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Optimal Design of Reinforced Concrete Frame Structures Using Cascade Optimization Method

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Abstract

Optimal design of structures is one of the goals of a structural engineer. Since a large number of design variables are involved, the high computational time for optimization process is one of the main problems of using single heuristic or meta-heuristic algorithms utilized for this purpose, especially in large-scale structures. Cascade optimization replaces the single optimization problem with a multiple stage process. Each step starts with the previous optimum design, with the number of variables being reduced thus increasing the speed of the convergence in each stage of optimization.

In this article a Cascade optimization method is developed for optimum design of RC frame structures. By using this algorithm in place of a single optimization method and ensuring its efficiency, the optimum section dimensions are determined by a new method. Then, genetic algorithm is utilized for optimizing of rebar arrangement. According to the results, this method performs optimum design and reduces the elapsed time considerably. Optimization of large-scale concrete structure is carried out by the developed method. It should be noted that the present method works with MATLAB and ETABS interfacing.

Keywords

Cascade optimization, reinforced concrete (RC) structures,meta-heuristics, genetic algorithm, MATLAB and CSI interfacing

1 Introduction

Methods and techniques to achieve the most economical and safest possible design for the structures is known as structural optimization. In other words, optimization means achieving the best result in a system under certain constraints [1]. One of the most popular optimization algorithms is genetic algorithm (GA) simulating Darwinian evolution [2]. Using meta-heuristics provide a good solution for optimal design of structures. Some new meta-heuristic methods using for optimization are thermal exchange optimization [3], vibrating particles system [4], cyclical parthenogenesis [5], Quantum evolutionary algorithm [6], water strider algorithm [7] and shuffled shepherd optimization [8]. Meta heuristic algorithms are used individually or in combination with other algorithms. Two algorithms heuristic big bang-big crunch (HBB-BC) based on BB-BC and a harmony search (HS) and a heuristic particle swarm ant colony optimization (HPSACO) including particle swarm with passive congregation (PSOPC), ant colony optimization (ACO), and harmony search scheme (HS) algorithms are used for discrete optimization of reinforced concrete planar frames by Kaveh and Sabzi [9]. Talatahari et al. [10] develop new optimization algorithm called ES-DE by using MATLAB and SAP2000 interface and combining the developed eagle strategy algorithm and differential evolution. A new hybrid algorithm called MDVC-UVPS included vibrating particles system (VPS) algorithm used as the main engine, multi-design variable configuration (Multi-DVC) Cascade optimization, and an upper bound strategy (UBS) is introduced by Kaveh and Ilchi Ghazaan [11] for large-scale dome truss structures. Also, Cascade algorithm using DVCs and UBS is used for reducing the number of variables and computational time, respectively. The results show the efficiency and power of this new technique.

Since optimization of used material in structures under considered constraints according to related codes is one of the most important issues for the structural designers, optimizing truss, steel and RC structures is the attractive field for researches.

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The optimization of continuous concrete beams design under serviceability, ductility, durability constraints is done with the application of genetic algorithm used for optimization of the dimensions of the beam as variable in Govindaraj and Ramasamy [12] research. In Yeo and Gabbai [13] research, the techniques traditionally employed for optimization of structural cost is used for optimizing the embodied energy. Optimization of the cost of material and construction in RC frames by using discrete Big Bang-Big Crunch algorithm is the goal of Kaveh and Sabzi [14] research. A new topology optimization procedure whose goal is optimization of RC structures weight is introduced by Amir [15]. Optimization of three-dimensional RC structure by the combination of two developed meta-heuristic algorithms, the charged system search and the enhanced charged system search, is done by Kaveh and Behnam [16]. In the research of Kaveh [17], Minimizing the construction material cost and carbon dioxide as objective function in RC structure is done by developed meta heuristic algorithms called Enhanced Colliding Bodies Optimization (ECBO) and the Non-dominated Sorting Enhanced Colliding Bodies Optimization (NSECBO).

The research of Esfandiari et al. finds DMPSO, combining multi criterion decision-making (DM) and Particle Swarm Optimization (PSO), as an efficient tool for accelerating convergence of optimization in three dimensional RC structures [18]. Vaez and Qomi [19] Introduce continuous method for optimizing the design of shear walls by using of several metaheuristic algorithms with the purpose of minimizing reinforcement details and the wall dimensions. Gan et al. [20] develop a novel optimize procedure for optimization both cost-optimal and low-carbon design in high-rise RC structures. This approach using the genetic algorithm includes the structural topology by first and then individual element size optimizations.

Optimization of RC structures by multi-objective algorithm interested in trade-off between cost and deflection is done by Afshari et al. [21]. The efficiency of this tool is established by a method based on purely random selection. The results show the efficiency of the derivative-free optimization algorithm. Since the process of structural optimization is trial-and-error approach, in the research by Dehnavipour et al. [22], the goal was to optimize structural design under flexural strength, shear strength, drift and construction constraint according to building code's required. The considered method accelerates the process of optimization and is carried out by the Particle Swarm optimization algorithm (PSO). Minimizing the cost of concrete arch bridge is the aim of Abd Elrehim et al. [23] research by the finite element method and the genetic algorithm in MATLAB. The results are shown by the cost reduction comparing the considered method with traditional design. In Kaveh et al. [24] research, three metaheuristic algorithms consisting of ECBO, Enhanced Vibrating Particles System (EVPS) and Particle Swarm Optimization (PSO) are used for investigate the relationship between minimizing the cost of structure and minimizing carbon dioxide emission in RC structures. In the research of Kaveh et al. [25], performance-based optimal seismic design of RC frames with minimizing the cost and CO2 emissions as an objective function under strength-based and performance-based constraints is done. For investigation, the relationship between optimal cost and optimal CO2 emissions the considered procedure is applied to RC frames. In Negrin-Diaz et al. [26] research, Biogeography-Based Optimization is used for optimization of reinforced concrete structures. Shakedown method is used for evaluate plastic limit load and plastic design parameters in pile foundations to which horizontal loads are applied in the research of Rad and Ibrahim [27]. Also, elasto-plastic analysis of reliability-based geometrically nonlinear topology optimization is presented by Rad et al. [28]. A new computational method is used for control the plastic behavior of RC hunch beams using the complementary strain energy of bars residual forces in Rad et al. [29] research.

