Optimum Design of Reinforced Concrete Multi-Story Multi-Span Frame Structures under Static Loads

Serdar Ulusoy, Aylin Ece Kayabekir, Gebrail Bekdaş, and Sinan Melih Nigdeli

***Abstract*—The construction economy is one of the major goals of engineers and only an experienced engineer can make an economical design after several trial efforts. Whereas, the optimum design of structures can be found by using metaheuristic methods. Especially, the optimum design of reinforced concrete (RC) structures is challenging since two materials with different price and behavior are used. In that case, the optimization problem is highly non-linear and the developed methods employing harmony search (HS) algorithm is effective to solve the problem in several random stages. As the numerical example, the method was tested for two-story two-span RC frames. The results show that the metaheuristic based methodology is feasible.**

***Index Terms*—Reinforced concrete, frames, optimization, metaheuristic algorithms, harmony search.**

I. Introduction

In the design of reinforced concrete (RC) structures, the dimension of structural elements is defined and the structural analyses are done in order to obtain internal forces. According to these forces, the design requirements are checked and the reinforcement design is done. In this process, there are structural rules according to the design codes. If a rule is not satisfied, the dimension of the elements must be changed and it means that the structural analyses for internal forces must be redone for statically indetermined structures. This process is only for a design. If the optimum design is needed to find as a goal of structural engineers, several trials must be done according to the experience of engineers. Whereas, this process can be automatically done by using iterative optimization techniques and this iterative search process may be shortened by using heuristic approaches.

The feasibility of metaheuristic methods has been proved by proposing optimization approaches for RC structures or members. In the developed studies, the dimensions of structural members are generally optimized for the minimization of the total cost of the structures. The nature inspired metaheuristic methods are used to randomly generate design variables (dimensions) according to the specific rules of the algorithms in order to converge to the best solution quickly without entrapping to a local optimum solution. In this process, the design constraints (defined according to the design codes) are also considered.

Genetic algorithm (GA) is one of the oldest metaheuristic algorithm and uses the stages of the evolution theory like selection, crossover and mutation. Firstly, GA has been employed in the optimum design of beams [1], biaxial columns [2], frames [3]-[6], continuous beams [7], T-shaped beams [8] and various members [9]. Also, GA combined with sequential quadratic programming (SQP) technique for shape optimization [10], simulated annealing (SA) for continuous beams [11] and discretized form of the Hook and Jeeves method for RC flat slab [12]. SA was employed for multi objective optimization of RC frames by Paya et al. [13]. Perea et al. developed a hybrid method combining four methods like random walk, the descent local search, the threshold accepting and SA for optimum design of RC bridges [14].

The minimum embedded CO_2 emission is also an objective in the optimization of RC members. By using SA [15] and Big Bang-Big Crunch (BB-BC) [16], two different methodologies aiming for the CO_2 emission of RC members were developed.

The optimum design of retaining walls is also an optimum exercise and RC retaining walls have been an interest for metaheuristic algorithm by considering both geotechnical and structural limit states as design constraints. Some of the employed algorithms for RC retaining walls are SA [17], [18], BB-BC [19], Harmony Search (HS) [20] and Charged System Search (CSS) [21].

HS; the music inspired metaheuristic algorithm is also a popular one for optimum RC member design. The optimized RC members by employing HS are continuous beams [22], frames [23], T-shaped beam [24] and retaining walls [20].

In the present study, a modified HS proposal is presented for optimum design of RC frames including the detailed design of reinforcements. The optimization is done for static loading and the rules of ACI 318- Building Code Requirements for Structural Concrete [25].

II. Methodology

Harmony Search (HS) algorithm was developed by Geem et al. [26] formulized the music performance of musicians which the best harmony is searched. Recently, HS has been employed in several structural engineering optimization problems such as cellular beams [27], trusses [28, 29], tuned mass dampers [30]-[32], structural frames [33], selection of scaled ground motion records [34], base isolation systems [35] and RC member mentioned in the introduction [20],

Manuscript received November 6, 2017; revised May 1, 2018.

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DOI: 10.7763/IJET.2018.V10.1092

[22]-[24].

