11th World Congress on Computational Mechanics (WCCM XI)
5th European Conference on Computational Mechanics (ECCM V)
6th European Conference on Computational Fluid Dynamics (ECFD VI)
E. Oñate, J. Oliver and A. Huerta (Eds)

OPTIMIZATION OF RC FRAME STRUCTURES SUBJECTED TO STATIC LOADING

GEBRAİL BEKDAŞ [*] AND SİNAN MELİH NİGDELİ [†]

[*] Department of Civil Engineering, Faculty of Engineering
Istanbul University
Avcılar, 34320 Istanbul, Turkey
e-mail: bekdas@istanbul.edu.tr

[†] Department of Civil Engineering, Faculty of Engineering
Istanbul University
Avcılar, 34320 Istanbul, Turkey
e-mail: melihnig@istanbul.edu.tr

Key Words: *Harmony Search, Optimization, Reinforced Concrete, Cost Optimization, ACI-318.*

Abstract. Generally, the initial design of reinforced concrete cross-sections are assumed by a designer and amount of reinforcements are calculated. Economy, which is the main goal of engineers, is only provided if the engineer is expert. Optimization techniques can be employed to find best design variable. In this study, reinforced concrete (RC) frame structures are optimally designed by using harmony search algorithm. The design constraints given in ACI-318: Building Code Requirements for Structural Concrete are taken into consideration. Optimum cross-sections and detailed reinforcements of a single-bay single-story frame structure are found for minimum material cost of the structure. The results showed that the proposed method is effective to find optimum design variable with minimum costs.

1 INTRODUCTION

In the design of reinforced concrete (RC) structures, procedure of analyses and constraints given in several design codes are considered by the design engineers. Cross sectional dimensions are assumed according to experience of the engineer and requirements reinforcements are calculated. The area of the reinforcements is never exactly placed in the corresponding section because of reinforcement bars with constant diameter sizes. Also, reinforcements with special sizes (reinforcements providing the exact required area) cannot be used because of economy in production and practice in construction. Since RC is a composite of steel and concrete, the cost of the design cannot be foreseen. Although several experienced engineers know approximate cost and economical design, prices of the concrete and steel may show great differences according to region of the construction. For that reason, optimization of RC frames is an important subject.

Optimum design of several RC members has been proposed by several researchers. Since the optimum cross sectional dimensions and reinforcements are searched for an objective function such as weight and cost, metaheuristic methods have been used in the proposal of researchers. Generally, these approaches were compared with the assumed design of the engineer like Coello et al. did when genetic algorithm (GA) was employed to find optimum design of RC beams [1]. Also, GA has been used in the development of several methodologies such as optimization of RC biaxial columns [2], RC frames [3-6], continuous beams [7], T-shaped beams [8] and several members [9]. Genetic algorithm has been also merged with other methods. Rath et al. used GA for the cost optimization and sequential quadratic programming (SQP) technique for shape optimization [10]. In the optimum design of continuous beams GA is employed together with simulated annealing (SA) method [11]. A hybrid optimization algorithm was developed by Sahab et al. for RC flat slab building. The developed method is the combination of GA and discretized form of the Hook and Jeeves method [12]. Also, a multi objective optimization approach for RC frames employing SA was proposed by Paya et al. [13]. For the optimum design of RC bridges, four different methods (heuristic methods: random walk and the descent local search, metaheuristic methods: the threshold accepting and the simulated annealing) were used together by Perea et al. [14]. In addition to total cost, minimum embedded CO2 emission was also considered in the optimization objective by employing SA [15] and big bang-big crunch [16]. Several metaheuristic algorithms have been employed in the optimum design of RC retaining walls [17-21]. Music inspired metaheuristic algorithm, harmony search algorithm have been used in production of optimization methodologies for RC continuous beams [22], RC frames [23] and T-shaped RC beams [24]. Also, several approaches for optimum design of RC members have been done in several studies [25-31].

In this study, a single-story single-span RC frame is optimized by using an optimization methodology. The methodology considers ACI318 [32] design code rules detailed reinforcement design is done. Harmony search algorithm was employed together with additional random search iterations.

2 METHODOLOGY

Harmony search algorithm developed by Geem et al. [33] by observing musical performances is a metaheuristic algorithm using various disciplines including structural engineering [20, 22-24, 34-45].

