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Optimization of T-shaped RC Flexural Members for Different Compressive Strengths of Concrete

G. Bekdas, and S.M. Nigdeli

Abstract— In this study, cost optimization of T-shaped reinforced concrete (RC) beams under flexural effect was investigated for different compressive strengths of concrete. Harmony search (HS) algorithm which is a music inspired metaheuristic algorithm, was employed to find the minimum cost per unit length of the beam elements by searching best suitable cross-section dimensions and amount of the reinforced steel bars. The RC beams were designed according to ACI 318-Building Code Requirements for Structural Concrete. In additional to different compressive strengths of concrete, the optimum values with minimum costs were investigated for different cross-section ranges under various objective flexural moments. According to optimum results, the proposed optimization approach may be a great source for the preliminary design of RC members.

Keywords— Flexural Effect, Harmony Search, Reinforced Concrete Beams, Cost Optimization, ACI 318, T-shaped Beams.

I. INTRODUCTION

OPTIMIZATION is a process in which an objective function is maximized or minimized. In engineering design, especially in civil engineering, the security measures and cost must be taken into account together. Thus, the optimization is one of the vital issues in civil engineering.

In several studies, the optimum cost design of the reinforced concrete (RC) elements has been investigated. Metaheuristic methods such as genetic algorithm (GA) and simulated annealing (SA) have been employed in the most of these studies.

By using a search technique employing genetic algorithm (GA), Coello *et. al.* optimized RC beams [1]. Also, genetic algorithm was employed to find the optimum design of reinforced concrete biaxial columns [2]. The shape optimization of RC flexural members by using GA to optimize the diameter and number of main reinforcement bars was studied by Rath et. al [3]. Camp *et. al.* optimally designed RC flexural frames by using GA [4]. Ferreira *et. al.* studied on the optimal design of T-shaped RC beams according to various design codes [5]. The simulated annealing algorithm was also employed to find optimum values of continuous steel reinforced beams [6]. Cost optimization of singly and doubly RC beams was investigated by Barros *et. al.* [7]. Govindaraj and Ramasamy studied on the detailed optimum design of RC continuous beams using GA. Different groups of reinforcements were considered to find the solution with the optimum cost [8]. Also, Govindaraj and Ramasamy studied on the optimization of RC frames by using GA [9]. The optimum height and area of the reinforcement bars was investigated for RC beams by Barros *et. al.* [10].

In this study, T-shaped RC beam elements under flexural effect were optimized for the minimum cost. Harmony search (HS) algorithm was employed for the optimization process. Optimum design of the beam height and web width for the concrete and diameter and number for reinforcement steel both at compressive and tensile sections were searched according to the modified methodology of HS for RC design procedure according to ACI 318-Building Code Requirements for Structural Concrete [11]. Different cases of the cross sectional areas were investigated for various objective flexural moments and compressive strengths of concrete.

II. HARMONY SEARCH ALGORITHM

Metaheuristic methods have a significant importance on the optimization because of easy implementability to the problem and robustness of results without dealing with complex expressions. HS algorithm is a music inspired metaheuristic algorithm developed by Geem *et. al.* [12].

HS algorithm is inspired from three possible options of the musician. These options are to play any famous part of music, to play something similar to the famous one and to compose new or random notes [13]. This algorithm has been used for optimization of several engineering problems from different disciplines. Examples include tuned mass damper (TMD) optimization [14-20], design of RC elements [21], natural reserve selection problem [22], layout optimization of branched networks [23], component sizing of plug-in hybrid electric vehicle [24], optimal placement and sizing of flexible AC transmission systems (FACTS) [25] and economic load dispatch problems [26].

III. COST OPTIMIZATION OF BEAMS

A program was developed for the HS optimization process and the RC design. The flowchart of the program can be seen in Fig. 1.

G. Bekdas, Department of Civil Engineering, Istanbul University, 34320 Avcilar Istanbul, TR (phone: 90-212-4737070; fax: 90-212-4737176; e-mail: bekdas@istanbul.edu.tr).

S. M. Nigdeli, Department of Civil Engineering, Istanbul University, 34320 Avcilar Istanbul, TR (e-mail: melihnig@istanbul.edu.tr).

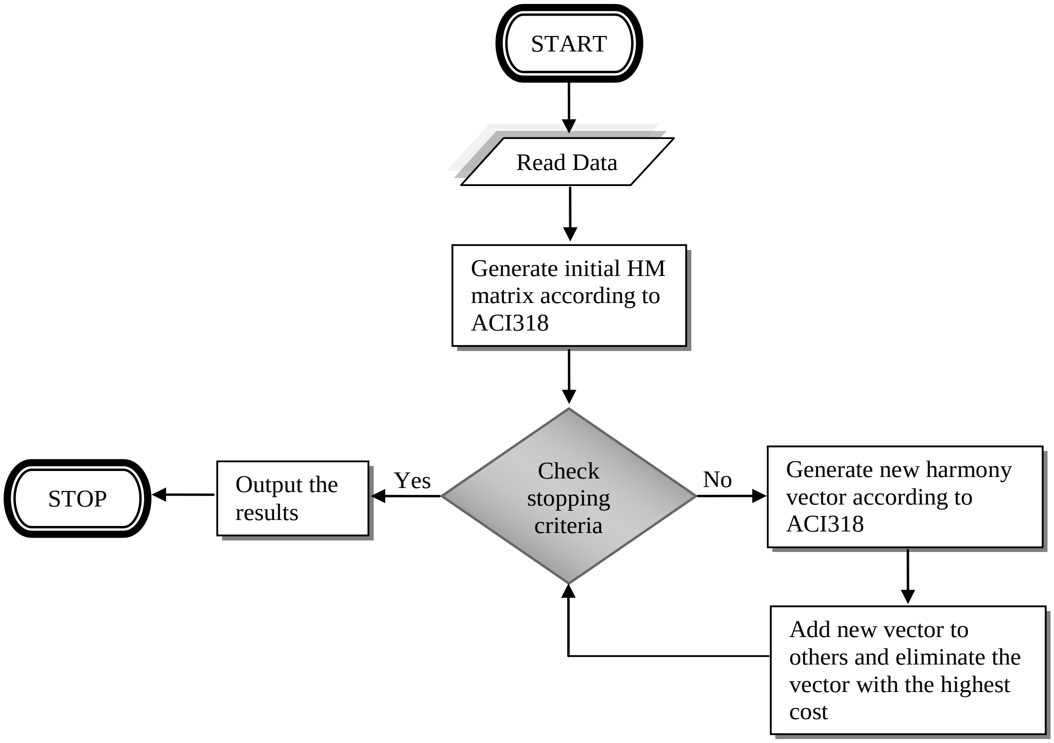

Fig. 1 Flowchart of the program

First, data of the problem must be entered to the program. These data contain the objective flexural moment, width of the compressive face, thickness of the slab, clear cover of reinforcement, the biggest aggregate diameter, the range of the web width and height of the beam, specified compressive strength of concrete, specified yield strength of reinforcement, the diameter of stirrup, the diameter range of the main reinforcement bars and cost of the materials. Also, special HS parameters must be defined in this stage.

