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Optimal parameters and performance of artificial bee colony algorithm for minimum cost design of reinforced concrete frames

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ABSTRACT

This study investigates the effect of controlling parameters on the performance of an artificial bee colony (ABC) algorithm in the optimum design of reinforced concrete frames under combination loads according to the ACI318-08 building code requirements for structural concrete. The objective function is the total cost of reinforced concrete frames, which consists of concrete cost, reinforcing bars cost, and formwork cost. The cross section of structure, diameter, and number of reinforcing bars are considered as the design variables. The effect of the number of bees, food source quantities, trial limit, and stopping condition on the cost design are studied and presented with statistical results. Three design examples are collected from related literature to evaluating the performance of ABC algorithm. The results demonstrate that the number of trial limits is critical to the quality of food source, while the numbers of bees, food sources, and trial limits impact the obtained optimum solution and usage time. The statistical results reveal that when the food source quantities are lower than the number of bees, ABC algorithm provides high performance for all the design examples.

1. Introduction

Artificial bee colony (ABC) algorithm was first proposed by Karaboga in 2005 [1]; this algorithm imitates the foraging behaviors of a honey bee swarm in nature. It has been widely utilized for solving unconstrained and constrained optimization problems in numerous fields, such as some benchmark functions [2–5], composite functions [6], data clustering [7], job scheduling [8] and numerical optimization [9,10]. In addition, a number of researchers have improved ABC algorithm to obtain a global optimum by using numerous techniques such as the Gbest-guided technique for solving the numerical function problem [11], improved searching function [12,13], quick local search [14], and memory mechanism [15]. Those results demonstrated that ABC and improved ABC algorithms are more efficient and robust than the compared metaheuristic algorithms.

In recent years, the application of ABC algorithm in structural engineering has been investigated by numerous researchers. Sonmez [16,17] applied the ABC algorithm for obtaining the minimum weight of 2D or 3D steel trusses. The results demonstrated ABC algorithm's higher effectiveness with respect to the compared algorithms [18–20]. Ozturk et al. [21] presented the use of ABC algorithm for the optimum design of simply supported reinforced concrete (RC) beams according to ACI318-08 provision [22]. Coello et al. [23] and Chakrabarty [24] demonstrated ABC algorithm's superior performance compared to a simple genetic algorithm. Jahjouh et al. [25] introduced the minimum cost design of RC continuous beams by using the ABC algorithm. In a more recent study, Aydoğdu et al. [26] presented the ABC algorithm in conjunction with Levy flight distribution (LFABC) for scout bee [27] to design 3D steel frames for real-world application as per LRFD-AISC design parameters. The obtained results demonstrated that the LFABC was more robust and efficient than the standard ABC algorithms and other compared algorithms [28].

The performance of ABC algorithm is controlled by the four parameters, namely, number of bees, number of food sources, number of trial limit, and stopping condition. It is challenging to select the appropriate value of these controlling parameters for the minimum cost design of reinforced concrete frames. This study investigates the effect of these controlling parameters on the performance of ABC algorithm in the optimum design of reinforced concrete frames under combination loads according to the building code requirements for structural concrete: ACI318-08 [22]. The data of the three RC frame designs with dissimilar lateral and vertical loads are collected from the research paper of Kaveh and Sabzi [29] to compare the performance of algorithms. The objective function of this study is the total cost of the RC frame. The design

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constraints of ACI318-08 are designated as the penalty functions. The optimal parameters and performance of ABC algorithm are presented with statistical and the optimum solution results.

2. The reinforced concrete frame design constraints

In this research study, the finite element method is used to evaluate the internal forces of a RC frame, which consists of axial and flexural forces. The rectangular cross sections of beams and columns are considered as the pattern of reinforcing bars in Fig. 1. The RC beam is considered to be a singly reinforced beam, in which A_{s1} and A_{s2} denote the resistances of a negative and positive bending moment, respectively (as illustrated in Fig. 1A). The RC column is considered as a short tied reinforced column which the longitudinal reinforcing bars in the column are held in position by separate lateral ties (as illustrated in Fig. 1B). The upper and lower bounds of the design variables in this study are listed in Table 1.

From the engineering perspective, the RC frame optimization problem is to design an economically viable structure that is safe and corresponds to the design code. Therefore, the objective function of this study is the frame cost function as with other similar studies [30–37]; the objective function is expressed in Eq. (1). In conjunction with the objective function, ACI318-08 design standards are taken into consideration from the perspective of security.

$$F = Min \sum_{i=1}^{n} L_i (C_c V_{i,c} + S_c V_{i,s} + W_c V_{i,w}) \tag{1}$$

where F is the total cost of RC frame, L_i is the length of the ith member, C_c is the unit cost of concrete, $V_{i,c}$ is the quantity of concrete, S_c is the unit cost of reinforcing bars, $V_{i,s}$ is the total quantity of reinforcing bars, W_c is the unit cost of formwork, and $V_{i,w}$ is the quantity of formwork. Eq. (1) under the design constraints as follows:

$$K = \{k_1, k_2, k_3, \ldots, k_n\} \leqslant 0 \tag{2}$$

where K is the constraints function and $k_1, k_2, k_3, \ldots, k_n$ are the design constraint of kth. Each constraint is represented by an expression which must evaluate to less than zero.

