Journal of Constructional Steel Research 82 (2013) 111–130

Contents lists available at SciVerse ScienceDirect

Journal of Constructional Steel Research

Optimal design of steel frames under seismic loading using two meta-heuristic algorithms

A. Kaveh *, P. Zakian

Centre of Excellence for Fundamental Studies in Structural Engineering, Department of Civil Engineering, Iran University of Science and Technology, Narmak, Tehran-16, Iran

ARTICLE INFO

Article history:
Received 13 April 2012
Accepted 19 December 2012
Available online 24 January 2013

Keywords:
Steel moment frame
Seismic loading
Time history analysis
Structural optimization
Charged system search (CSS)
Improved harmony search (IHS)

ABSTRACT

In this paper, optimal design of steel frames is performed under seismic loading. The variables of the problem are taken as the cross-sectional areas of the members. These variables are considered as discrete, and are selected from a list of existing cross sections. Here, the charged system search and improved harmony search algorithms are utilized for optimization. For optimal design of steel frames in the first phase a time history analysis with the relative lateral displacement constraints is performed, and in the second phase a simultaneous dynamic–static analysis with the relative displacement and stress constraints is utilized using two meta-heuristic algorithms. Moment frames and their shear frame counterparts are considered, and their performances are compared for optimal design. In the case of moment frames, apart from the columns, the cross sections of the beams are also considered as design variables. The results indicate a good performance of the optimized moment frame and show that considering the effect of both drift and stress constraints, instead of only drift constraints, one obtains a better design. These results also show the suitability of the charged system search algorithm for optimal design of frames under seismic loading, as an extremely nonlinear problem.

1. Introduction

Optimal design of structures is usually performed to determine the variables leading to minimum weight or cost, while satisfying the design criteria. Considering dynamic loading, optimization requires a dynamic analysis corresponding to a highly nonlinear problem, and the use of an efficient method becomes vital. Furthermore, in structural earthquake engineering the process for the analysis and design of structures to withstand the effects of earthquake ground motions are in a progressive state of development. Employing dynamic analysis together with the static analysis in the assessment of the structural performance leads to safe design of the structures and reduces the earthquake induced damages.

Using time history analysis often results in an overestimate design, therefore an optimization process can be beneficial in seismic design of structures. There are a number of publications which have addressed structural design optimization associated with seismic analysis. Most of these have used classic and evolutionary methods for this purpose.

Kocer and Arora [1,2] used simulated annealing and genetic algorithm for optimal design of frames with nonlinear time history analysis. Cheng et al. [3] employed the game theory and genetic algorithm for multi-objective optimization of 2D frames under dynamic loading. Chan and Zou [4] proposed the use of an optimality criteria based dynamic optimization procedure for 2D concrete frames. Prendes Gero et al. [5,6] employed a modified elitist genetic algorithm for dynamic design optimization of 3D steel structures. Salajegheh and Heidari [7,8] utilized wavelets, neural network and genetic algorithm for optimum design of structures under earthquake loading. Gholizadeh and Salajegheh [9] employed a meta-modeling based real valued PSO algorithm for optimizing structures subjected to time history loading. Gholizadeh and Samavati [10] proposed a hybrid methodology for optimal dynamic design of structures.

Nowadays meta-heuristic approaches are utilized in many fields of engineering optimization, and are rapidly improved. In this study, optimal design of planar steel frame structures is performed under seismic loading. For practical reasons discrete size optimization is performed and cross-sections are selected from an available section list. The constraints imposed in the first phase consist of the relative lateral drifts based on the ASCE code [11], and in the second phase apart from relative drifts, the stress constraints are also considered. In the previous works, evolutionary methods were used for optimization. Here, the charged system search and improved harmony search algorithms are utilized. In the first phase of optimization a time history analysis is performed, and in the second phase employing simultaneous dynamic–static analysis and using two meta-heuristic algorithms optimal designs are performed. Both moment and shear frames are considered and their performances for optimal design of two 4-story and two 8-story frames are compared.

Moreover, the results show the good performance of the optimized moment frame and indicate that considering the simultaneous effect of drift and stress constraints, one can perform a suitable design. These results also show the suitability of the CSS algorithm for

* Corresponding author. Tel.: +98 21 44202710.
E-mail address: alikaveh@iust.ac.ir (A. Kaveh).

0143-974X/$ – see front matter
http://dx.doi.org/10.1016/j.jcsr.2012.12.003

structural dynamic design optimization as an extremely complex problem.

2. Formulation of structural dynamic design optimization

Structural optimization problems can be divided into three types: size optimization, shape optimization, and topology optimization. In the size optimization that is the concern of this paper usually design variables are in the form of thickness or dimensions of the members of the structure.

For practical reasons, the cross-section areas of the structural members are considered as design variables, which are selected from a list of available sections. The discrete optimization is formulated as follows:

$$\begin{aligned} &\textit{Minimize} \quad \mathrm{f(X)} \\ &\text{subject to } \mathrm{g}_j(\mathrm{X}) \le 0 \\ &\mathrm{X} = [\mathrm{x}_1, \mathrm{x}_2, \ldots, \mathrm{x}_{\mathrm{nv}}] \\ &\mathrm{i} = 1, 2, \ldots \mathrm{nv} \\ &\mathrm{x_i} \in \mathrm{R^d} \end{aligned} \tag{1}$$

$$\text{to minimize} \quad Obj(X) = f(X) \times f_{\text{penalty}}(X) \tag{2}$$

where X is the vector of design variables containing the cross section areas, nv is the number of design variables or the number of member groups, and R^d is the domain of the design variables.