Then, initial Harmony Memory (HM) matrix is generated by the vectors as many as Harmony Memory Size (HMS). This vector contains random values of the web width and height of the beam, diameters of the reinforcement bars in tensile and compressive sections with two lines placement and the number of reinforcement bars. These values are chosen according to defined range, ACI 318 and reinforcement bar layout.

The flexural moment capacity and the cost of the beam are calculated according the corresponding vector. Vectors which are not suitable for the flexural moment capacity, reinforcement layout and ACI 318, are eliminated and a new vector is generated until all conditions are satisfied.

After the generation of the initial HM matrix, a new vector according to the rules of the HS is generated. This vector can be generated from the whole range or around an existing vector in HM. The program assigns a value around the existing vectors with the possibility of Harmony Memory Considering Rate (HMCR).

Pitch Adjusting Rate (PAR) is the ratio between the sizes of the ranges taken around the existing values and whole solution domain. The program assigns web width and height with the values divisible to 50 mm for practical application in the construction yard.

The generated new vector is added to HM matrix and the worst one with the highest cost is eliminated. This process is continuing until the stopping criteria are satisfied.

For the stopping criteria, the difference of the web width and height for the different vectors in HM matrix must be smaller or equal to 50 mm. Also, the differences between resultant flexural moments must be lower than 5%.

When the stopping criteria are satisfied, the results with the lowest cost are output.

IV. NUMERICAL EXAMPLE

The optimization process is done for T-shaped beam with 100 mm slab thickness (h_f) and 1000 mm width of compressive face of the beam (b). The cross-section of the beam can be seen in Fig. 2.

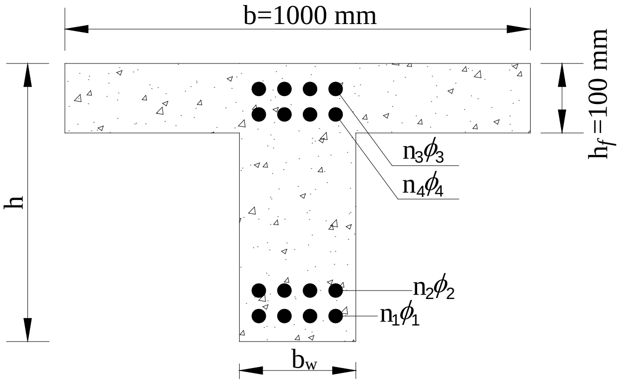

Fig. 2. Cross-section of the beam

Optimization process was repeated for the objective flexural moments between 50 kNm and 500 kNm. The optimization problem was solved for 20 MPa, 25 MPa, 30 MPa, 35 MPa and 40 MPa compressive strength of concrete.

The clear cover of reinforcement, maximum size of aggregate diameter, specified yield strength of reinforcement and diameter of stirrup were taken as 35 mm, 16 mm, 420 MPa and 10 mm, respectively. The diameter range of the main reinforcement bars is 10-30 m. The different cases of range of the web width (b_w) and height (h) of the beam under different flexural moment objectives were investigated. These ranges can be seen in Table I. The HS parameters were taken as 5, 0.5 and 0.2, respectively.

Table I. The ranges for cases

	b_w (mm)		h (mm)	
	Min	Max	Min	Max
CASE 1	250	350	350	500
CASE 2	250	500	350	650
CASE 3	250	600	350	800
CASE 4	250	1000	350	1000

The cost of the reinforcement bars were taken as 400 \$/ton. For different compressive strength of concrete, the cost were taken as 40 \$/m^3, 43 \$/m^3, 46 \$/m^3, 48 \$/m^3 and 51 \$/m^3 for 20 MPa, 25 MPa, 30 MPa, 35 MPa and 40 MPa, respectively. These prices can be entered by the user according the location of the construction.

The optimum design values for all cases and compressive strengths are given in the Appendix.

According to the results, singly reinforced concrete beams are optimum for all objective flexural moments. Because of the 1000 mm width in the compressive section, the usage of steel bars is not needed according to the results. If the design of the RC beam is done for rectangular cross-sections, the doubly reinforced concrete beams may be needed.

For all optimum reinforcement layouts, steel bars in tensile section are positioned in two lines with different diameter size. The area of the different bars in diameter size may be more suitable in order to find the exact required reinforcement steel area. Also, the two line layout is needed for the placement rules to obtain adherence and serviceability.

The clear spacing between reinforcement bars must be longer than the diameter of the bars and 25 mm. In addition to that, the maximum size of coarse aggregate shall be not larger than 3/4 of the minimum clear spacing between steel bars. The upper bound for spacing of the bars is taken as 300 mm.

For example, 3 ϕ30 is the maxi allowed for the placement in a 250 mm web width in a single line. For that reason, the optimum results contain two line designs for the steel bars.

A. 20 MPa compressive strength of concrete

The optimum costs of the flexural member for different objective flexural moments are given in Fig. 3. The costs per unit length are between 7.96 \$/m-20.33 \$/m, 7.96 \$/m-18.14 \$/m, 7.96 \$/m-16.72 \$/m and 7.96 \$/m-16.91 \$/m for cases 1, 2, 3 and 4, respectively. Since the cost of the concrete is lower than steel bars, the optimum cost is more economic for the cases with big dimension ranges. This situation can be seen for the results of the big flexural moment values, but the cases with small dimension ranges can be more suitable for small flexural moments. For 50 kNm moment objective, the optimum results are same for all cases. Hereby, the effectiveness of the approach is proved.

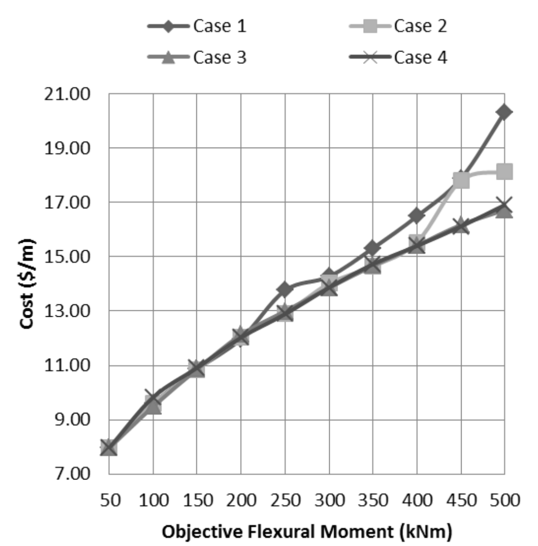

Fig. 3. Optimum Cost (20 MPa)

The ratio (ρ_w) of longitudinal tension reinforcements (A_s) to effective concrete area ($b_w d$) can be seen in Fig. 4. For Case 1, the reinforcement ratio increases for the big flexural moments because the optimum dimension results at the upper limit and reinforcement steel is needed to reach the objective flexural moment.