In methodology, RC frame is defined with boundary conditions of joints and coordinates of the elements. In order to search the optimum parameters, ranges for breadth (b_w), height (h), reinforcement and shear reinforcement are defined. Loading conditions (intensity and shape) are defined for live (L) and dead (D) loads. The shape of the distributed load can be defined as equally distributed, triangular distributed or trapezium distributed. In addition to the design variables, design constants such as clear cover (c_c), maximum aggregate diameter (D_{max}), compressive strength of concrete (f_c'), yield strength of steel (f_y), elasticity modulus of steel (E_s) and specific gravity of steel (γ_s), specific gravity of concrete (γ_c), cost of concrete per m^3 (C_c), cost of the steel per ton (C_s) are entered to the program. After the ranges and design constant are defined, the initial harmony memory (HM) matrix is constructed. This matrix contains harmony vectors (HVs). These vectors contain randomly assigned design variables and the number of these vectors defined with the parameter harmony memory size (HMS).

The cross sectional dimensions are assigned with the values which are multiple of 50 mm for practical construction. After the cross sectional dimension are randomized, internal forces are calculated according to static loads. Then, ductile behavior conditions are checked for the RC elements. If the ductility conditions are provided, the required reinforcement is calculated by using an assumed value of depth of the element. The depth of the beam is updated after orientation of reinforcement bars is provided. In this stage, longitudinal reinforcement bars are also randomized in order to find closest area to calculate. An additional random search is done for this randomization to find optimum values quickly and generally for all structural members. The program has ability to place reinforcement in two lines or in compressive section (for beams, columns are symmetric) if needed. If a suitable solution cannot be found after several iterations, the cost of the frame is assigned with penalized cost. In optimization, slenderness of RC columns are also considered according to ACI 318. The best suitable shear reinforcements are also chosen within the range. After the initial HM matrix is constructed, a new harmony vector is generated. Differently from classical HS approach, with a possibility defined with the parameter; harmony memory considering rate (HMCR), solution range of cross-section dimensions are updated according to best existing harmony vector with minimum cost. The cost of the frame is constructed for all harmony vectors and minimization of this cost is the objective of the optimization. This procedure is repeated for several iterations.

3 NUMERICAL EXAMPLES

The single-span single-story RC frame is given in Fig. 1 with loading conditions and length of the structural members. Also, the elements are numbered. The beam is loaded with 15 kN/m dead load (D) and 5 kN/m live load (L). Design constant such as clear cover (c_c), maximum aggregate diameter (D_{max}), yield strength of steel (f_y), compressive strength of concrete (f_c'), elasticity modulus of steel (E_s), specific gravity of steel (γ_s), specific gravity of concrete (γ_c), cost of the concrete per m^3 (C_c), cost of the steel per ton (C_s) are taken as 30 mm, 16 mm, 420 MPa, 25 MPa, 200000 MPa, 7.86 t/m^3, 2.5 t/m^3, 40 $ and 400 $, respectively. Ranges of web width (b_w), height (h), longitudinal reinforcement (ϕ) and shear reinforcement (ϕ_v) are taken between 250 mm-400 mm, 300 mm-600 mm, 16 mm-30 mm and 8 mm-14 mm, respectively.

The optimum results for the columns and beam are given in Table 1 and Table 2, respectively. The total cost of the design is 81.20 $.

Table 1: Optimum results of columns

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

Table 2: Optimum results of beam

Element Number	b_w (mm)	h (mm)	Bars in comp. section	Bars in tensile section	Shear reinforcement diameter/distance (mm)
Joint	250	300	1Φ26+ 1Φ14+1Φ12	2Φ16	Φ8/120
Span	250	300	1Φ22+ 1Φ18+1Φ12	2Φ12	