Here, $Obj(\mathrm{X})$ is the objective function, $f(\mathrm{X})$ is the structural weight function, and $f_{\text{penalty}}(X)$ is penalty function in order to control the constraints:

$$f(X) = \sum_{i=1}^{nv} \gamma_i \cdot x_i \cdot l_i \tag{3}$$

$$f_{\text{penalty}}(X) = (1 + \kappa_1 \cdot \nu)^{\kappa_2}, \ \ \nu = \sum_{i=1}^{n} \max[0, \nu_i] \tag{4}$$

l_i is the length, and γ_i is the material density of the member i. Here, the parameters κ_1 and κ_2 for the penalty function are selected as 1 and 2, respectively. ν represents the sum of the violated constraints.

Design constraints are as follows:

Drift constraints:

$$\frac{\delta_i - \delta_{i-1}}{h_i} < DR_a \ \ i = 1, 2, \ldots, ns \tag{5}$$

where δ_i is the lateral displacement of the center of the mass in the story i, h_i is the height of the story i, and DR_a is the allowable drift ratio of each story. ns is the number of the frame stories. This constraint is time-dependent, and it is handled by a conventional method as described in [12]. This method is simple and can easily be implemented. The time interval is divided into subintervals i.e. a transformation to grid points is performed, and the time-dependent constraints are imposed at grid points. The stress constraints are imposed considering the sum of the stress demands of the static and dynamic analyses. The total stresses are determined as follows:

$$\sigma^i_{\text{total}} = \sigma^i_{\text{static}} \pm \max\left(\sigma^{i,t}_{\text{dynamic}}\right) \ \ i = 1, 2, \ \ldots, nm. \tag{6}$$

σ^i_{total} and σ^i_{static} are the total stress and static stress of the member i, respectively. $\sigma^{i,t}_{\text{dynamic}}$ is the dynamic stress of member i at the time t, and nm denotes the number of members. According to the AISC-ASD code [13], the stress constraints for the columns and beams are as: For columns:

$$\begin{aligned} &\frac{f_a}{0.6F_y} + \frac{f_{bx}}{F_{bx}} + \frac{f_{by}}{F_{by}} \le 1 \qquad \text{for } \frac{f_a}{F_a} > 0.15 \\ &\frac{f_a}{F_a} + \frac{f_{bx} c_{mx}}{F_{bx}\left(1 - \frac{f_a}{F'_{ex}}\right)} + \frac{f_{by} c_{my}}{F_{by}\left(1 - \frac{f_a}{F'_{ey}}\right)} \le 1 \end{aligned} \tag{7}$$

$$\frac{f_a}{F_a} + \frac{f_{bx} c_{mx}}{F_{bx}} + \frac{f_{by} c_{my}}{F_{by}} \le 1 \qquad \textit{for } \frac{f_a}{F_a} \le 0.15 \tag{8}$$

For beams:

$$\frac{M_x}{S_x} < F_b = 0.66F_y \tag{9}$$

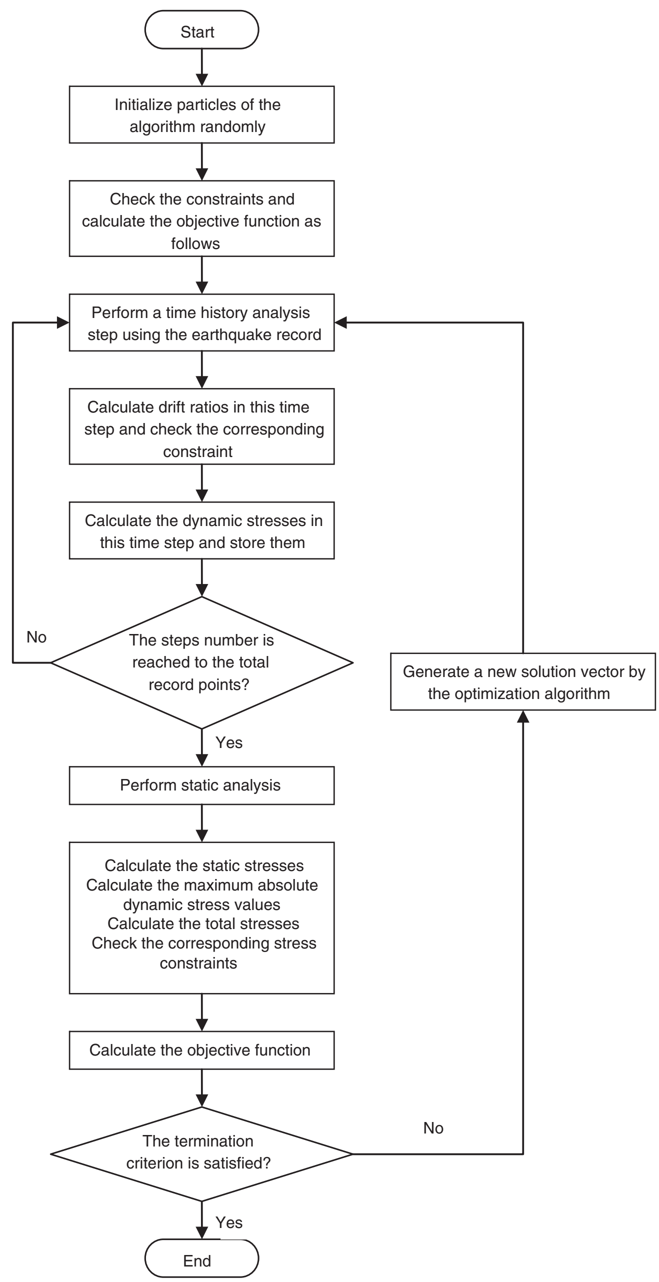

Fig. 1. Flowchart of the structural dynamic design optimization.