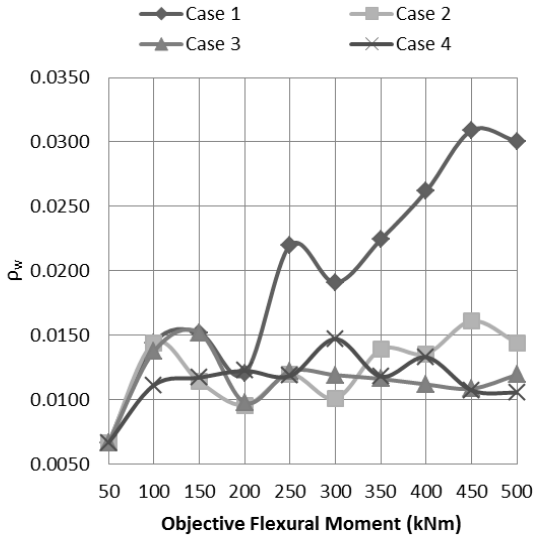

Fig. 4. Optimum ρ_w (20 MPa)

Optimum reinforcement ratios are fluctuant because practicality of construction was also taken into account in the optimization by checking placement of reinforcement bars and using dimensions divisible to 50 mm.

B. 25 MPa compressive strength of concrete

For 25 MPa compressive strength of concrete, the behavior is observed with 20 MPa compressive strength of concrete. Although the cost of the concrete per unit area is 3$ expensive than the concrete with 20 MPa strength, it is still cheaper than steel. Thus, the results are more economical than 20 MPa case for big flexural moments while the cost is higher for low flexural moments. The graphs of the optimum cost and ρ_w can be seen in Fig. 5 and 6, respectively.

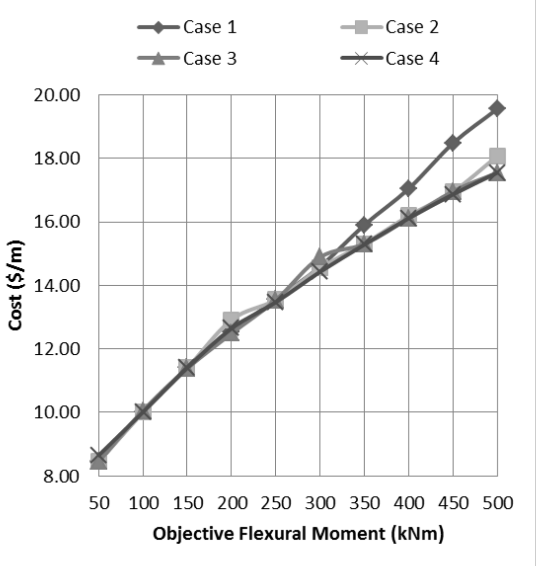

Fig. 5. Optimum Cost (25 MPa)

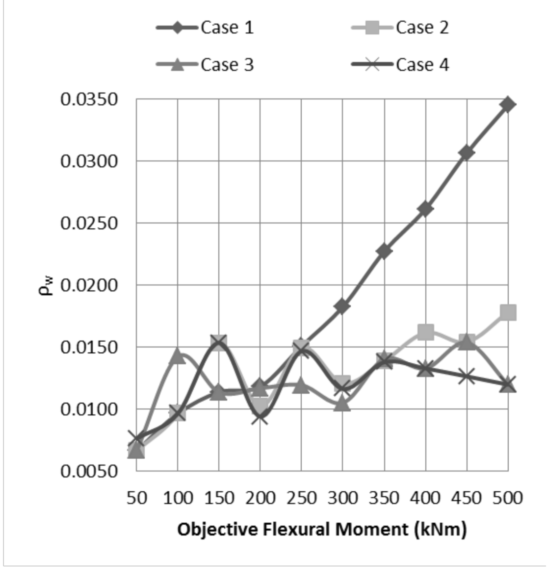

Fig. 6. Optimum ρ_w (25 MPa)

C. 30 MPa compressive strength of concrete

According to ACI 318, factor relating depth of equivalent rectangular compressive stress block to neutral axis depth (β_1) is 0.85 for the compressive strengths between 17-28 MPa. For every 7 MPa increase of compressive strength, β_1 is reduced with 0.05. For that reason, β_1 is 0.836 for 30 MPa, while it is taken as 0.85 for 20 MPa and 25 MPa. This factor, which represents the increase of brittle response with the increase of compressive strength, may reduce the flexural moment capacity. In additional to this factor, a 5 MPa increase of strength will be more effective on flexural moment, but the increase of the cost prevents to find more economical results than 25 MPa strength. Fig. 7 and 8 show the optimum cost and ρ_w, respectively for 30 MPa strength.

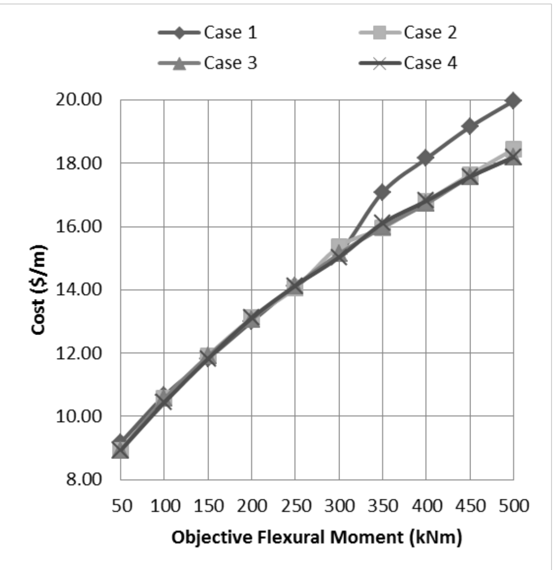

Fig. 7. Optimum Cost (30 MPa)

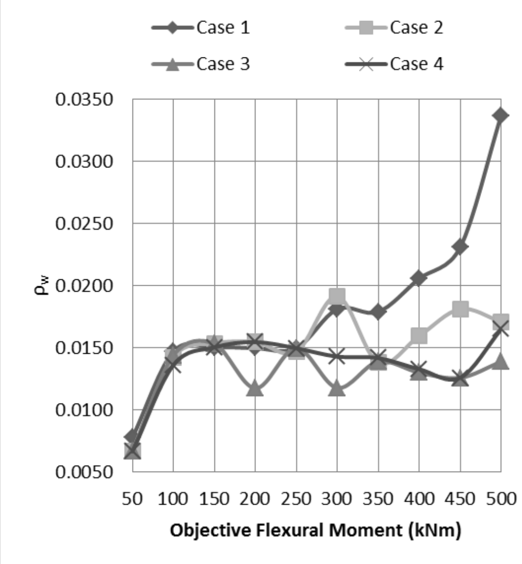

Fig. 8. Optimum ρ_w (30 MPa)

D. 35 MPa and 40 MPa compressive strength of concrete

According to the results, the comments for 30 MPa strength are also suitable for 35 MPa and 40 MPa compressive strengths. The β_1 factor was taken as 0.8 and 0.764 for 35 MPa and 40 MPa, respectively. The optimum cost and ρ_w graphs are given between Fig. 9-12.