According to the research of Charmpis et al. [30], achieving to the best optimal design by setting design variable options is the result of using large-size databases from which the design variables take values. The accuracy of the optimum result depends on the time elapsed, especially for large-scale structures. In other word, optimization of large-scale problems having high number of design variables and constraints requiring many analyses using high computational time. Cascade algorithms are used for reducing the time and increasing the accuracy of the answers. It replaces a single optimization problem with several optimization stages. Fig. 1 presents single optimization process and Cascade method flowcharts. Reduction of objective function is provided in research of Kaveh and Ilchi Ghazaan [31]. By initially operating small number of variables in a step-by-step optimization process using enhanced colliding bodies. Three examples have been used to show the accuracy and speed of convergence of the proposed method. In Kaveh and Boland Gerami [32] research, in order to reduce the number of variables, three large-scale space frames are optimized

Fig. 1 Comparison of (a) optimum design method of [1] and (b) Cascade method

with Cascade algorithm using enhanced colliding bodies algorithm in all the stages. The results showed the efficiency of this method. In Kaveh [33], a new accurate and efficient Cascade algorithm is introduced for optimizing the design of truss towers with large number of design variables. A large-scale suspendome is used to investigate the new algorithm defined in the research of Kaveh et al. [34] as an efficient tool. The weight of dome is considered as objective function under LRFD constraints. Also, optimum height of crown and tubular sections of these domes, the initial strain, the length of the struts, and the cross-sectional areas of the cables are considered as design variables.

In this research the combination of a new method and genetic algorithm is used for optimization of concrete structures. Creating some column sections with specified depth and calculated width according to $\frac{\text{applied moment in the direction of the local axis 3}}{\text{applied moment in the direction of the local axis 2}}$ is the first step of this new Cascade algorithm using for three dimensional RC structures. By assigning these sections to column members, optimal section is extracted and saved. The square sections of beam whose dimension are less than the section dimension of columns to which the beam is connected are assigned and the section with minimum cost is extracted. After this process, according to required reinforcement area of columns, the genetic algorithm is used for rebar arrangement. The result shows the efficiency of this new Cascade algorithm for optimization of RC structures.

2 Methodology

In this section, the new Cascade algorithm is used for optimize 1-story and 6-story, a small and large-scale concrete structure respectively, as numerical examples. The purpose of these examples is to optimize the beams and columns by using the Cascade method.

2.1 Numerical examples

2.1.1 A 1-story RC structure

In the first example, a 1-story structure, as shown in Fig. 2, with 3.5 m height, 8 m and 4.5 m central line distance in x and y direction, respectively, is employed for optimization with the new Cascade algorithm. The dimension of beams and columns are evaluated, and optimization of rebar arrangements is performed with the new method and the Genetic algorithm, respectively, under the considered constraints. The data of earthquake and loading are from [35], and materials are those of [36], and costs are presented in Table 1 to Table 4. It is worth mentioning that the waffle system is used as the ceiling. The penalty function is also used for the accuracy and speed of the Genetic algorithm convergence.

The process of considered method is explained in the following. First, the quantity of $\frac{\text{applied moment in the direction of the local axis 3}}{\text{applied moment in the direction of the local axis 2}}$ for each section is calculated according to Fig. 3. Due to the symmetry, it is the same for all columns. According to $M \propto EI$ and $I = \frac{bh^3}{12}$, the following equation can be writtenas Eq. (1):

Table 1 Earthquake parameters

Base shear Coefficient (C)	Building height Exponent (K)
0.125	1

Table 2 Loading

Load	(kgf, m)
Dead on stories	$600\frac{\text{kgf}}{\text{m}^2}$
Live on stories	$200\frac{\text{kgf}}{\text{m}^2}$
Dead on perimeter beams	$250\frac{\text{kgf}}{\text{m}^2}$

Table 3 The utilized material

Material	Weight	Strength
Concrete	$2500\frac{\text{kgf}}{\text{m}^2}$	$f_c' = 28\times10^5\ \frac{\text{kgf}}{\text{m}^2}$
Steel of longitudinal bars	$7850\frac{\text{kgf}}{\text{m}^2}$	$f_y = 400\times10^5\ \frac{\text{kgf}}{\text{m}^2}$ $f_u = 600\times10^5\ \frac{\text{kgf}}{\text{m}^2}$
Steel of confinement bars	$7850\frac{\text{kgf}}{\text{m}^2}$	$f_y = 300\times10^5\ \frac{\text{kgf}}{\text{m}^2}$ $f_u = 500\times10^5\ \frac{\text{kgf}}{\text{m}^2}$

Table 4 Costs

	Cost
Cost of concrete	$0.01\frac{\$}{\text{kg}}$
Cost of steel	$0.57\frac{\$}{\text{kg}}$
Cost of framework, rebar tying, concrete pouring	$8.33\frac{\$}{\text{kg}}$

$$\frac{M_3}{M_2} = \frac{I_3}{I_2} = \frac{bh^3}{hb^3} \rightarrow \frac{M_3}{M_2} = \frac{h^2}{b^2}. \tag{1}$$

Table 5 and Table 6 show the ratio of and dimensions of the column sections, respectively.