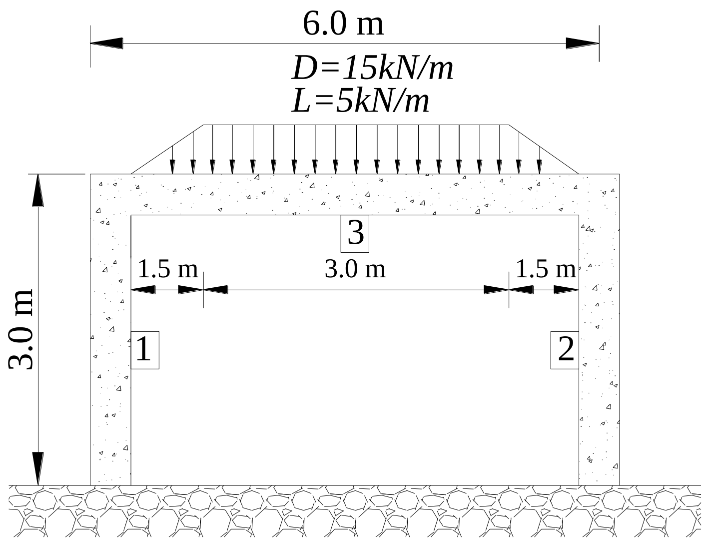

Figure 1: Single-bay single-story frame structures

4 CONCLUSIONS

By using proposed method, the optimum design variables can be found for the selected design constants and material costs. In Fig. 2, the optimum results after several iterations are given.

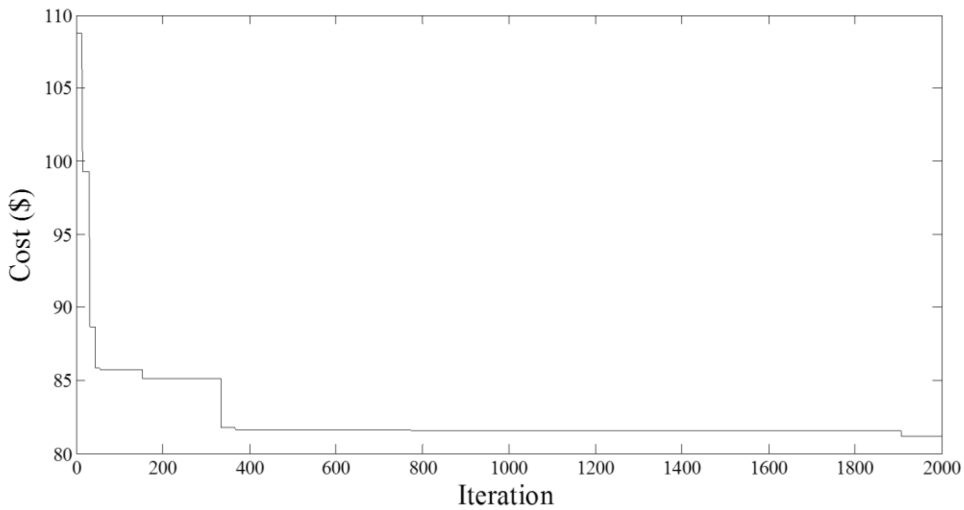

Figure 2: Total cost vs. iteration number

The first cost of the random design is 108.76 $ and this value is updated to 99.23 $. If an engineer design the RC frame by assuming design variables, the cost of the design may be 108.76 $ or 99.23 $ if engineer is experienced. Thus, the optimization method is effective to find optimum results with cost which are up to 25% less of the conventional design.

REFERENCES

[1] Coello C.C., Hernandez, F.S., Farrera, F.A. Optimal Design of Reinforced Concrete Beams Using Genetic Algorithms. *Expert Syst. Appl.* (1997) **12**: 101-108.

[2] Rafiq M.Y., Southcombe C. Genetic algorithms in optimal design and detailing of reinforced concrete biaxial columns supported by a declarative approach for capacity checking. *Comput. Struct.* (1998) **69**: 443-457.

[3] Rajeev S., Krishnamoorthy C.S. Genetic Algorithm–Based Methodology for Design Optimization of Reinforced Concrete Frames. *Comput-Aided Civ. Inf.* (1998) **13**: 63–74.

[4] Lee C., Ahn J. Flexural Design of Reinforced Concrete Frames by Genetic Algorithm. *J Struct. Eng.-ASCE* (2003) **129(6)**: 762–774.

[5] Camp C.V., Pezeshk S., Hansson H. Flexural Design of Reinforced Concrete Frames Using a Genetic Algorithm. *J Struct. Eng.-ASCE* (2003) **129**: 105-11.