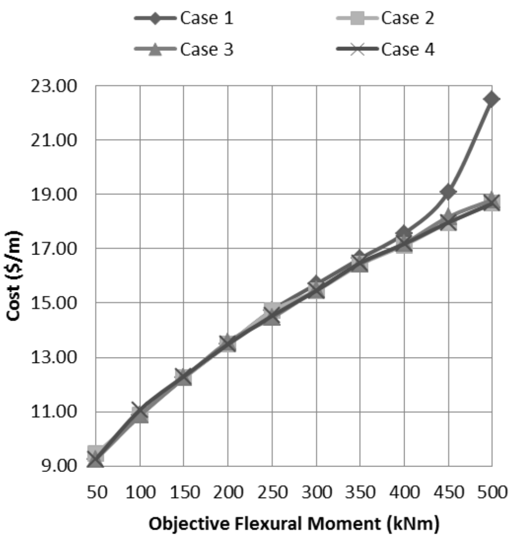

Fig. 9. Optimum Cost (35 MPa)

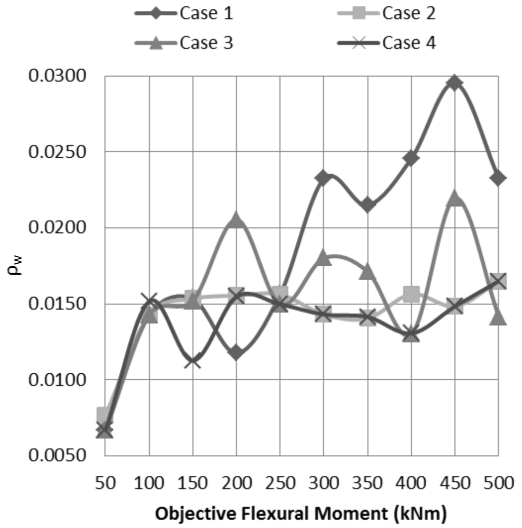

Fig. 10. Optimum ρ_w (35 MPa)

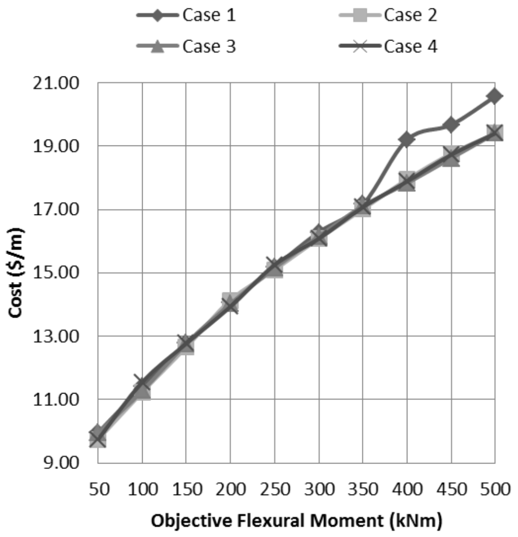

Fig. 11. Optimum Cost (40 MPa)

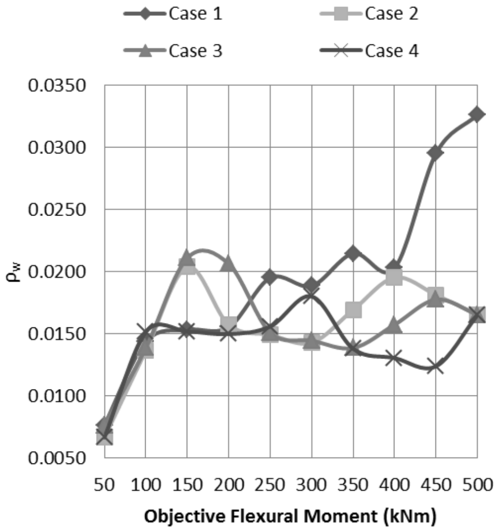

Fig. 12. Optimum ρ_w (45 MPa)

V. CONCLUSION

In this study, the optimum values of T-shaped beams are investigated under various flexural moment objectives for five different compressive strength of concrete. In order to show that the developed program is capable to find the optimum cost level between concrete and steel, different limitation cases for the beam dimensions were studied. According to the results, the program is capable to find the optimum values when doubly reinforcement is necessary or not.

The results show that the usage of bigger dimensions limits is more economical. Under 500 kNm objective flexural moment, the costs of the beams using concrete with 20 MPa compressive strength are 10.77%, 17.76% and 16.82% lower of the case 1 for the cases 2, 3 and 4, respectively. According to this information, the maximum cost reduction is between cases 1 and 2. Although the results are more economical for the cases 3 and 4, these cases may not be suitable for architectural esthetic and design of other structural members because of heaviness. In that situation, the dimension limit used for case 2 is suitable for a standard RC building.

The usage of concrete with higher compressive strength may be more suitable for the design. The results obtained by using 25 MPa compressive strength confirm this situation. Besides, the brittle response of the concrete is increased with the increase of the compressive strength. By considering this effect, a lower flexural moment capacity may be obtained. This situation can be seen from the results of 30 MPa-40 MPa compressive strengths.

The main handicap of the optimization programs is long processing time. The optimization of dynamic analysis of a structure may take too much time. For the present approach, the processing time of the computer during optimization is nearly one second for a computer with i7-2600K processer. For that reason, the proposed approach is suitable for preliminary design and control of the analyses results obtained by computer programs.