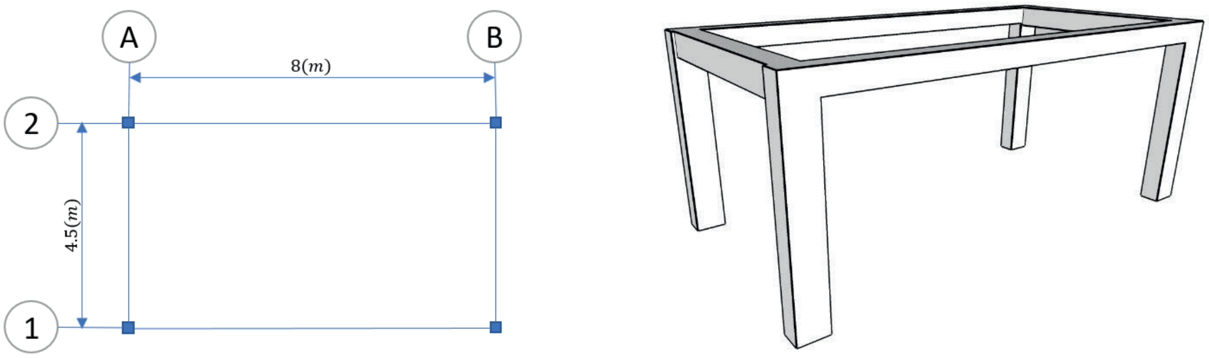


Fig. 2 The 1-story concrete structure with the height of 3.5 m

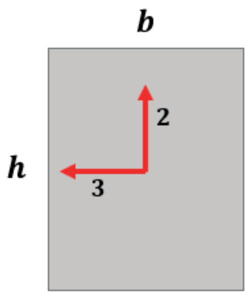


Fig. 3 Schematic of section

Table 5 M3/M2

Position of columns	story 1
1 – *A*	0.6
1 – *B*	0.6
2 – *A*	0.6
2 – *B*	0.6

Table 6 Depth/width ratios of the columns

Position of columns	story 1
1 – *A*	0.7746
1 – *B*	0.7746
2 – *A*	0.7746
2 – *B*	0.7746

According to Table 6, a list of sections for each column can be created. The steps of the considered method are as follows:

1. The depth of column section starts from 35 cm to 70 cm with the steps of 5 cm, and the width is created in ETABS software based on the depth and Eq. (I). These created sections are assigned to each column one by one.
2. The required reinforcements of each column are extracted
3. Each section which its required reinforcements are in the range of 1% to 4% is saved.
4. Each section having less material cost and payment is chosen among step 3 sections.
5. Square sections starting from 30 cm to 70 cm with the steps of 5 cm are used of for beams.
6. Each section which its width is less than or equal to width of columns connected is saved.
7. Each section having less material cost and payment is chosen among step 6 sections.

After coding these steps and analyzing the model, the following results are obtained:

Optimized sections of columns and beams are shown in Table 7 and Table 8, respectively. Also, Table 9 shows the percentage of the column longitudinal reinforcement.

Table 7 Optimized column sections

Position of columns	Depth(m)	Width(m)
1 – *A*	0.35	0.5
1 – *B*	0.35	0.5
2 – *A*	0.35	0.5
2 – *B*	0.35	0.5

Table 8 Optimized beam sections

Position of columns	Depth(m)	Width(m)
1	0.35	0.35
2	0.35	0.35
A	0.4	0.4
B	0.4	0.4

Table 9 Percentage of the longitudinal reinforcement of the optimized columns

Position of columns	story 1
1 – *A*	1.41
1 – *B*	1.41
2 – *A*	1.41
2 – *B*	1.41

Table 10 Final optimum cost and the computational time in considered Cascade algorithm

Final cost	Time elapsed
564.543 $	608.844499 seconds

The final optimum cost and the computational time in the considered algorithm are shown in Table 10.

According to the required reinforcement area of columns, genetic algorithm is used for optimizing the arrangement of reinforcements of column sections under the following constraints: (clear cover = 4.5 cm).

1. The bars with diameter of 16, 20 and 25 mm are used.
2. Free bar spacing should be more than 7cm and less than 20 cm.
3. Demand capacity ratio of columns should be less than 1.

Figs. 4 and 5 show the optimized section of the columns and the whole structure, respectively. Demand capacity ratio of the columns is 0.964. It is observed that all the constraints are satisfied. Diameter of the bars is 16 mm.

2.1.2 A 6-strory RC structure

The goal of this section, as previous, is optimization of beams and columns section using Cascade algorithm including the optimum dimension of section in the first step and the arrangement of reinforcement in the next as two mechanisms.

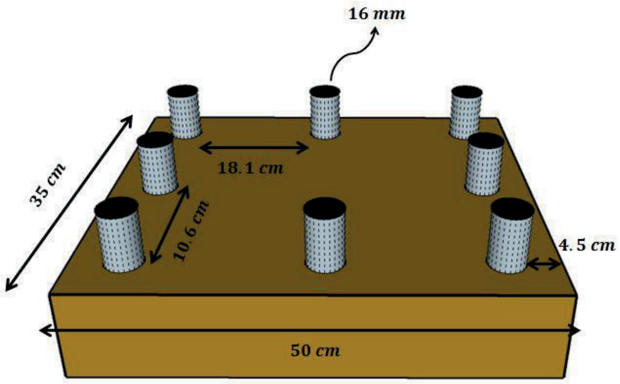


Fig. 4 Optimized section for columns

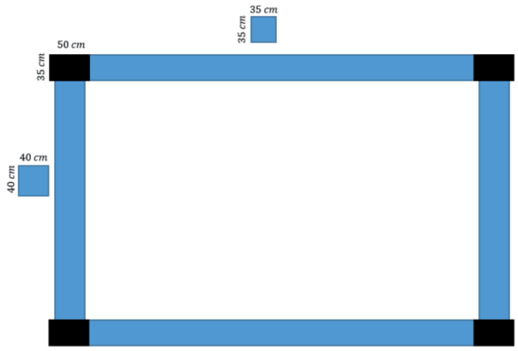


Fig. 5 The plan of optimized structure

In the following, the effect of considered Cascade algorithm on a 6-story concrete structure as shown in Fig. 6(a) with the height of 3.5 m in each story is investigated. Because of the symmetry and in order to reduce the volume of the data, the tables of data in this section are related to the part of the plan in the dash line shown in Fig. 6(b).