[6] Govindaraj V., Ramasamy J.V. Optimum detailed design of reinforced concrete continuous beams using Genetic Algorithms. *Comput. Struct.* (2005) **84**: 34–48.

[7] Govindaraj V., Ramasamy J.V. Optimum detailed design of reinforced concrete frames using genetic algorithms. *Eng. Optimiz.* (2007) **39(4)**: 471–494.

[8] Fedghouche F., Tiliouine B. Minimum cost design of reinforced concrete T-beams at ultimate loads using Eurocode2. *Eng. Struct.* (2012) **42**: 43–50.

[9] Koumousis V.K., Arsenis S.J. Genetic Algorithms in Optimal Detailed Design of Reinforced Concrete Members. *Comput-Aided Civ. Inf.* (1998) **13**: 43-52.

[10] Rath D.P., Ahlawat A.S., Ramaswamy A. Shape Optimization of RC Flexural Members. *J Struct. Eng.-ASCE* (1999) **125**: 1439-1446.

[11] Leps M., Sejnoha M. New approach to optimization of reinforced concrete beams. *Comput. Struct.* (2003) **81**: 1957–1966.

[12] Sahab M.G., Ashour A.F., Toropov V.V. Cost optimisation of reinforced concrete flat slab buildings. *Eng. Struct.* (2005) **27**: 313–322.

[13] Paya I., Yepes V., Gonzalez-Vidosa F., Hospitaler A. Multiobjective Optimization of Concrete Frames by Simulated Annealing. *Comput-Aided Civ. Inf.* (2008) **23**: 596–610.

[14] Perea C., Alcala J., Yepes V., Gonzalez-Vidosa F., Hospitaler A. Design of reinforced concrete bridge frames by heuristic optimization. *Adv. Eng. Softw.* (2008) **39**: 676–688

[15] Paya-Zaforteza I., Yepes V., Hospitaler A., Gonzalez-Vidosa F. CO2-optimization of reinforced concrete frames by simulated annealing. *Eng. Struct.* (2009) **31**: 1501-1508.

[16] Camp C.V., Huq F. CO_2 and cost optimization of reinforced concrete frames using a big bang-big crunch algorithm. Eng. Struct. (2013) **48**: 363–372.

[17] Ceranic B., Freyer C., Baines R.W. An application of simulated annealing to the optimum design reinfroced concrete retaining structure. *Comput. Struct.* (2001) **79**: 1569-1581.

[18] Yepes V., Alcala J., Perea C., Gonzalez-Vidosa F. A parametric study of optimum earth-retaining walls by simulated annealing. *Eng. Struct.* (2008) **30**: 821–830.

[19] Camp C.V., Akin A. Design of Retaining Walls Using Big Bang–Big Crunch Optimization. *J Struct. Eng.-ASCE* (2012) **138(3)**: 438–448.

[20] Kaveh A., Abadi A.S.M. Harmony search based algorithms for the optimum cost design of reinforced concrete cantilever retaining walls. *Int. J Civil Eng.* (2011) **9(1)**: 1-8.

[21] Talatahari S., Sheikholeslami R., Shadfaran M., Pourbaba M. Optimum Design of Gravity Retaining Walls Using Charged System Search Algorithm. *Mathematical Problems in Engineering* (2012) Vol. 2012, pp. 1-10.

[22] Akin A., Saka M.P. Optimum Detailed Design of Reinforced Concrete Continuous Beams using the Harmony Search Algorithm, In: B.H.V. Topping, J.M. Adam, F.J. Pallarés, R. Bru, M.L. Romero, (Editors), Proceedings of the Tenth International Conference on Computational Structures Technology, Civil-Comp Press, Stirlingshire, UK, (2010) Paper 131, doi:10.4203/ccp.93.131

[23] Akin A., Saka M.P. Optimum Detailing Design of Reinforced Concrete Plane Frames to ACI 318-05 using the Harmony Search Algorithm, in B.H.V. Topping, (Editor), Proceedings of the Eleventh International Conference on Computational Structures Technology, Civil-Comp Press, Stirlingshire UK (2012) Paper 72, doi:10.4203/ccp.99.72

[24] Bekdaş G., Nigdeli S.M. Cost Optimization of T-shaped Reinforced Concrete Beams under Flexural Effect According to ACI 318. In: 3rd European Conference of Civil Engineering, December 2-4 2012, Paris, France.