APPENDIX

Table 2. The optimum results of the numerical example (20 MPa compressive strength of concrete)

	Objective Flexural Moment (kNm)	50	100	150	200	250	300	350	400	450	500
CASE 1	h (mm)	350	350	400	500	450	500	500	500	500	500
	b_w (mm)	250	250	250	250	250	250	250	250	250	300
	ϕ_1 (mm)	10	22	18	20	30	20	30	30	30	30
	ϕ_3 (mm)	-	-	-	-	-	-	-	-	-	-
	n_1	4	2	4	3	2	4	3	3	3	3
	n_3	-	-	-	-	-	-	-	-	-	-
	ϕ_2 (mm)	10	10	12	12	16	18	10	14	26	26
	ϕ_4 (mm)	-	-	-	-	-	-	-	-	-	-
	n_2	2	3	2	3	3	3	3	4	2	3
	n_4	-	-	-	-	-	-	-	-	-	-
	M_u (kNm)	55.91	113.77	168.96	225.20	295.84	342.27	401.67	453.38	509.70	575.89
	Cost ($/m)	7.96	9.59	10.86	11.98	13.76	14.27	15.31	16.49	17.88	20.33
CASE 2	h (mm)	350	350	450	550	550	650	600	650	600	650
	b_w (mm)	250	250	250	250	250	250	250	250	300	300
	ϕ_1 (mm)	10	22	18	16	18	22	24	22	30	30
	ϕ_3 (mm)	-	-	-	-	-	-	-	-	-	-
	n_1	4	2	3	4	4	3	3	3	3	3
	n_3	-	-	-	-	-	-	-	-	-	-
	ϕ_2 (mm)	10	10	10	12	16	10	14	16	10	12
	ϕ_4 (mm)	-	-	-	-	-	-	-	-	-	-
	n_2	2	3	4	3	2	4	3	4	5	3
	n_4	-	-	-	-	-	-	-	-	-	-
	M_u (kNm)	55.91	113.77	168.05	226.36	278.26	346.50	389.14	450.67	528.99	570.89
	Cost ($/m)	7.96	9.59	10.84	12.05	12.91	14.01	14.65	15.54	17.80	18.24
CASE 3	h (mm)	350	350	400	550	550	600	650	700	750	750
	b_w (mm)	250	250	250	250	250	250	250	250	250	250
	ϕ_1 (mm)	10	16	18	16	22	20	24	22	26	28
	ϕ_3 (mm)	-	-	-	-	-	-	-	-	-	-
	n_1	4	4	4	3	3	4	3	3	3	3
	n_3	-	-	-	-	-	-	-	-	-	-
	ϕ_2 (mm)	10	10	12	12	14	14	14	16	10	10
	ϕ_4 (mm)	-	-	-	-	-	-	-	-	-	-
	n_2	2	2	2	5	2	2	2	3	3	2
	n_4	-	-	-	-	-	-	-	-	-	-
	M_u (kNm)	55.91	112.61	168.96	227.60	284.05	339.99	394.62	444.69	509.71	557.75
	Cost ($/m)	7.96	9.48	10.86	12.13	13.00	13.86	14.67	15.41	16.18	16.72
CASE 4	h (mm)	350	400	450	500	550	550	650	650	750	800
	b_w (mm)	250	250	250	250	250	250	250	250	250	250
	ϕ_1 (mm)	10	16	22	26	20	30	28	26	24	22
	ϕ_3 (mm)	-	-	-	-	-	-	-	-	-	-
	n_1	4	3	2	2	4	2	2	3	3	3
	n_3	-	-	-	-	-	-	-	-	-	-
	ϕ_2 (mm)	10	14	12	10	10	10	12	14	12	18
	ϕ_4 (mm)	-	-	-	-	-	-	-	-	-	-
	n_2	2	2	3	3	2	4	4	2	4	3
	n_4	-	-	-	-	-	-	-	-	-	-
	M_u (kNm)	55.91	123.30	169.70	227.78	280.90	333.51	394.14	447.89	501.53	561.67
	Cost ($/m)	7.96	9.83	10.91	12.03	12.89	13.86	14.73	15.40	16.12	16.91

Table 3. The optimum results of the numerical example (25 MPa compressive strength of concrete)

Objective Flexural Moment (kNm)		50	100	150	200	250	300	350	400	450	500
CASE 1	h (mm)	350	400	450	500	500	500	500	500	500	500
	b_w (mm)	250	250	250	250	250	250	250	250	250	250
	ϕ_1 (mm)	10	12	18	16	22	26	30	30	26	30
	ϕ_3 (mm)	-	-	-	-	-	-	-	-	-	-
	n_1	4	5	3	4	3	3	2	3	3	3
	n_3	-	-	-	-	-	-	-	-	-	-
	ϕ_2 (mm)	10	10	10	14	14	12	20	16	26	30
	ϕ_4 (mm)	-	-	-	-	-	-	-	-	-	-
	n_2	2	3	4	3	3	3	3	3	3	2
	n_4	-	-	-	-	-	-	-	-	-	-
	M_u (kNm)	56.15	111.20	169.26	223.28	279.79	336.76	390.61	459.13	514.46	565.67
	Cost ($/m)	8.45	10.01	11.40	12.53	13.57	14.59	15.91	17.05	18.48	19.56
CASE 2	h (mm)	350	400	400	550	500	600	600	600	650	650
	b_w (mm)	250	250	250	250	250	250	250	250	250	250
	ϕ_1 (mm)	10	12	20	24	20	26	24	26	30	26
	ϕ_3 (mm)	-	-	-	-	-	-	-	-	-	-
	n_1	4	5	3	2	4	2	3	3	2	3
	n_3	-	-	-	-	-	-	-	-	-	-
	ϕ_2 (mm)	10	10	14	10	12	18	14	18	22	20
	ϕ_4 (mm)	-	-	-	-	-	-	-	-	-	-
	n_2	2	3	2	4	3	2	3	2	2	3
	n_4	-	-	-	-	-	-	-	-	-	-
	M_u (kNm)	56.15	111.20	169.26	240.68	281.87	337.07	392.57	449.84	501.21	584.29
	Cost ($/m)	8.45	10.01	11.40	12.92	13.55	14.55	15.32	16.19	16.95	18.07
CASE 3	h (mm)	350	350	450	500	550	650	600	650	650	750
	b_w (mm)	250	250	250	250	250	250	250	250	250	250
	ϕ_1 (mm)	10	18	18	18	18	24	30	22	30	20
	ϕ_3 (mm)	-	-	-	-	-	-	-	-	-	-
	n_1	4	3	3	4	4	2	2	3	2	4
	n_3	-	-	-	-	-	-	-	-	-	-
	ϕ_2 (mm)	10	12	14	10	16	16	16	18	18	18
	ϕ_4 (mm)	-	-	-	-	-	-	-	-	-	-
	n_2	2	2	2	3	2	3	2	3	3	3
	n_4	-	-	-	-	-	-	-	-	-	-
	M_u (kNm)	56.15	115.16	168.11	224.42	280.35	354.74	389.20	445.49	502.50	558.61
	Cost ($/m)	8.45	10.06	11.38	12.49	13.54	14.89	15.31	16.12	16.96	17.55
CASE 4	h (mm)	350	400	400	550	500	600	600	650	700	750
	b_w (mm)	250	250	250	250	250	250	250	250	250	250
	ϕ_1 (mm)	14	12	20	12	20	22	24	22	24	20
	ϕ_3 (mm)	-	-	-	-	-	-	-	-	-	-
	n_1	2	5	3	5	4	3	3	3	3	4
	n_3	-	-	-	-	-	-	-	-	-	-
	ϕ_2 (mm)	12	10	14	12	10	10	12	18	14	18
	ϕ_4 (mm)	-	-	-	-	-	-	-	-	-	-
	n_2	2	3	2	5	4	5	4	3	4	3
	n_4	-	-	-	-	-	-	-	-	-	-
	M_u (kNm)	62.05	111.20	169.26	222.93	278.06	333.76	390.93	445.49	505.27	558.61
	Cost ($/m)	8.64	10.01	11.40	12.64	13.47	14.43	15.29	16.12	16.87	17.55