The data of earthquake [35], loading [35], materials [36], and costs are shown in Table 11 to Table 14. By fitting the experimental principle of several contractors and frame worker, the following equation is obtained for payment of the columns:

payment = ([(Column dimension(cm) – 30) + (Column dimension(cm) – 30)] × Payment rates + 1) × Payment for 30 cm × 30 cm column

For example, the payment for 40 cm × 40 cm column is: ([(40 – 30) + (40 – 30)] × 0.003 + 1) × 8.33 = 8.83

Table 11 Earthquake parameter

Base shear Coefficient (C)	Building height Exponent (K)
0.1022	1.23

Table 12 Loading

Load	(kgf, m)
Dead on stories	$600\,\frac{\text{kgf}}{\text{m}^2}$
Live on stories	$200\,\frac{\text{kgf}}{\text{m}^2}$
Dead on roof	$650\,\frac{\text{kgf}}{\text{m}^2}$
Live on roof	$150\,\frac{\text{kgf}}{\text{m}^2}$
Dead on perimeter beams	$250\,\frac{\text{kgf}}{\text{m}^2}$

Table 13 Material

Materials	Strength	Weight
concrete	$f_c' = 28\times10^5\,\frac{\text{kgf}}{\text{m}^2}$	$2500\,\frac{\text{kgf}}{\text{m}^2}$
Steel of longitudinal bars	$f_y = 400\times10^5\,\frac{\text{kgf}}{\text{m}^2}$ $f_u = 600\times10^5\,\frac{\text{kgf}}{\text{m}^2}$	$7850\,\frac{\text{kgf}}{\text{m}^2}$
Steel of confinement bars	$f_y = 300\times10^5\,\frac{\text{kgf}}{\text{m}^2}$ $f_u = 500\times10^5\,\frac{\text{kgf}}{\text{m}^2}$	$7850\,\frac{\text{kgf}}{\text{m}^2}$

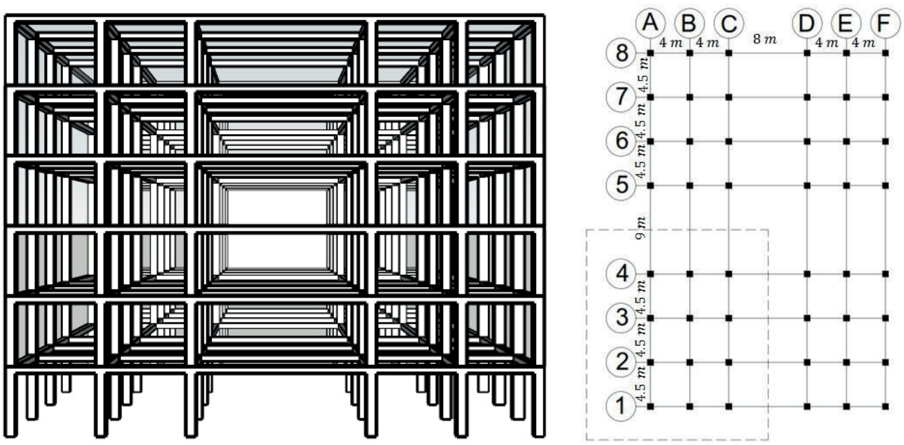


Fig. 6 The 6-story concrete structure with the height of 3.5 m in each story

Table 14 Costs

	Costs
concrete	$0.01\frac{\$}{kg}$
steel	$0.57\frac{\$}{kg}$
Land	$1000\frac{\$}{kg}$
Payment for 30 cm × 30 cm column (Framework, rebar tying, concrete pouring)	$8.33\frac{\$}{kg}$
Payment rates	$0.3\%\frac{1}{cm}$

All constraints mentioned below are satisfied by the proposed method:

1. Section dimension of upper story column should be less than its lower one.
2. Width of each beam should be less than or equal to the width of columns connected to.
3. Bending, shear and torsion demand of each beam should be less than their resistance.
4. Ratio of section reinforcement of each beam should be less than maximum and more than minimum defined in [36].
5. Bars with diameter of 16, 20 and 25 mm are used.
6. Free bar spacing should be more than 7 cm and less than 20 cm.
7. Diameter and number of bars in upper column should be less than those in lower one.
8. Demand capacity ratio of columns should be less than allowable 1.

According to Table 15 showing $\frac{M_3}{M_2}$ as the first step of proposed method for selecting optimum sections, a list of sections can be created for each column. The steps of the considered method are the same as describe in Section 2.1.1. Table 16 and Table 17 show created optimum sections and the percentage of longitudinal reinforcement, respectively. Final cost of beams and columns is 97179.52 $.

Table 15 The ratios

Position of column	story 6	story 5	story 4	story 3	story 2	story 1
1 – *A*	1	1	1	1	1	1
1 – *B*	1.1	1.3	1.5	1.6	1.6	1.1
1 – *C*	0.60	0.70	0.70	0.60	0.60	0.90
2 – *A*	0.90	0.80	0.70	0.70	0.70	0.90
2 – *B*	1.1	1	1.1	1.1	1.1	1
2 – *C*	0.50	0.80	0.80	0.90	0.90	1
3 – *A*	0.80	0.80	0.70	0.70	0.70	0.90
3 – *B*	1	1	1.1	1.1	1.1	1
3 – *C*	0.50	0.80	0.80	0.90	0.90	1
4 – *A*	0.50	0.60	0.60	0.60	0.60	0.90
4 – *B*	0.50	0.80	0.80	0.90	0.90	1
4 – *C*	0.90	0.90	0.90	0.90	0.90	1

Table 16 Created optimum sections (the unit is meter)

Position of column	story 6		story 5		story 4		story 3		story 2		story 1	
	Width	Depth	Width	Depth	Width	Depth	Width	Depth	Width	Depth	Width	Depth
1 – *A*	0.40	0.35	0.40	0.35	0.40	0.35	0.40	0.40	0.40	0.40	0.40	0.45
1 – *B*	0.30	0.35	0.30	0.35	0.30	0.40	0.40	0.45	0.40	0.55	0.50	0.50
1 – *C*	0.50	0.35	0.40	0.35	0.40	0.35	0.50	0.40	0.50	0.40	0.50	0.50
2 – *A*	0.40	0.35	0.40	0.35	0.40	0.35	0.50	0.40	0.50	0.45	0.50	0.50
2 – *B*	0.30	0.35	0.40	0.35	0.40	0.40	0.40	0.45	0.40	0.45	0.50	0.50
2 – *C*	0.50	0.35	0.40	0.40	0.40	0.40	0.50	0.45	0.50	0.45	0.50	0.50
3 – *A*	0.40	0.35	0.40	0.35	0.40	0.35	0.40	0.35	0.50	0.45	0.50	0.50
3 – *B*	0.40	0.35	0.40	0.40	0.40	0.45	0.40	0.45	0.40	0.45	0.50	0.50
3 – *C*	0.50	0.35	0.40	0.40	0.40	0.40	0.50	0.45	0.50	0.45	0.50	0.50
4 – *A*	0.50	0.35	0.50	0.35	0.50	0.40	0.50	0.35	0.50	0.40	0.50	0.50
4 – *B*	0.50	0.35	0.40	0.40	0.40	0.40	0.50	0.45	0.50	0.50	0.50	0.50
4 – *C*	0.50	0.45	0.40	0.40	0.50	0.45	0.50	0.50	0.50	0.50	0.60	0.60