[25] Ferreira C.C., Barros M.H.F.M., Barros A.F.M. Optimal design of reinforced concrete T-sections in bending. *Eng. Struct.* (2003) **25**: 951-964.

[26] Balling J.R., Yao X. Optimization of Reinforced Concrete Frames. *J Struct. Eng.-ASCE* (1997) **123**: 193-202.

[27] Barros M.H.F.M., Martins R.A.F., Barros A.F.M. Cost optimization of singly and doubly reinforced concrete beams with EC2-2001. *Struct. Multidiscip. O.* (2005) **30**: 236–242.

[28] Guerra A., Kiousis P.D. Design optimization of reinforced concrete structures. *Comput. Concrete.* (2006) **3**: 313–334.

[29] Gil-Martin L.M., Hernandez-Montes E., Aschheim M. Optimal reinforcement of RC columns for biaxial bending. *Mater. Struct.* (2010) **43**: 1245–1256.

[30] Barros A.F.M., Barros M.H.F.M., Ferreira C.C. Optimal design of rectangular RC sections for ultimate bending strength. *Struct. Multidiscip. O.* (2012) **45**: 845–860.

[31] Kaveh A., Sabzi O. Optimal design of reinforced concrete frames Using big bang-big crunch algorithm. *Int. J Civil Eng.* (2012) **10(3)**: 189-200.

[32] ACI 318M-05, Building code requirements for structural concrete and commentary, American Concrete Institute, 2005.

[33] Geem Z.W., Kim J.H., Loganathan G.V. A new heuristic optimization algorithm: harmony search. *Simulation* (2001) **76**: 60–68.

[34] Erdal F., Dogan E., Saka M.P. Optimum design of cellular beams using harmony search and particle swarm optimizers. *J Constr. Steel Res.* (2011) **67(2)**: 237-247.

[35] Togan V., Daloglu A.T., Karadeniz H. Optimization of trusses under uncertainties with harmony search. *Struc. Eng. Mech.* (2011) **37(5)**: 543-560.

[36] Degertekin S.O. Improved harmony search algorithms for sizing optimization of truss structures. *Comput. Struct.* (2012) **92-93**: 229-241.

[37] Toklu Y.C., Bekdas G., Temur R. Analysis of trusses by total potential optimization method coupled with harmony search. *Struc. Eng. Mech.* (2013) **45(2)**: 183-199.

[38] Gholipour Y., Shahbazi M.M., Behnia A. An improved version of Inverse Distance Weighting metamodel assisted Harmony Search algorithm for truss design optimization. *Lat. Am. J. Solids Stru.* (2013) **10(2)**: 283-300.

[39] Bekdaş G, Nigdeli S.M. Estimating optimum parameters of tuned mass dampers using harmony search, *Eng. Struct.* (2011) **33**: 2716-2723.

[40] Bekdaş G, Nigdeli S.M. Mass Ratio Factor for Optimum Tuned Mass Damper Strategies. International Journal of Mechanical Sciences, (2013) **71**: 68-84.

[41] Nigdeli S.M, Bekdaş G. Optimum Tuned Mass Damper Design for Preventing Brittle Fracture of RC Buildings. *Smart Struct Syst.* (2013) **12**: 137-155.
[42] Kaveh A., Sabzi O. Optimal design of reinforced concrete frames Using big bang-big crunch algorithm. *Int. J Civil Eng.* (2012) **10(3)**: 189-200.
[43] Martini K. Harmony Search Method for Multimodal Size, Shape, and Topology Optimization of Structural Frameworks. *J Struct. Eng.-ASCE* (2011) **137(11)**: 1332-1339.
[44] Kayhan A.H. Selection and Scaling of Ground Motion Records Using Harmony Search. *Teknik Dergi*, (2012) **23(1)**: 5751-5775.
[45] Nigdeli S.M., Bekdaş G., Alhan, C. Optimization of Seismic Isolation Systems via Harmony Search. Eng. Optimiz., DOI:10.1080/0305215X.2013.854352.