In the optimum design of RC frames, different types of structural member (column and beams) with different design constraints (i.e. slenderness for column, reinforcement below balanced strains for beam) are in progress. For that reason, HS is modified with additional random stages, as seen in Fig. 1. Also, the local search part of the algorithm is modified since discrete variables are used in the practical design of RC members. Only fixed dimensions can be constructed in a construction yard. Also, reinforcements are produced in constant sizes.

In classical HS search, two optimization stages exist. After the randomly generation of initial values of design variables within a user defined range, the initial harmony memory matrix (HMM) is constructed. HMM is updated by generating new solutions according to the rules of HS. Musician can play new harmonies or they can also play favorite songs with small differences. Similar to this, new solutions from the whole range is generated in global search. As the local search, a new solution is searched around the existing ones with a possibility called harmony memory consideration rate (HMCR). At the end of all iterations, HMM including solutions as many as harmony memory size (HMS) is updated if a new solution is better than the worst ones in mean of the objective function. The objective function (OF) of the present study is the total cost to minimize as seen in (1).

$$OF = \sum_{i=1}^{n} \left(C_e\right)_i \quad \text{n:number of elements.} \qquad (1)$$

The cost of elements (C_c) are as defined in (2).

$$C_e = (A_g - A_{st})l_e C_c + (A_{st} + \frac{A_v}{s} u_{st})l_e \gamma_s C_s \qquad (2)$$

In (2), A_g, A_{st}, A_v, u_{st}, C_c, C_s, l_e and γ_s represents the area of cross section, the area of longitudinal reinforcement, the area of shear reinforcements spacing s, the length of shear reinforcements, the material cost of the concrete per m^3, the material cost of per ton, the length of element and specific gravity of steel, respectively. All design constants are shown in Table I.

The local search is modified for the problem and the solution ranges are updated. The lower or upper bound of the ranges remains the same, but the other bound is changed with an existing solutions for an iteration.

III. Numerical Example

The two story two span frame model shown in Fig. 2 is optimized. The beams are loaded with trapezoidal distributed loads. The iterative analyses are done for maximum 20000 iterations and the total cost is penalized with 10^6 $ if the design constraints are violated.

D and L represent the dead and live loads, respectively. In optimization, the unfavorable loading of live loads is also considered. The ratio of *a*/*l* is ¼ and *a* is the length of triangular loading and *l* is the total length of loading distance.

The design constants are defined in Table I with the numerical values and the optimum results are presented in Table II and III for columns and beams, respectively. In optimization, the distances are assigned to the values which are the multiples of 50mm. The reinforcements are searched with 2mm increments. LJ and RJ represent the left and right joints the elements.

TABLE I. Design Constants and Ranges of Design Variables

Definition	Symbol	Unit	Value
Range of web width	b_w	mm	250-400
Range of height	h	mm	300-600
Clear cover	c_c	mm	30
Range of reinforcement	ϕ	mm	16-30
Range of shear reinforcement	ϕ_v	mm	8-14
Max. aggregate diameter	D_{max}	mm	16
Yield strength of steel	f_y	MPa	420
Comp. strength of concrete	f'_c	MPa	25
Elasticity modulus of steel	E_s	MPa	200000
Specific gravity of steel	γ_s	t/m3	7.86
Specific gravity of concrete	γ_c	t/m3	2.5
Cost of the concrete per m3	C_c	$	40
Cost of the steel per ton	C_s	$	400