Table 17 Percentage of the longitudinal reinforcement

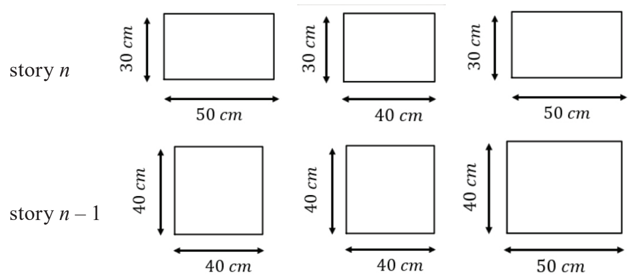
Position of column	story 6	story 5	story 4	story 3	story 2	story 1
1 – *A*	1	1	1.136	1.333	1.481	2.261
1 – *B*	1.664	1.979	2.920	1.566	1	1.680
1 – *C*	1.008	1.643	2.309	1.279	1	2.184
2 – *A*	1	1.398	1.539	1	1	1.791
2 – *B*	1.305	1.416	1.997	3.809	2.076	1.625
2 – *C*	1.229	1.696	2.459	1.388	1.254	2.520
3 – *A*	1	1.409	2.087	1.400	1	1.725
3 – *B*	1	1.273	1.367	1.760	1.394	1.624
3 – *C*	1.275	1.722	2.592	1	1.044	2.627
4 – *A*	1	1.116	1	1	1.439	2.330
4 – *B*	1.437	2.499	3.709	1	1.380	2.726
4 – *C*	1.861	2.727	2.694	1.579	2.688	3.762

Because of applying the constraint number 1, if section dimensions of upper column are more than bottom column, there will be two methods: a) an upper column dimension is replaced with the same in bottom column. b) a bottom column dimension is replaced with the same as in the upper column. The description of these two methods is illustrated in Table 18. By comparison these two methods, the optimized method is chosen. Table 19 and Table 20 are related to method (a). Table 21 and Table 22 are related to method (b). Final cost of method (a) and method (b) are 5732.77 $ and 5815.12 $, respectively. It can be seen the first state has lower cost.

By applying the constraints number 5, 6, 7 and 8, Fig. 7 shows the column optimum section of 2 – *A* in story 5. Also, the used column sections in the frames and the utilized beam sections in the stories of the structure are displayed in Fig. 8 to Fig. 11.

Table 18 Illustration of method (a) and method (b)

	Sections used before applying (a) or (b)	method (a)	method (b)



Tables 23 and 24 are related to reinforcement arrangement and column Demand capacity ratio, respectively. Also, Table 25 shows beams section dimension satisfying the constraints numbers 2 and 3. Beams section dimension and rebar ratio of each section beam defining in constraint 4 are

Table 19 Column section dimensions in method (a) (the unit is meter)

Position of column	story 6		story 5		story 4		story 3		story 2		story 1	
	Width	Depth	Width	Depth	Width	Depth	Width	Depth	Width	Depth	Width	Depth
1 – *A*	0.40	0.35	0.40	0.35	0.40	0.35	0.40	0.40	0.40	0.40	0.40	0.45
1 – *B*	0.30	0.35	0.30	0.35	0.30	0.40	0.40	0.45	0.40	0.55	0.50	0.55
1 – *C*	0.50	0.35	0.50	0.35	0.50	0.35	0.50	0.40	0.50	0.40	0.50	0.50
2 – *A*	0.40	0.35	0.40	0.35	0.40	0.35	0.50	0.40	0.50	0.45	0.50	0.50
2 – *B*	0.30	0.35	0.40	0.35	0.40	0.40	0.40	0.45	0.40	0.45	0.50	0.50
2 – *C*	0.50	0.35	0.50	0.40	0.50	0.40	0.50	0.45	0.50	0.45	0.50	0.50
3 – *A*	0.40	0.35	0.40	0.35	0.40	0.35	0.40	0.35	0.50	0.45	0.50	0.50
3 – *B*	0.40	0.35	0.40	0.40	0.40	0.45	0.40	0.45	0.40	0.45	0.50	0.50
3 – *C*	0.50	0.35	0.50	0.40	0.50	0.40	0.50	0.45	0.50	0.45	0.50	0.50
4 – *A*	0.50	0.35	0.50	0.35	0.50	0.40	0.50	0.40	0.50	0.40	0.50	0.50
4 – *B*	0.50	0.35	0.50	0.40	0.50	0.40	0.50	0.45	0.50	0.50	0.50	0.50
4 – *C*	0.50	0.45	0.50	0.45	0.50	0.45	0.50	0.50	0.50	0.50	0.60	0.60

Table 20 Percentage of longitudinal reinforcement in method (a)

Position of column	story 6	story 5	story 4	story 3	story 2	story 1
1 – *A*	1	1	1	1.335	1.477	2.057
1 – *B*	1.662	1.579	2.165	1.546	1	1.734
1 – *C*	1	1	1.038	1.125	1	1.783
2 – *A*	1	1.209	1.342	1	1	1.756
2 – *B*	1.309	1.143	1.686	3.144	1.714	1.615
2 – *C*	1.195	1	1	1.175	1	1.980
3 – *A*	1	1.239	1.683	1.349	1	1.700
3 – *B*	1.024	1.099	1.231	1.691	1.107	1.616
3 – *C*	1.247	1	1	1	1	2.096
4 – *A*	1	1	1	1	1.263	1.856
4 – *B*	1.409	1	1.511	1	1.179	2.226
4 – *C*	1.812	1	1.536	1.294	2.094	3.291

Table 21 Column section dimension in method (b)

