 https://doi.org/10.3311/PPci.23460

Periodica Polytechnica Civil Engineering, 68(2), pp. 588–599, 2024

Optimal Design of Shear Walls for Minimizing the Structural Torsion Using Cascade Optimization Algorithm

Hossein Ali Rahimi Bondarabadi[1], Ali Kaveh[2*], Pariya Salimi[3]

[1] Department of Civil Engineering, Yazd University, P. O. B. 8915818411, Yazd, Iran
[2] School of Civil Engineering, Iran University of Science and Technology, P. O. B. 16846-13114, Tehran, Iran
[3] Department of Civil Engineering, Yazd University, P. O. B. 8915818411, Yazd, Iran
[*] Corresponding author, e-mail: alikaveh@iust.ac.ir

Received: 16 September 2023, Accepted: 29 December 2023, Published online: 07 February 2024

Abstract

Due to a large number of design variables involved in the optimization of RC structures, a multi stage cascade optimization is used. This algorithm speeds up an accurate optimal design for the large-scale structures reducing the number of variables by dividing single optimization to a number of stages such that the optimization of each stage starts with the optimum results of the previous one. Here, the first stage of cascade optimization method uses the assembling of the stiffness matrix of the entire RC structure for minimizing the torsion of the stories as an objective function. By assembling the stiffness matrix of the RC frame without shear walls and the shear wall alone, the length and thickness of the shear wall on each story are taken as design variables of the first stage. The optimized reinforcement arrangement of walls according to the required wall rebar area is the goal of the next stage. Using this method, designing the RC structure and minimizing the structural torsion of each floor simultaneously, can result in different length and thickness for the shear walls in different stories. Reducing the structural torsion leads to economical structure. Here, the MATLAB and ETABS interfacing are utilized.

Keywords

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

1 Introduction

Optimization of structure is one of the popular fields in civil engineering. For this purpose, many meta-heuristic algorithms have been developed such as Colliding Bodies Optimization [1, 2], Enhance Bat Algorithm [3], Vibration Particle System [4, 5], Black Hole Mechanics Optimization [6], and many other optimization algorithms [7–13]. These algorithms are used alone or in combination with other algorithms for optimizing many types of structures such as domes, trusses, frames being steel or concrete via minimizing the weight or the cost as an objective function ordinarily.

In the research of Boulaouad and Amour [14], the Displacement-Based Design method has been used for RC structures. The metaheuristic algorithms so-called Enhanced Colliding Bodies Optimization (ECBO) and the Non-dominated Sorting Enhanced Colliding Bodies Optimization (NSECBO) were used for optimization of RC frame by Kaveh [15]. The research of Liu et al. [16] aimed in designing collision-free layout of rebar in RC structures automatically. Salimi et al. used cascade algorithm and genetic algorithm for optimizing the RC structures [17].

Shear walls mainly withstanding lateral loads due to wind or earthquake are one of the most commonly members used in structures. Since the cost of materials used in shear walls in RC structures influences the final manufacturing cost and economic issues as one of the today's most important concerns, optimization of this member is one of the challenges for experienced structural engineers.

Atabay optimized the cost of 3D beamless RC shear walls by genetic algorithm [18]. In the research of Kaveh and Zakian [19], charged system search algorithm was used for optimizing seismic design of RC dual systems according to the ACI code. The research of Kaveh and Zakian [19], combined a ground structure program formulation, a modified evolutionary algorithm, and innovative computational techniques for accelerating the optimization process shear wall layout in tall buildings. Nikzad and Yoshitomi [20] utilized an optimization procedure for designing shear walls in the RC

Cite this article as: Rahimi Bondarabadi, H. A., Kaveh, A., Salimi, P. "Optimal Design of Shear Walls for Minimizing the Structural Torsion Using Cascade Optimization Algorithm", Periodica Polytechnica Civil Engineering, 68(2), pp. 588–599, 2024. https://doi.org/10.3311/PPci.23460

structures. In the research of Kaveh and Farhadmanesh [21], three well-known metaheuristic algorithms comprising of Colliding Bodies Optimization, Enhanced Colliding Bodies Optimization, and Particle Swarm Optimization were used for optimizing low seismic and high seismic design of steel plate shear wall. In the research of Talatahari and Rabiei [22], Quantum Charged System Search (QCSS) was developed improving the convergence of the CSS for optimizing shear wall in RC structures considering as lateral resistant system focusing on both structural and architectural requirements. In the research of Patidar and Jamle [23], 12 stability cases of shear wall with different thickness and grade of concrete located at the core of apartment building located in seismic zone III were modelled for optimizing the stability of tall buildings. In the research of Lou et al. [24], the optimization of shear walls in tall buildings was carried out with a new design methodology based on the Tabu Search (TS) algorithm and an extended Evolutionary Structural Optimization (ESO) [25]. Kaveh et al. used different metaheuristic algorithms comprising of SSOA, and Plasma Generation Optimization, PGO, for optimizing RC cantilever retaining walls against different loading conditions in [26] and [27]. Lou et al. [28], optimized the shear walls in high-raised buildings with a hybrid optimization framework. In the research of Abualreesh et al. [29], the optimization of RC shear wall-frame structures was performed under El-Centro earthquake with known safety level by an additional constraint, known as the desired level of reliability.

Designing shear walls normally start with floor plan generated by architect and passed to structural engineer for its locating decision satisfying some required constraints as per the related code. Since these steps are repetitive, inefficient, and time-consuming process needing a lot of time for trial and error, hence it cannot be used for achieving the optimum results. The presence of torsion irregularity, meaning the torsion exceeding from 1.2, the redundancy factor of 1.3 may cause divergence from optimum design of the structures [30]. Automatic program for optimum design of shear walls resisting the lateral loads, satisfying the required constraints, and protecting the structure from irregularity requires high experience of the engineers.