Table 4. The optimum results of the numerical example (30 MPa compressive strength of concrete)

Objective Flexural Moment (kNm)		50	100	150	200	250	300	350	400	450	500
CASE 1	h (mm)	350	350	400	450	500	500	500	500	500	500
	b_w (mm)	250	250	250	250	250	250	300	300	300	250
	ϕ_1 (mm)	10	12	26	20	22	24	28	30	28	30
	ϕ_3 (mm)	-	-	-	-	-	-	-	-	-	-
	n_1	4	5	2	4	3	3	3	3	4	3
	n_3	-	-	-	-	-	-	-	-	-	-
	ϕ_2 (mm)	10	14	10	10	12	12	16	10	12	24
	ϕ_4 (mm)	-	-	-	-	-	-	-	-	-	-
	n_2	3	3	2	2	4	5	2	6	4	3
	n_4	-	-	-	-	-	-	-	-	-	-
	M_u (kNm)	64.76	117.99	167.05	224.98	280.27	334.73	390.68	445.84	501.47	568.36
	Cost ($/m)	9.18	10.66	11.83	13.00	14.13	15.16	17.09	18.15	19.15	19.97
CASE 2	h (mm)	350	350	400	450	500	500	600	600	600	650
	b_w (mm)	250	250	250	250	250	250	250	250	250	250
	ϕ_1 (mm)	10	16	20	22	20	28	24	28	30	30
	ϕ_3 (mm)	-	-	-	-	-	-	-	-	-	-
	n_1	4	3	3	3	4	2	3	3	3	3
	n_3	-	-	-	-	-	-	-	-	-	-
	ϕ_2 (mm)	10	10	14	14	10	22	12	10	10	14
	ϕ_4 (mm)	-	-	-	-	-	-	-	-	-	-
	n_2	2	5	2	2	4	2	4	3	3	2
	n_4	-	-	-	-	-	-	-	-	-	-
	M_u (kNm)	56.30	114.53	170.34	226.85	279.77	338.27	393.19	453.61	510.23	574.65
	Cost ($/m)	8.93	10.56	11.92	13.11	14.07	15.37	15.96	16.80	17.65	18.45
CASE 3	h (mm)	350	350	400	500	500	600	600	650	700	700
	b_w (mm)	250	250	250	250	250	250	250	250	250	250
	ϕ_1 (mm)	10	22	24	20	22	20	24	20	24	28
	ϕ_3 (mm)	-	-	-	-	-	-	-	-	-	-
	n_1	4	2	2	3	3	3	3	4	3	3
	n_3	-	-	-	-	-	-	-	-	-	-
	ϕ_2 (mm)	10	10	12	14	12	16	14	14	16	10
	ϕ_4 (mm)	-	-	-	-	-	-	-	-	-	-
	n_2	2	3	3	2	4	3	3	4	3	4
	n_4	-	-	-	-	-	-	-	-	-	-
	M_u (kNm)	56.30	115.48	167.74	222.85	280.27	334.65	394.86	444.92	504.72	559.54
	Cost ($/m)	8.93	10.56	11.90	13.07	14.13	15.14	15.99	16.73	17.57	18.20
CASE 4	h (mm)	350	350	400	450	500	550	600	650	700	650
	b_w (mm)	250	250	250	250	250	250	250	250	250	250
	ϕ_1 (mm)	10	12	26	22	24	24	20	26	24	30
	ϕ_3 (mm)	-	-	-	-	-	-	-	-	-	-
	n_1	4	5	2	3	3	3	4	3	3	3
	n_3	-	-	-	-	-	-	-	-	-	-
	ϕ_2 (mm)	10	10	10	14	10	12	16	14	16	12
	ϕ_4 (mm)	-	-	-	-	-	-	-	-	-	-
	n_2	2	5	2	2	3	3	3	2	3	2
	n_4	-	-	-	-	-	-	-	-	-	-
	M_u (kNm)	56.30	111.22	167.05	226.85	283.42	335.19	402.86	454.14	504.72	557.64
	Cost ($/m)	8.93	10.44	11.83	13.11	14.13	15.03	16.11	16.81	17.57	18.20

Table 5. The optimum results of the numerical example (35 MPa compressive strength of concrete)