Position of column	story 6		story 5		story 4		story 3		story 2		story 1	
	width	depth	width	depth	width	depth	width	depth	width	depth	width	depth
1 – *A*	0.40	0.35	0.40	0.35	0.40	0.35	0.40	0.40	0.40	0.40	0.40	0.45
1 – *B*	0.30	0.35	0.50	0.35	0.30	0.40	0.40	0.45	0.40	0.50	0.50	0.50
1 – *C*	0.40	0.35	0.40	0.35	0.40	0.35	0.50	0.40	0.50	0.40	0.50	0.50
2 – *A*	0.40	0.35	0.45	0.35	0.40	0.35	0.50	0.40	0.50	0.45	0.50	0.50
2 – *B*	0.30	0.35	0.45	0.35	0.40	0.40	0.40	0.45	0.40	0.45	0.50	0.50
2 – *C*	0.40	0.35	0.45	0.40	0.40	0.40	0.50	0.45	0.50	0.45	0.50	0.50
3 – *A*	0.40	0.35	0.45	0.35	0.40	0.35	0.40	0.35	0.50	0.45	0.50	0.50
3 – *B*	0.40	0.35	0.45	0.40	0.40	0.45	0.40	0.45	0.40	0.45	0.50	0.50
3 – *C*	0.40	0.35	0.45	0.40	0.40	0.40	0.50	0.45	0.50	0.45	0.50	0.50
4 – *A*	0.50	0.35	0.40	0.35	0.50	0.35	0.50	0.35	0.50	0.40	0.50	0.50
4 – *B*	0.40	0.35	0.50	0.40	0.40	0.40	0.50	0.45	0.50	0.50	0.50	0.50
4 – *C*	0.40	0.40	0.50	0.40	0.50	0.45	0.50	0.50	0.50	0.50	0.60	0.60

Table 22 Percentage of the longitudinal reinforcement in method (b)

Position of column	story 6	story 5	story 4	story 3	story 2	story 1
1 – *A*	1	1	1.169	1.303	1.482	2.069
1 – *B*	1.665	1.734	2.521	1.591	1	1.690
1 – *C*	1.638	1.584	1.810	1.202	1	1.820
2 – *A*	1	1.299	1.425	1	1	1.776
2 – *B*	1.323	1.321	1.802	3.049	1.736	1.621
2 – *C*	1.765	1.629	1.785	1.275	1	2.045
3 – *A*	1	1.325	1.780	1.293	1.003	1.722
3 – *B*	1.054	1.187	1.276	1.662	1.235	1.621
3 – *C*	1.804	1.681	1.917	1	1	2.153
4 – *A*	1	1	1.050	1	1.290	1.866
4 – *B*	2.208	2.171	2.887	1	1.150	2.248
4 – *C*	4.240	2.772	2.182	1.209	2.109	3.348

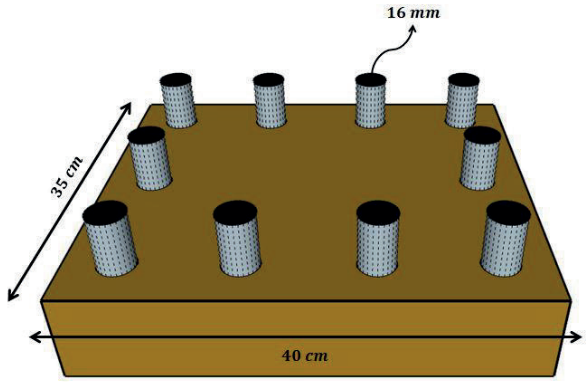


Fig. 7 Reinforcement arrangement of the 2-C column in the story 5 using the Genetic algorithm

shown in Tables 25 and 26, respectively. Fig. 7 shows the column optimum section of $2 - A$ in story 5. Also, the used column sections in the frames and the utilized beam sections in the stories of the structure are displayed in Fig. 11.

3 Conclusions

This paper has provided a Cascade algorithm combining two phases including a new method and the Genetic algorithm for optimizing both beams and columns sections dimensions and rebar arrangement in concrete structures. Two three-dimensional example, 1-story and 6-story, small and large-scale concrete structure respectively, have been optimized by this Cascade algorithm as numerical examples. The first phase includes two mechanisms for extracting needed beams and columns section dimension simultaneously. The first mechanism based on bending force applying to each direction of local coordinate of column section has been provided. Column sections satisfying the considered constraints have been saved. The section with minimum cost has been chosen among those saved. The second mechanism consists of obtaining section dimensions of beams based on the related constraint