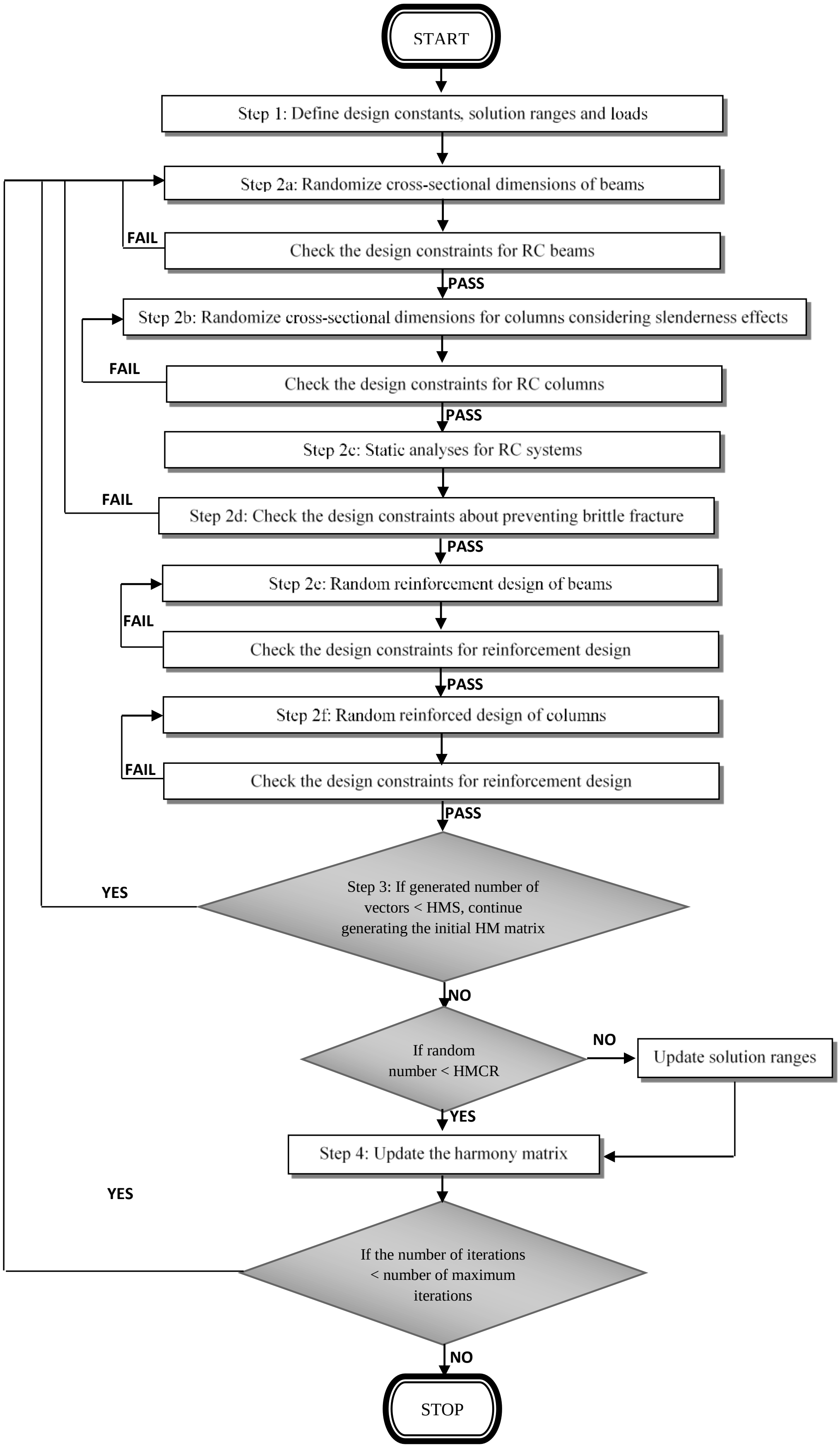

Fig. 1. Flowchart of methodology

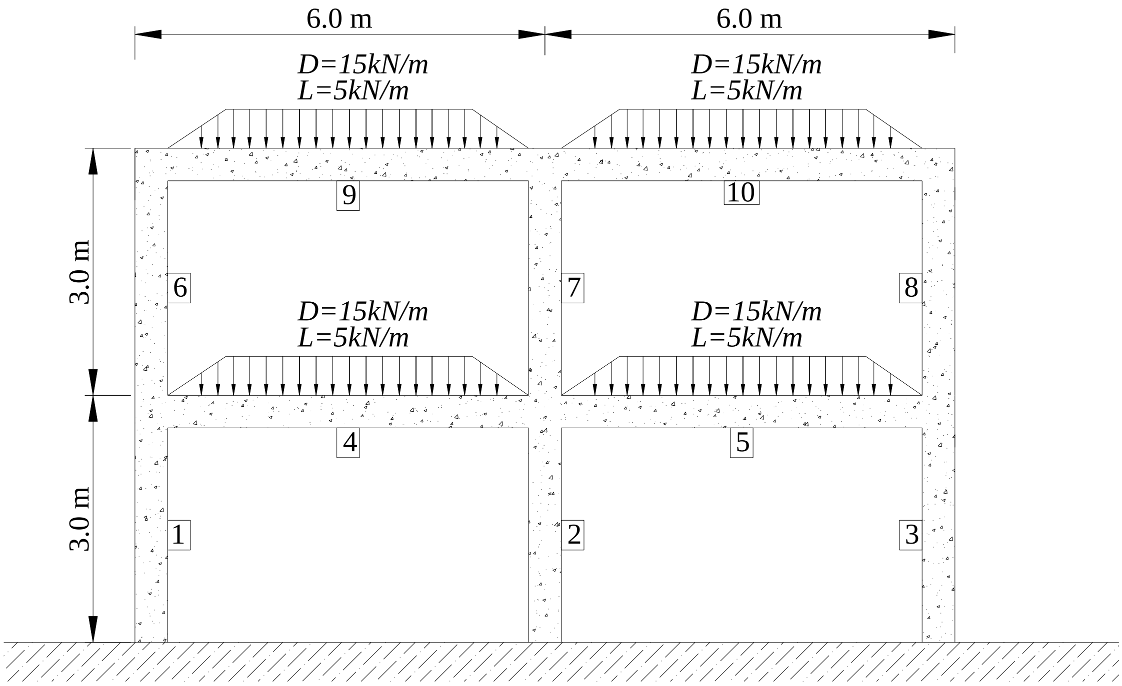

Fig. 2. Model of the numerical example.

TABLE II: OPTIMUM DESIGN OF COLUMNS

Element Number	b_w (mm)	h (mm)	Bars in each face	Shear reinforcement diameter/distance (mm)
1	250	300	2Φ10+ 2Φ12	Φ8/120
2	250	300	2Φ10+ 2Φ12	Φ8/120
3	250	300	2Φ10+ 2Φ12	Φ8/120
6	250	300	2Φ10+ 2Φ12	Φ8/120
7	250	300	2Φ10+ 2Φ12	Φ8/120
8	250	300	2Φ10+ 2Φ12	Φ8/120

TABLE III: OPTIMUM DESIGN OF BEAMS

Element Number	b_w (mm)	h (mm)	Bars in comp. section	Bars in tensile section	Shear reinforcement diameter/distance (mm)
LJ4			1Φ16+1Φ22	2Φ26	
4	250	300	2Φ12	1Φ14+1Φ24	Φ8/120
RJ4-LJ5			2Φ10+3Φ14	1Φ30+1Φ26	
5	250	300	2Φ12	4Φ14	Φ8/120
RJ5			1Φ16+1Φ20	1Φ22+1Φ28	
LJ9			1Φ14+ 1Φ18	1Φ14+2Φ20	
9	250	300	2Φ12	1Φ14+1Φ26	Φ8/120
RJ9-LJ10			1Φ14+2Φ18	1Φ20+1Φ24+1Φ26	
10	250	300	2Φ12	3Φ14+1Φ16	Φ8/120
LJ10			1Φ12+ 1Φ20	1Φ14+1Φ18+1Φ22	

IV. CONCLUSION

The proposed methodology is a feasible method for the cost optimization of RC frames. At the end of the optimization process, the optimum cost is 300.6193 \$. The user defined ranges are reasonable values for the design of RC frame and an engineer can choose a dimension from these values. If this situation is considered, every iteration of the proposed method may be a manual design of an engineer. The total costs of five iterations are 500.2729 \$, 467.1681 \$, 457.1243 \$, 454.6946 \$ and 445.6569 \$. In that case, the optimum design is useful to reduce the total cost by 39.91%. In the future, the optimum design of space frame structures with the other metaheuristic algorithms will be investigated.

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