	Objective Flexural Moment (kNm)	50	100	150	200	250	300	350	400	450	500
CASE 1	h (mm)	350	350	400	500	500	450	500	500	500	500
	b_w (mm)	250	250	250	250	250	250	250	250	250	350
	ϕ_1 (mm)	10	18	24	20	20	28	20	30	30	22
	ϕ_3 (mm)	-	-	-	-	-	-	-	-	-	-
	n_1	4	3	2	3	4	3	4	3	3	5
	n_3	-	-	-	-	-	-	-	-	-	-
	ϕ_2 (mm)	10	12	12	10	16	10	18	12	20	22
	ϕ_4 (mm)	-	-	-	-	-	-	-	-	-	-
	n_2	2	2	3	4	2	4	4	4	3	4
	n_4	-	-	-	-	-	-	-	-	-	-
	M_u (kNm)	56.41	116.32	168.50	224.91	294.60	334.90	390.96	446.17	516.47	573.27
	Cost ($/m)	9.26	10.86	12.25	13.49	14.74	15.69	16.64	17.57	19.08	22.82
CASE 2	h (mm)	350	350	400	450	500	550	600	600	650	650
	b_w (mm)	250	250	250	250	250	250	250	250	250	250
	ϕ_1 (mm)	14	18	24	20	22	24	30	26	24	30
	ϕ_3 (mm)	-	-	-	-	-	-	-	-	-	-
	n_1	2	3	2	3	3	3	2	3	3	3
	n_3	-	-	-	-	-	-	-	-	-	-
	ϕ_2 (mm)	12	12	12	18	18	12	16	12	18	12
	ϕ_4 (mm)	-	-	-	-	-	-	-	-	-	-
	n_2	2	2	3	2	2	3	2	4	3	2
	n_4	-	-	-	-	-	-	-	-	-	-
	M_u (kNm)	62.39	116.32	168.50	225.14	289.88	336.61	393.11	444.61	500.07	560.36
	Cost ($/m)	9.45	10.86	12.25	13.49	14.71	15.45	16.42	17.13	17.97	18.67
CASE 3	h (mm)	350	350	400	400	500	500	550	650	550	700
	b_w (mm)	250	250	250	250	250	250	250	250	250	250
	ϕ_1 (mm)	10	18	18	24	30	26	20	20	30	26
	ϕ_3 (mm)	-	-	-	-	-	-	-	-	-	-
	n_1	4	3	4	3	2	3	4	4	3	3
	n_3	-	-	-	-	-	-	-	-	-	-
	ϕ_2 (mm)	10	12	12	10	10	14	22	14	12	16
	ϕ_4 (mm)	-	-	-	-	-	-	-	-	-	-
	n_2	-	-	-	-	-	-	-	-	-	-
	n_4	0	0	0	0	0	0	0	0	0	0
	M_u (kNm)	56.41	116.32	172.40	226.95	279.67	336.18	392.57	446.65	500.20	565.92
	Cost ($/m)	9.26	10.86	12.25	13.57	14.46	15.48	16.44	17.20	18.17	18.80
CASE 4	h (mm)	350	350	450	450	500	550	600	650	650	650
	b_w (mm)	250	250	250	250	250	250	250	250	250	250
	ϕ_1 (mm)	10	16	14	22	24	24	28	24	24	30
	ϕ_3 (mm)	-	-	-	-	-	-	-	-	-	-
	n_1	4	3	4	3	3	3	2	3	3	3
	n_3	-	-	-	-	-	-	-	-	-	-
	ϕ_2 (mm)	10	12	12	14	10	12	16	18	18	12
	ϕ_4 (mm)	-	-	-	-	-	-	-	-	-	-
	n_2	2	4	4	2	3	3	3	2	3	2
	n_4	-	-	-	-	-	-	-	-	-	-
	M_u (kNm)	56.41	120.96	167.95	227.88	284.68	336.61	394.23	444.62	500.07	560.36
	Cost ($/m)	9.26	11.07	12.31	13.48	14.53	15.45	16.48	17.18	17.97	18.67

Table 6. The optimum results of the numerical example (40 MPa compressive strength of concrete)

Objective Flexural Moment (kNm)		50	100	150	200	250	300	350	400	450	500
CASE 1	h (mm)	350	350	400	450	450	500	500	500	500	500
	b_w (mm)	250	250	250	250	250	250	250	300	250	250
	ϕ_1 (mm)	10	14	24	20	26	26	28	24	30	30
	ϕ_3 (mm)	-	-	-	-	-	-	-	-	-	-
	n_1	4	4	2	3	3	2	3	4	3	3
	n_3	-	-	-	-	-	-	-	-	-	-
	ϕ_2 (mm)	12	10	12	18	12	24	16	14	20	28
	ϕ_4 (mm)	-	-	-	-	-	-	-	-	-	-
	n_2	2	5	3	2	2	2	2	5	3	2
	n_4	-	-	-	-	-	-	-	-	-	-
	M_u (kNm)	63.91	117.48	169.08	225.92	286.62	335.67	395.06	448.41	519.94	559.80
	Cost ($/m)	9.96	11.41	12.77	14.05	15.19	16.28	17.16	19.20	19.67	20.57
CASE 2	h (mm)	350	350	350	450	500	550	550	550	600	650
	b_w (mm)	250	250	250	250	250	250	250	250	250	250
	ϕ_1 (mm)	10	14	20	18	24	24	26	28	26	30
	ϕ_3 (mm)	-	-	-	-	-	-	-	-	-	-
	n_1	4	4	4	4	3	3	3	3	3	3
	n_3	-	-	-	-	-	-	-	-	-	-
	ϕ_2 (mm)	10	12	10	14	12	12	16	12	18	10
	ϕ_4 (mm)	-	-	-	-	-	-	-	-	-	-
	n_2	2	3	2	3	2	3	2	4	3	3
	n_4	-	-	-	-	-	-	-	-	-	-
	M_u (kNm)	56.49	111.75	167.34	232.47	284.01	337.68	393.97	451.39	506.57	564.52
	Cost ($/m)	9.75	11.24	12.66	14.14	15.10	16.08	17.01	17.95	18.76	19.40
CASE 3	h (mm)	350	350	350	400	500	550	600	600	600	650
	b_w (mm)	250	250	250	250	250	250	250	250	250	250
	ϕ_1 (mm)	10	12	22	30	22	20	18	26	28	26
	ϕ_3 (mm)	-	-	-	-	-	-	-	-	-	-
	n_1	4	5	3	2	3	4	4	3	3	3
	n_3	-	-	-	-	-	-	-	-	-	-
	ϕ_2 (mm)	12	16	14	10	14	14	16	14	14	18
	ϕ_4 (mm)	-	-	-	-	-	-	-	-	-	-
	n_2	2	2	2	3	3	3	4	3	3	3
	n_4	-	-	-	-	-	-	-	-	-	-
	M_u (kNm)	63.91	112.50	167.83	223.52	283.78	341.46	395.05	447.84	501.33	556.05
	Cost ($/m)	9.96	11.28	12.77	14.03	15.16	16.15	17.11	17.83	18.62	19.40
CASE 4	h (mm)	350	350	400	450	500	500	600	650	700	650
	b_w (mm)	250	250	250	250	250	250	250	250	250	250
	ϕ_1 (mm)	10	16	18	20	28	26	24	24	26	26
	ϕ_3 (mm)	-	-	-	-	-	-	-	-	-	-
	n_1	4	3	4	4	2	3	3	3	3	3
	n_3	-	-	-	-	-	-	-	-	-	-
	ϕ_2 (mm)	10	12	12	10	16	14	12	18	12	18
	ϕ_4 (mm)	-	-	-	-	-	-	-	-	-	-
	n_2	2	4	2	2	2	2	4	2	3	3
	n_4	-	-	-	-	-	-	-	-	-	-
	M_u (kNm)	56.49	121.37	172.97	226.71	287.21	337.52	396.02	445.91	504.87	556.05
	Cost ($/m)	9.75	11.55	12.77	13.94	15.25	16.08	17.07	17.88	18.73	19.40

NOTATIONS

ϕ : Strength Reduction Factor
ϕ_i : Diameter of Reinforcement Bars in ith Line
β_1: Factor Relating Depth of Equivalent Rectangular Compressive Stress Block to Neutral Axis Depth
ACI 318 : American Concrete Institute Building Code Requirements for Structural Concrete
A_s : Area of Longitudinal Tension Reinforcements
b : Width of Compressive Face of The Beam
b_w : Web Width of The Beam
d : Effective height of The Beam
GA : Genetic Algorithm
h : Height of The Beam
h_f : Slab Thickness
HM : Harmony Memory
HMCR : Harmony Memory Considering Rate
HMS : Harmony Memory Size
HS : Harmony Search
M_n : The Objective Moment
M_u : The Moment Capacity of The Beam
n_i : Number of Reinforcement Bars in ith Line
RC : Reinforced Concrete
PAR : Pitch Adjusting Rate

REFERENCES

[1] C. C. Coello, F. S. Hernandez, F. A. Farrera, “Optimal Design of Reinforced Concrete Beams Using Genetic Algorithms”, *Expert Systems with Applications*, Vol. 12, pp. 101-108, 1997.