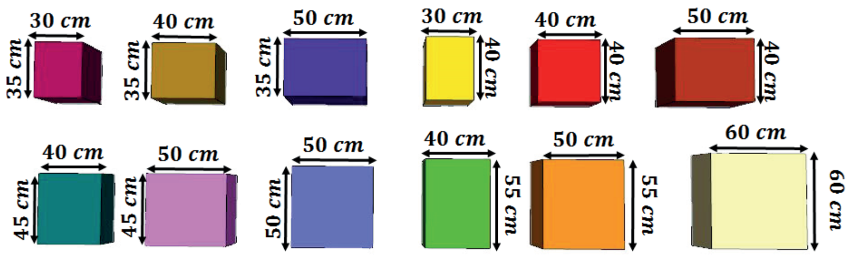


Fig. 8 The used column sections

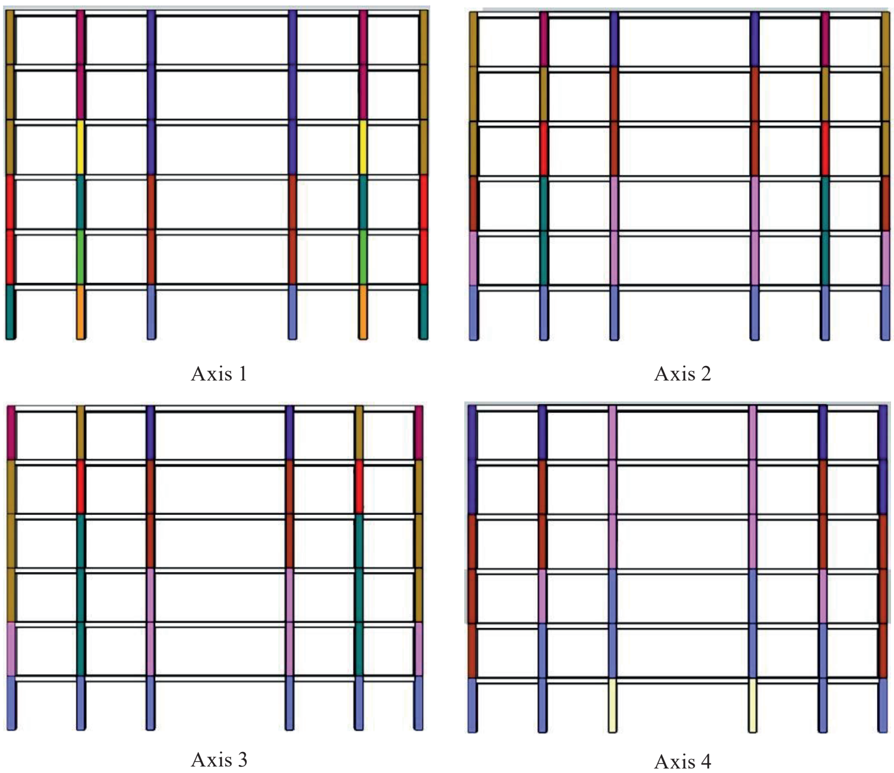


Fig. 9 Display of columns in frame 1 to 4 of the structure

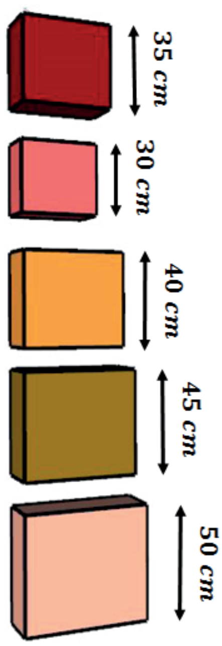


Fig. 10 The used beam sections

satisfaction and selecting those with minimum cost. In the second phase, optimizing the arrangement of the column rebar is provided with the help of the Genetic algorithm. The entire Cascade algorithm is carried out by MATLAB and ETABS interfacing.

Conflict of interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

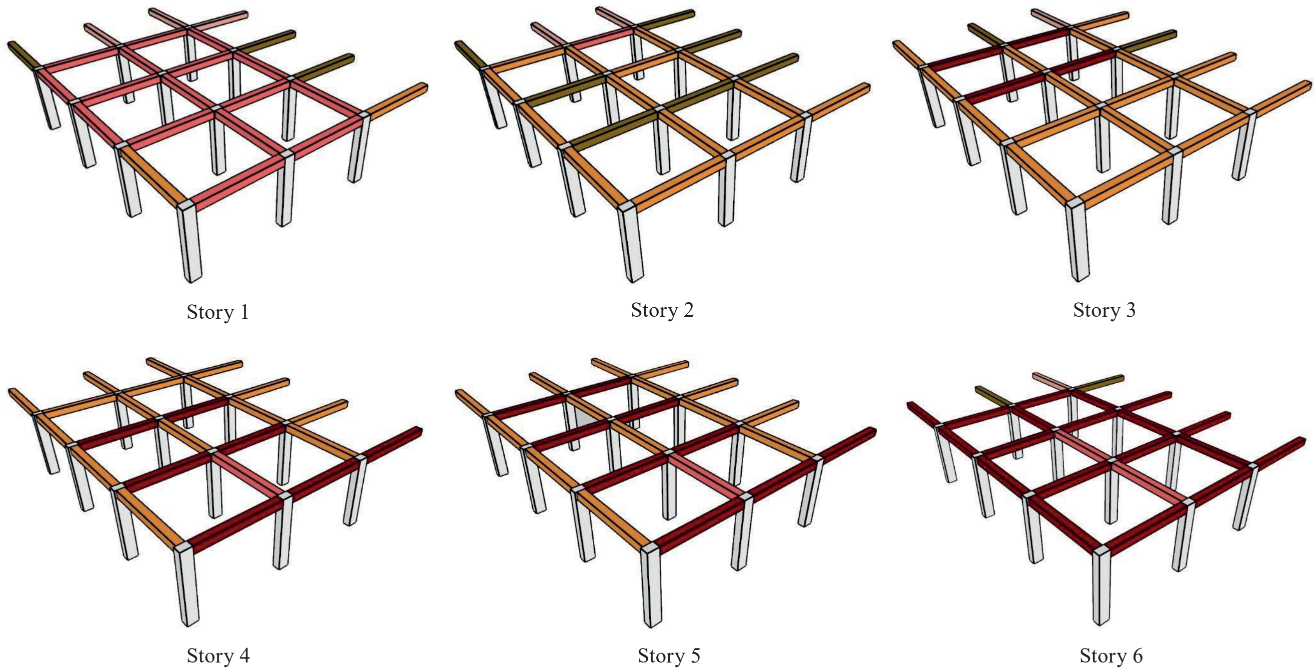


Fig. 11 Display of the beams in the story 1 to story 6

Table 23 Reinforcement arrangement of the columns (number of rebar in the direction of the local axis 3- number of rebar in the direction of the local axis 2-diameter of rebar(mm))

Position of column	story 6	story 5	story 4	story 3	story 2	story 1
1 – *A*	3-3-T16	3-3-T16	3-3-T16	4-3-T16	4-4-T16	4-4-T20
1 – *B*	4-4-T16	4-4-T16	4-4-T16	5-4-T16	6-4-T16	6-6-T20
1 – *C*	3-4-T16	3-4-T16	3-5-T16	3-5-T16	3-5-T16	5-5-T25
2 – *A*	3-3-T16	3-4-T16	3-4-T16	3-5-T16	3-5-T16	5-5-T20
2 – *B*	3-3-T16	3-3-T16	4-4-T16	4-4-T20	4-4-T25	5-5-T25
2 – *C*	3-5-T16	3-5-T16	3-5-T16	5-5-T16	5-5-T16	5-5-T25
3 – *A*	3-3-T16	3-4-T16	3-4-T20	3-4-T20	3-5-T20	5-5-T20
3 – *B*	3-3-T16	3-4-T16	3-4-T16	4-4-T20	4-4-T20	5-5-T20
3 – *C*	3-6-T16	4-6-T16	4-6-T16	5-6-T16	5-6-T16	5-6-T25
4 – *A*	3-4-T16	3-4-T16	3-5-T16	3-5-T16	4-5-T16	5-5-T25
4 – *B*	3-6-T16	4-6-T16	4-6-T16	5-6-T16	5-6-T16	5-6-T25
4 – *C*	5-6-T20	5-6-T20	5-6-T20	5-6-T20	5-6-T20	6-6-T25

