Computers and Structures 147 (2015) 79–95

Contents lists available at ScienceDirect

Computers and Structures

journal homepage: www.elsevier.com/locate/compstruc

Harmony search algorithm based optimum detailed design of reinforced concrete plane frames subject to ACI 318-05 provisions

A. Akin [a], M.P. Saka [b,*]

[a] Civil Structural Engineer, Thomas& Betts – Meyer Steel Structures, Memphis, TN, USA
[b] University of Bahrain, Department of Civil Engineering, Isa Town, Bahrain

ARTICLE INFO

Article history:
Received 29 September 2014
Accepted 1 October 2014
Available online 30 October 2014

Keywords:
Cost optimization
Structural optimum design
Harmony search algorithm
Reinforced concrete structures
Heuristics

ABSTRACT

This paper presents the application of the harmony search based algorithm to the optimum detailed design of special seismic moment reinforced concrete (RC) frames under earthquake loads based on American Standard specifications. The objective function is selected as the total cost of the frame which includes the cost of concrete, formwork and reinforcing steel for individual members of the frame. The modular sizes of members, standard reinforcement bar diameters, spacing requirements of reinforcing bars, architectural requirements and other practical requirements in addition to relevant provisions are considered to obtain directly constructible designs without any further modifications. For the RC columns, predetermined section database is constructed and arranged in order of resisting capacity. The produced optimum design satisfies the strength, ductility, serviceability and other constraints related to good design and stated in the relevant specifications. The lateral seismic forces are calculated according to ASCE 7-05 and it is updated in each iteration. Number of design examples is considered to demonstrate the efficiency of the optimum design algorithm proposed. It is concluded that the developed optimum design model can be used in design offices for practical designs and this study is the first application of the harmony search method to the optimization of RC frames and also the optimization of special seismic moment RC frames to date.

1. Introduction

In recent years structural optimization has witnessed an emergence of robust and innovative search techniques that strictly avoid gradient-based search to counteract with challenges that traditional optimization algorithms have faced for years. The basic concept behind each of these techniques rests on simulating the paradigm of a biological, chemical, or social systems (such as evolution, immune system, and swarm intelligence or annealing process) that is automated by nature to achieve the task of optimization of its own [1–3]. The design algorithms developed using these meta-heuristic search techniques are particularly suitable for obtaining rapid and accurate solutions to problems in structural engineering discipline [4,5]. This is particularly true in the optimum design of steel structures where the design problem turns out to be a discrete optimization problem when it is formulated according to design codes used in practice.

In many practical engineering design problems, design variables may consist of continuous or discrete variables. In structural optimization problems, the design variables are functions of the cross sections of the members and they are often chosen from a limited set of available values. For example, steel structural members are chosen from standard steel profiles in the market, structural timber members are provided in certain sizes, and reinforced concrete members are usually designed and constructed with discrete dimensional increments. Design optimization of reinforced concrete (RC) structures is more challenging than that of steel structures because of the complexity associated with reinforcement design. Also, only one material is considered for the optimization problems of steel structures and the structural cost is directly proportional to its weight in general. But in the case of the optimum design of concrete structures, three different cost components due to concrete, steel and formwork are to be considered and the overall cost of the structure is affected from any slight variation in the quantity of these components. Therefore, the optimization problem of concrete structures becomes the selection of a combination of appropriate values of design variables to make the total cost component the minimum.

In the literature, there are a number of studies on optimization of RC members and frames. Practical applications of traditional optimization methods are not suitable for optimum design of RC

* Corresponding author. Tel.: +973 36089735.
E-mail addresses: aakin@yahoo.com (A. Akin), mpsaka@uob.edu.bh (M.P. Saka).