[2] M. Y. Rafiq, C. Southcombe, “Genetic algorithms in optimal design and detailing of reinforced concrete biaxial columns supported by a declarative approach for capacity checking”, *Computers and Structures*, Vol. 69, pp. 443-457, 1998.

[3] D. P. Rath, A. S. Ahlawat, A. Ramaswamy, “Shape Optimization of RC Flexural Members”, *Journal of Structural Engineering*, Vol. 125, pp.1439-1446, 1999.

[4] C. V. Camp, S. Pezeshk, H. Hansson, H., “Flexural Design of Reinforced Concrete Frames Using a Genetic Algorithm”, *Journal of Structural Engineering*, Vol. 129, pp.105-11, 2003.

[5] C. C. Ferreira, M. H. F. M. Barros, A. F. M. Barros, “Optimal design of reinforced concrete T-sections in bending”, *Engineering Structures*, Vol. 25, pp. 951-964, 2003.

[6] M. Leps, M. Sejnoha, “New approach to optimization of reinforced concrete beams”, *Computers and Structures*, Vol.81, pp.1957–1966, 2003.

[7] M. H. F. M. Barros, R. A. F. Martins, A. F. M. Barros, “Cost optimization of singly and doubly reinforced concrete beams with EC2-2001”, *Structural and Multidisciplinary Optimization*, Vol. 30, pp-236–242, 2005.

[8] V. Govindaraj, J. V. Ramasamy, “Optimum detailed design of reinforced concrete continuous beams using Genetic Algorithms”, *Computers and Structures*, Vol. 84, pp-34–48, 2005.

[9] V. Govindaraj, J. V. Ramasamy, “Optimum detailed design of reinforced concrete frames using genetic algorithms”, *Engineering Optimization*, Vol. 39(4), pp. 471–494, 2007.

[10] A. F. M. Barros, M. H. F. M. Barros, C. C. Ferreira, “Optimal design of rectangular RC sections for ultimate bending strength”, *Structural and Multidisciplinary Optimization*, Vol. 45, pp-845–860, 2012.

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

[12] Z. W. Geem, J. H. Kim, G. V. Loganathan, “A new heuristic optimization algorithm: harmony search, Simulation”, Vol. 76, pp. 60–68, 2001.

[13] X.-S. Yang, *Engineering Optimization: An Introduction with metaheuristic Applications*, John Wiley and Sons Inc., New Jersey, 2010.

[14] G. Bekdaş, S. M. Nigdeli, S.M., “Estimating Optimum Parameters of Tuned Mass Dampers using Harmony Search”, *Engineering Structures*, Vol. 33, pp. 2716-2723, 2011.

[15] G. Bekdaş, S. M. Nigdeli, S.M., “Investigation of SDOF Idealization for Structures with Optimum Tuned Mass Dampers”, In: *Natural Cataclysms and Global Problems of the Modern Civilization Geocataclysms 2011*, September 19-21, Istanbul, Turkey.

[16] S. M. Nigdeli, G. Bekdaş, “Optimization Of Tuned Mass Damper Parameters for Structures Subjected To Earthquakes With Forward Directivity”, In: *Natural Cataclysms and Global Problems of the Modern Civilization Geocataclysms 2011*, September 19-21, Istanbul, Turkey.

[17] G. Bekdaş, S. M. Nigdeli, S.M., “Metaheuristic Algorithms in Structural Dynamics: An Application of Tuned Mass Damper Optimization”, In: *AIP Conf. Proc. 10th International Conference of Numerical Analysis and Applied Mathematics (ICNAAM)*, Kos, Greece, September 19-25, 2012, Vol. 1479, pp. 1903-1906.

[18] S. M. Nigdeli, G. Bekdaş, “Investigation of Earthquake Factor for Optimum Tuned Mass Dampers”, In: *AIP Conf. Proc. 10th International Conference of Numerical Analysis and Applied Mathematics (ICNAAM)*, Kos, Greece, September 19-25, 2012, Vol. 1479, pp. 1907-1910.

[19] G. Bekdaş, S. M. Nigdeli, S.M., “Preventing the Pounding of Adjacent Buildings with Harmony Search Optimized Tuned Mass Damper”, In: *3rd European Conference of Civil Engineering*, December 2-4 2012, Paris, France.

[20] S. M. Nigdeli, G. Bekdaş, “Improving the Seismic Behavior of RC Structures with Projection in Plan by using Optimum TMD”, In: *3rd European Conference of Civil Engineering*, December 2-4 2012, Paris, France.

[21] G. Bekdaş, S. M. Nigdeli, “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.

[22] Z. W. Geem, J. C. Williams, “Ecological Optimization Using Harmony Search”, In: *American Conference on Applied Mathematics (MATH’08)*, March 24-26, 2008, Harvard, Massachusetts, USA.

[23] Z. W. Geem, Y. Park, “Optimal Layout for Branched Networks using Harmony Search”, in *Proc. 5th WSEAS International Conference on Applied Computer Science*, Hangzhou, China, 2006, pp. 364-367.

[24] A. Khanjanzadeh, A. Rezazadeh, M. Sedighizadeh “Using Harmony Search Algorithm for Optimization the Component Sizing of Plug-in Hybrid Electric Vehicle”, in *Proc. 11th international conference on Applications of Electrical and Computer Engineering*, Athens, Greece March 7-9, 2012, pp. 142-150.

[25] A. Khanjanzadeh, A. Rezazadeh, M. Sedighizadeh “Optimal Placement and Sizing of FACTS Devices for Loadability Enhancement in Deregulated Power Systems”, in *Proc. 11th WSEAS international conference on Artificial Intelligence*, Cambridge. UK, February 22-24, 2012, pp. 148-156.

[26] T. Ratniyomchai, A. Oonsivilai, P. Pao-La-Or, T. Kulworawanichpong, “Solving Economic Dispatch Problems with Improved Harmony Search”, in *Proc. 5th IASME/WSEAS international conference on Energy & environment*, University of Cambridge, UK February 23-25, 2010, pp. 247-252.