Table 24 Demand capacity ratio of the columns

Position of column	story 6	story 5	story 4	story 3	story 2	story 1
1 – *A*	0.67404	0.73503	0.87739	0.98918	0.95588	0.93585
1 – *B*	0.87390	0.87187	0.91025	0.99092	0.66646	0.93402
1 – *C*	0.93638	0.84851	0.94807	0.95049	0.93100	0.90938
2 – *A*	0.70996	0.88605	0.97051	0.86327	0.96500	0.98966
2 – *B*	0.84908	0.98338	0.95804	0.99032	0.80932	0.83388
2 – *C*	0.92772	0.85318	0.92711	0.95021	0.97567	0.94188
3 – *A*	0.74217	0.89873	0.94544	0.87184	0.73080	0.92484
3 – *B*	0.93987	0.90891	0.91052	0.94017	0.88073	0.96140
3 – *C*	0.85428	0.78210	0.87816	0.86490	0.93879	0.92931
4 – *A*	0.87437	0.88707	0.88110	0.85421	0.99500	0.92469
4 – *B*	0.94141	0.82952	0.98804	0.78378	1.00915	0.94701
4 – *C*	0.92778	0.75546	0.91600	0.93334	0.92358	0.99324

Table 25 Beams section dimensions

Position of beams	story 6	story 5	story 4	story 3	story 2	story 1
1 – *A* – *B*	0.35	0.35	0.35	0.40	0.40	0.30
1 – *B* – *C*	0.35	0.35	0.35	0.40	0.40	0.30
1 – *C* – *D*	0.35	0.35	0.35	0.40	0.40	0.40
2 – *A* – *B*	0.35	0.35	0.35	0.40	0.45	0.30
2 – *B* – *C*	0.35	0.35	0.35	0.40	0.45	0.30
2 – *C* – *D*	0.35	0.40	0.40	0.40	0.45	0.45
3 – *A* – *B*	0.35	0.35	0.35	0.35	0.45	0.30
3 – *B* – *C*	0.35	0.35	0.35	0.35	0.40	0.30
3 – *C* – *D*	0.35	0.40	0.40	0.45	0.45	0.45
4 – *A* – *B*	0.35	0.35	0.40	0.35	0.40	0.30
4 – *B* – *C*	0.35	0.35	0.40	0.35	0.30	0.30
4 – *C* – *D*	0.45	0.40	0.40	0.40	0.45	0.50
1 – 2 – *A*	0.35	0.40	0.40	0.40	0.40	0.40
2 – 3 – *A*	0.35	0.40	0.40	0.40	0.40	0.30
3 – 4 – *A*	0.35	0.40	0.40	0.40	0.40	0.30
4 – 5 – *A*	0.35	0.40	0.40	0.40	0.45	0.45
1 – 2 – *B*	0.30	0.30	0.30	0.40	0.40	0.30
2 – 3 – *B*	0.30	0.40	0.40	0.40	0.40	0.30
3 – 4 – *B*	0.35	0.40	0.40	0.40	0.40	0.30
4 – 5 – *B*	0.45	0.40	0.40	0.45	0.50	0.50
1 – 2 – *C*	0.35	0.40	0.40	0.40	0.40	0.30
2 – 3 – *C*	0.35	0.40	0.40	0.40	0.40	0.30
3 – 4 – *C*	0.35	0.40	0.40	0.40	0.40	0.30
4 – 5 – *C*	0.50	0.40	0.40	0.50	0.50	0.50

Table 26 Rebar ratios of beam sections

Position of beams	story 6	story 5	story 4	story 3	story 2	story 1
$1-A-B$	0.00640	0.00661	0.00889	0.01533	0.01628	0.00924
$1-B-C$	0.00773	0.00699	0.00963	0.0168	0.0174	0.00936
$1-C-D$	0.00781	0.01256	0.01373	0.01814	0.01794	0.01745
$2-A-B$	0.00722	0.00560	0.00942	0.01687	0.02016	0.00975
$2-B-C$	0.00920	0.00581	0.0101	0.01834	0.02064	0.00975
$2-C-D$	0.01018	0.01187	0.01695	0.01709	0.01672	0.02188
$3-A-B$	0.00724	0.00572	0.01229	0.01367	0.0192	0.00987
$3-B-C$	0.00944	0.00763	0.01343	0.01431	0.01669	0.00965
$3-C-D$	0.01018	0.01182	0.01335	0.01798	0.01734	0.02165
$4-A-B$	0.00774	0.00774	0.0153	0.01116	0.01744	0.00953
$4-B-C$	0.00916	0.01449	0.01666	0.01118	0.01068	0.00932
$4-C-D$	0.00742	0.01346	0.01792	0.01871	0.01976	0.01481
$1-2-A$	0.00360	0.00676	0.00901	0.01088	0.01219	0.01474
$2-3-A$	0.00645	0.00660	0.00850	0.01026	0.01209	0.00949
$3-4-A$	0.00765	0.00738	0.01002	0.01132	0.01229	0.00955
$4-5-A$	0.00696	0.00995	0.01411	0.01504	0.01558	0.01993
$1-2-B$	0.00724	0.00545	0.00686	0.01899	0.02196	0.01365
$2-3-B$	0.00710	0.00699	0.00993	0.01065	0.01095	0.01353
$3-4-B$	0.00924	0.00793	0.01068	0.01206	0.01236	0.01015
$4-5-B$	0.00713	0.01024	0.01367	0.01806	0.01957	0.01484
$1-2-C$	0.00780	0.00747	0.00978	0.01168	0.01254	0.01017
$2-3-C$	0.00771	0.00737	0.00970	0.01151	0.01221	0.0102
$3-4-C$	0.00896	0.00819	0.01108	0.01226	0.01324	0.01002
$4-5-C$	0.00827	0.01233	0.01314	0.0215	0.02246	0.01367

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