Apart from satisfying the objective function, the design must conform to the ACI318-08 standard so that it can be used in actual construction. This study also enhances all design constraints in the form of the penalty functions, k_1 to k_{13} defined in the next section.

2.1. Beam formulation and design constraints

To compare the performance of the algorithm with the study by Kaveh and Sabzi [29], in this study, the RC beam is designed to resist only the applied bending moments, while the vertical shearing force and deflection are not considered. The beams generally have width (b) less than height (h), which is expressed in the form of penalty function k_1 as follows:

$$k_1 = \frac{b}{h} - 1 \text{ and } \frac{h}{3b} - 1 \leqslant 0 \text{ or } b < h \text{ and } h \leqslant 3b \tag{3}$$

The bending moment capacity of RC beam (ϕM_n) is defined as

$$\phi M_n = \phi A_s f_y \left(d - \frac{a}{2}\right) \tag{4}$$

where M_n is the nominal bending moment capacity of the RC beam, ϕ is the strength reduction factor for the RC beam which is defined as 0.90, A_s is the total area of reinforcing bars, f_y is the yield strength of reinforcing bars, d is the distance from the edge to the centroid of the reinforcing bars under consideration, and a is the depth of the equivalent rectangular compressive stress block, which can be calculated as follows:

$$a = \frac{A_s f_y}{0.85 f'_c b} \tag{5}$$

The penalty function for evaluating the bending moment capacity is defined as

$$k_2 = \frac{|M_u|}{\phi M_n} - 1 \leqslant 0 \text{ or } \phi M_n > M_u \tag{6}$$

where M_u is the applied ultimate bending moment.

The ACI code defines the minimum amount of reinforcing bars as

$$A_{s,\min} = \frac{1.4}{f_y} bd \tag{7}$$

The maximum amount of reinforcing bars is defined as

$$A_{s,\max} = 0.75(0.85\beta_1)\frac{f'_c}{f_y}\frac{600}{600 + f_y} bd \tag{8}$$

where $A_{s,\min}$ is the minimum allowable total area for reinforcing bars, $A_{s,\max}$ is the maximum allowable total area for reinforcing bars, f'_c is the concrete compressive strength, and β_1 is the factor corresponding to the equivalent depth of rectangular compressive stress block to the neutral axis depth and is defined as

$$\beta_1 = 0.85 \geqslant 0.85 - 0.008(f'_c - 30) \geqslant 0.65 \tag{9}$$

The minimum number of reinforcing bars penalty function is defined as

$$k_3 = \frac{A_{s,\min}}{A_s} - 1 \leqslant 0 \text{ or } A_s \geqslant A_{s,\min} \tag{10}$$

and the maximum reinforcing bars penalty function is defined as

$$k_4 = \frac{A_s}{A_{s,\max}} - 1 \leqslant 0 \text{ or } A_s \leqslant A_{s,\max} \tag{11}$$

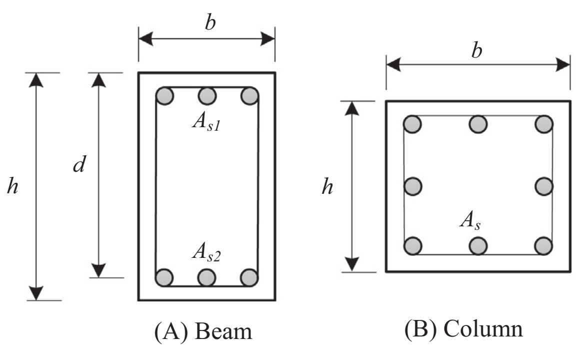
The penalty function for reinforcing bar spacing is defined as

$$k_5 = \frac{40}{\left(\frac{b - n_s d_s - 2d'}{n_s - 1}\right)} - 1 \leqslant 0 \text{ or } 40 \leqslant \left(\frac{b - n_s d_s - 2d'}{n_s - 1}\right) \tag{12}$$

where 40 is the minimum required distance between reinforcing bar, n_s is the number of reinforcing bars in the arrangement, and d_s is the reinforcing bar diameter.

2.2. Column formulation and constraints

The strength capacity of a rectangular tied column takes into consideration the interaction diagram illustrated in Fig. 2. In this study, the RC column is satisfactory when an applied axial force



(A) Beam (B) Column

Fig. 1. Position of reinforcing bars in the cross section.