http://dx.doi.org/10.1016/j.compstruc.2014.10.003
0045-7949/

frames and these algorithms require additional modifications to fit the discrete nature of structural design variables. Choi and Kwak [6] haves suggested more practical discrete optimization techniques. They used direct search method to select appropriate design sections from some pre-determined discrete member sections for the cost optimization of rectangular beams and columns of RC frames based on the ACI and Korean codes. Balling and Yao used the simulated annealing method which is one of the metaheuristic algorithm to optimize three-dimensional reinforced concrete frames [7]. Discrete variables as well as limits on the number of reinforcing bars and their topological arrangements are considered in their study. Rajeev and Krishnamoorthy [8] applied a simple genetic algorithm to the cost optimization of two-dimensional RC frames. The detailing of reinforcement is considered as a design variable in addition to cross-section dimensions. The allowable combinations of reinforcement bars for columns and beams were tabulated. Camp et al. [9] used genetic algorithms (GAs) by constructing a database for beams and columns which contains the sectional dimensions and the reinforcement data in the practical range to optimize for optimum design of plane frames. Lee and Ahn [10] used to the genetic algorithms to optimize reinforced concrete plane frames subject to gravity loads and lateral loads. In their study, the constructing data sets, which contain a finite number of sectional properties of beams and columns in a practical range removed the difficulties in finding optimum sections from a semi-infinite set of member sizes and reinforcement arrangements. Kwak and Kim [11] studied on optimum design of RC plane frames based on pre-determined section database. In their study, pre-determined section databases of RC columns and beams are constructed and arranged in order of resisting capacity and optimum solutions are obtained using direct search method. They also used genetic algorithms for similar optimization problems [12]. Govindaraj and Ramasamy [13] used genetic algorithms for optimum detailed design for RC frames based on Indian Standard specifications. The dimensions and reinforcement arrangement of column, and the dimensions of beam members alone are considered as a design variables and the detailing of reinforcements in the beam members is carried out as a sub-level optimization problem. The modular sizes of members, available standard reinforcement bar diameters, spacing requirements of reinforcing bars, architectural requirements on member sizes and other practical requirements are arranged in order to obtain for the optimum designs to be directly constructible without any further modifications.

In the studies available in the literature the shear design calculations of concrete members are not considered and the cost of shear reinforcement (ties) is not taken into consideration in the total cost of the frame. Only the simple constraints such as capacity and regulations for flexural reinforcement are included. The detailing of the reinforcement bars is oversimplified and the development length of bars is not considered in the cost calculations. In some of these studies, the lateral loading on the frame is considered; however, the values of the lateral loads are taken as a constant even though the value of lateral loads change with the weight of the structure subject to seismic specifications. Akin and Saka [14] presented optimum design algorithm based on harmony search method for the detailed design of special seismic moment reinforced concrete plane frames considering provisions of ACI 318-05 [15] and ASCE 7-05 [16]. The design algorithm presented in this study considers all required code provisions and obtains the optimum solution by using harmony search algorithm for reinforced concrete frames which is ready for practical design application.

In this study, the algorithm is extended to cover the optimum design of large size reinforced concrete frames. The paper is arranged as follows. In Section 2, the modeling of the detailed optimum design problem is explained; the objective function, the design variables and the constraints derived from design provisions of ACI 318-05 are described. In Section 3, the harmony search algorithm is introduced and the optimum design process of reinforced concrete frames based on the harmony search algorithm is presented. In Section 4, illustrative examples are provided to demonstrate the efficiency and the performance of the algorithm presented in this study. In Section 5, the summary and conclusions are provided.

2. Modeling of optimum detailing design problem of reinforced concrete plane frames

In this study, harmony search method is used to obtain the optimum detailed design for reinforced concrete special seismic moment frames. Reinforced concrete special moment frames are used as part of seismic force-resisting systems in buildings that are designed to resist earthquakes. Beams, columns, and joints in moment frames are proportioned and detailed to resist flexural, axial, and shearing actions during an earthquake. RC frames with special proportioning and detailing requirements are capable of resisting strong earthquake shaking without significant loss of stiffness or strength. These moment-resisting frames are called "Special Moment Frames" because of these additional requirements. A new optimum design algorithm is developed for the RC special seismic moment frames and the variable pool constructed to obtain buildable optimum designs. In the design formulation, the objective function is selected as the cost of the RC structure which includes the cost of concrete, reinforcement and formwork. To satisfy uniformity of the structure and to obtain constructible designs, the beam and column members are separated to design groups. The design variables are categorized into two groups and arranged for the beam and column members. For the columns, the section database which includes the dimensions and the reinforcement detailing of column sections is constructed with the most commonly used sections. The design constraints are implemented according to ACI 318-05. The constraints derived from the code are checked to obtain feasible designs. This study not only considers the flexural design constraints, but also the shear design constraints and the seismic design constraints. The development lengths of the reinforcement steel bars are calculated according to the given regulations in the design specifications. The cost of the shear reinforcement and the impact of the development length on the cost are considered. In the design of frames, the matrix displacement method is used for the structural analysis and the load combinations are taken from the ACI code. The self-weight of RC beams is included in the structural analysis and it is updated in each iteration of the optimization process. The lateral seismic forces are calculated according to ASCE 7-05 and it is updated in each iteration according to the selected design weight.

This paper is unique as it is the first application of the harmony search method to the design optimization of RC frames. Additionally, the detailing of the reinforcement in the concrete members, the consideration of the shear design of members, and the derivation of the constraints are handled in more detail in this study. The lateral seismic forces affecting the RC frame are obtained for the site properties according to ASCE 7-05 even though other existing studies do not consider the lateral seismic forces in their design. Also, this study is the sole study about the optimization of *Special Seismic Moment RC Frames*to date.

2.1. Objective function

In structural optimization problems, the objective function is generally described as the weight or total cost of structure. Usually, the weight of structure is used for the optimum design of steel