject to seismic loading (see, for example, Refs. [47,50,51]).

Recently, structural optimization has been playing a significant role in analysis and design of steel frames, for it helps decrease structural costs while performance of the system is maintained. In a steel frame optimization problem, beams and columns are optimized by choosing the lightest cross-sectional areas in a predefined list (for example, Eurocode [5], AISC [6], etc.). Therefore, steel frame optimization is a discrete optimization problem that can be effectively solved by using metaheuristic algorithms [10]. Some popular metaheuristic algorithms are GA [11], Tabu search (TS) [12], HS [13], PSO [14], ant colony optimization (ACO) [15], etc. As far as metaheuristic algorithms are applied in structural optimization, many studies of optimization of steel moment frames subject to static loading have been carried out. Some recent prominent studies of steel frame optimization subject to static loadings using metaheuristic algorithms can be mentioned here as following. Hasançebi [16] minimized the total structural cost of real world steel frames by implementing the evolution strategy (ES) and parallel computing in order to reduce computational cost. In that work, all production stages including material, manufacturing, erection and transportation were considered. Aydogdu et al. [17] optimized space steel frames by using Levy flight distribution in the search of scout bees to improve the artificial bee colony (ABC) algorithm. Kaveh and BolandGerami [18] developed a new metaheuristic algorithm named as cascade enhanced colliding body optimization to optimize the elastic steel frames. Kaveh et al. [19] optimized elastic truss and frame structures by using the big-bang big-crunch

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algorithm in which a new individual is chosen based on the weight averaging and its objective function.

The optimization of steel frames subject to seismic loading has also attracted the significant interest of researchers. For example, Xu et al. [20] proposed a direct optimization method of steel frames using pushover analysis to perform seismic effect. Gong et al. [21] developed a design optimization method of moment-resisting steel frames using multi-objective GA and nonlinear response history analysis. Kaveh and Zakian [22] used two metaheuristic algorithms such as charged system search (CSS) and improved HS (IHS) to optimize steel moment frames. Time history analysis is employed to predict the structural response subject to seismic loading. Gholizadeh and Salajegheh [23] integrated PSO and a proposed adaptive virtual sub-population (AVSP) algorithm for the optimal seismic design of steel frames. Kaveh et al. [24] used enhanced colliding bodies optimization (ECBO) algorithm to optimize steel moment frames in which two connection types (simple and rigid) are considered. In the above-mentioned works, total steel weight of frames was minimized by assuming that structural connections were perfectly rigid or pinned. Since the real behavior of beam-to-column and base restraint connections is semi-rigid, the optimization results of those works are unreliable.

In order to consider the effect of nonlinear behavior of semi-rigid connections, the optimization of semi-rigid steel frames subject to static loading has been carried out by many researchers (see Refs. [25–31], among others). In most of those studies, the total cost of beams, columns, and semi-rigid connections was optimized by representing the connection cost as the equivalent steel weight [26,27,31]. The different types of semi-rigid beam-to-column connections were also considered as the design variables of the optimization by Hagishita and Ohsaki [29] and Truong et al. [31]. The optimization results in those studies proved that better optimum designs can be found by considering the connection type in the optimization. Regarding optimization of semi-rigid steel frames under seismic loading, to the authors' knowledge, only one study [32] has been published in literature. In that work, Oskouei et al. optimized the weight of the frames by using GA and nonlinear static analysis (pushover). Pushover analysis takes much less time than a time-history dynamic analysis, but this method only works well if the structure is dominated by its first vibration mode. Furthermore, neglecting the connection cost can lead to an unreliable optimum design.

The objective of this study is to develop a robust seismic optimization method to minimize the semi-rigid steel frame cost. In the proposed method, the design variables are not only column and beam cross-sections but also connection types of beam-to-column and base restraint semi-rigid joints. A PAA method using the zero-length element, plastic-hinge beam-column element, and time-history dynamic analysis is employed to capture the structural nonlinear seismic behaviors. An improved HS is proposed to solve the discrete optimization problems of semi-rigid steel frames under seismic loading. To demonstrate the efficiency of the proposed method, three semi-rigid steel frames are considered. A comparison is also presented between the proposed method and GA, micro-GA, and PSO. In this study, the panel shear deformations in semi-rigid connections of the structure are not considered.

2. Formulation of design optimization problem

The design task of the optimization is to minimize the total cost of beams, columns, beam-to-column connections, and base restraints of seismic resistant steel frames. The design variables are beam and column cross-sections and connection types of beam-to-column and base restraint joints. The constraints are the limits on member strength, inter-story drift, and geometric constructability.

2.1. Objective function

In a semi-rigid steel frame optimization, the objective function is formulated as follows:

$$Min \quad C = T_F + T_C + T_B, \tag{1}$$

where C is the frame cost; T_F, T_C, and T_B are the cost of beams and columns, semi-rigid connections, and base restraints, respectively.

T_F is calculated as follows:

$$T_F = C_F \rho \left(\sum_{i=1}^{n} A_i L_i \right), \tag{2}$$

where ρ and C_F are the unit weight and cost per unit weight of steel columns and beams, respectively; A_i and L_i are the cross-section and length of beam-column element i^{th}, respectively; and, n is the number of columns and beams. For simplicity, C_F is assumed to be equal to 1.0 or T_F is the total weight of steel columns and beams.

T_C is determined as:

$$T_C = \sum_{j=1}^{m} C_j^C k_j^C, \tag{3}$$

where m is the number of semi-rigid connection types; C_j^C and k_j^C are the cost of one connection, and number of connection type j^{th}, respectively. C_j^C is estimated by using the following equation proposed by Truong et al. [31]:

$$C_{R_i}^C = 0.125 \rho A_b L_b \left(1 + 1.8 \frac{R_i - R_i^L}{R_i^U - R_i^L} \right) = c_{R_i}^C \rho A_b L_b = c_{R_i}^C W_b, \tag{4}$$

where R_i is the connection rotational stiffness; $C_{R_i}^C$ and $c_{R_i}^C$ are the cost and cost coefficient of the connection, respectively; A_b and L_b are the cross-sectional area, and length of the corresponding beam, respectively; W_b is the weight of the beam; and, R_i^L and R_i^U are equal to $2.26 * 10^8$ (Nmm/rad) and $5.65 * 10^{11}$(Nmm/rad), respectively. Additional information can be found in Ref. [31].

T_B can be calculated as

$$T_B = \sum_{j=1}^{l} C_j^B k_j^B, \tag{5}$$

where C_j^B and k_j^B are the cost of one base restraint and number of semi-rigid base restraint type j^{th}, respectively; and, l is the number of types of semi-rigid base restraints. C_j^B can be estimated by modifying the Eq. (4) as follows:

$$C_{R_i} = 0.125 \left(1 + 1.8 \frac{R_i - R_i^L}{R_i^U - R_i^L} \right) \rho \left(\sum A_C L_C \right) = c_{R_i}^B W_C, \tag{6}$$

where $C_{R_i}^B$ and $c_{R_i}^B$ are the cost and cost coefficient of the base restraint having rotational stiffness R_i, respectively; and, W_C is the weight of the corresponding column.

2.2. Constraints

The strength constraints of the structure are expressed as

$$C^{str} = 1 - \frac{R}{S} \le 0, \tag{7}$$

where R is the structural load-carrying capacity and S is the applied load.