In the present method, first the locations of shear walls are decided by structural engineer and introduced to a program as an input. Then the program starts to minimize the structural torsion due to the earthquake as objective function under considered constraints. The length and thickness of the wall which are the design variables in each story taken are as much as needed and not necessarily the same as the wall in the previous story. This optimization program uses the cascade algorithm combining the genetic algorithm and a recent method increasing the speed of the process,

2 Methodology

The purpose of the cascade algorithm used in this paper is the minimization of structural torsion in 3-dimensions RC dual systems as the first stage and the arrangement of the rebars in the next one [27] and [28]. The first stage of this process includes the application of the new method and the selected metaheuristic algorithm applied to shear walls story by story while satisfying all considered constraints. According to Fig. 1 and Eq. (3), the new method uses the assembled condensed stiffness matrix of frames and condensed stiffness matrix of shear wall for minimizing the torsion of the stories. This process evaluates the length and thickness of shear wall as the design variables in the utilized meta-heuristic algorithm with related constraints. Noteworthy, the condensed stiffness matrix of frame is related to the three degrees of freedom of each story mass center which are transition along X and Y and rotation around Z axes. Also, the condensed stiffness matrix of shear wall is the transitional degree of freedom along the shear wall in each story horizontally, Fig. 1. Equation (4) is an objective function of genetic algorithm causing minimization of torsional structure and using materials.

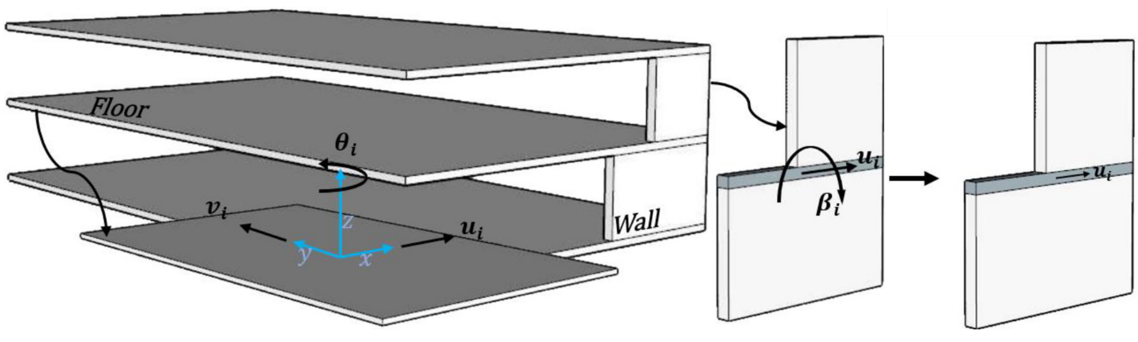


Fig. 1 Considered degree of freedom in each story

The optimization process of reinforcement arrangement will be performed in the next stage of the cascade algorithm with the objective function expressed as in Eq. (5). Fig. 2 illustrates the flowchart of the explained method.

$$\boldsymbol{K}_{\text{wall}} = \begin{bmatrix} \boldsymbol{k}_{uu} & \boldsymbol{k}_{u\beta} \\ \boldsymbol{k}_{u\beta}^{T} & \boldsymbol{k}_{\beta\beta} \end{bmatrix} \quad (1)$$

$$\boldsymbol{K}_{\text{condensed of wall}} = \left[\boldsymbol{k}_{uu}\right] - \left[\boldsymbol{k}_{u\beta}\right]\left[\boldsymbol{k}_{\beta\beta}\right]^{-1}\left[\boldsymbol{k}_{u\beta}\right]^{T} \quad (2)$$

$$\boldsymbol{K}_{\text{total}} = \boldsymbol{K}_{\text{condensed of wall}} + \boldsymbol{K}_{\text{condensed of each story}} = \begin{bmatrix} \boldsymbol{k}_{11} & \cdots & \boldsymbol{k}_{1n} \\ \vdots & \ddots & \vdots \\ \boldsymbol{k}_{n1} & \cdots & \boldsymbol{k}_{nn} \end{bmatrix} \quad (3)$$

$$\text{Fitness function of stage 1 of cascade algorithm} = \theta_i \quad (4)$$

$$\text{Fitness function of stage 2 of cascade algorithm} = \text{required rebar Area} - C \times \text{Area of used rebar} \quad (5)$$

$\boldsymbol{K}_{\text{total}}$ = assembled stiffness matrix of frames and condenced shear walls

θ = torsion of story

n = number of story

C = number of used rebars

The constraints expected to be satisfied in the first stage of cascade optimization are described in detail in [17].

The constraints expected to be satisfied in the second stage of cascade optimization are as follow:

1. The length of each shear walls should be enough to be considered a wall as per the code.
2. The length of each wall on each floor should be enough to not create geometric irregularities.
3. The length of each wall on each floor should be enough to not create short beam.
4. The length of the wall of upper story should be less than its lower one.
5. The thickness of the wall of upper story should be less than its lower one.
6. The walls thickness is 15 to 30 cm.
7. The walls resistance should be more than the demand.
8. The walls must resist at least 50% of the base shear.
9. The frames must resist at least 25% of the base shear.
10. The drift of the structure must be less than allowable drift.

The constraints expected to be satisfied in the third stage of cascade optimization (cover = 3 cm) are as follow:

1. Bars with diameter of 12, 16, 20 and 25 mm are used.
2. Rebar spacing and ratio of sections reinforcement of walls should be less than maximum, and more than minimum defined in [31].

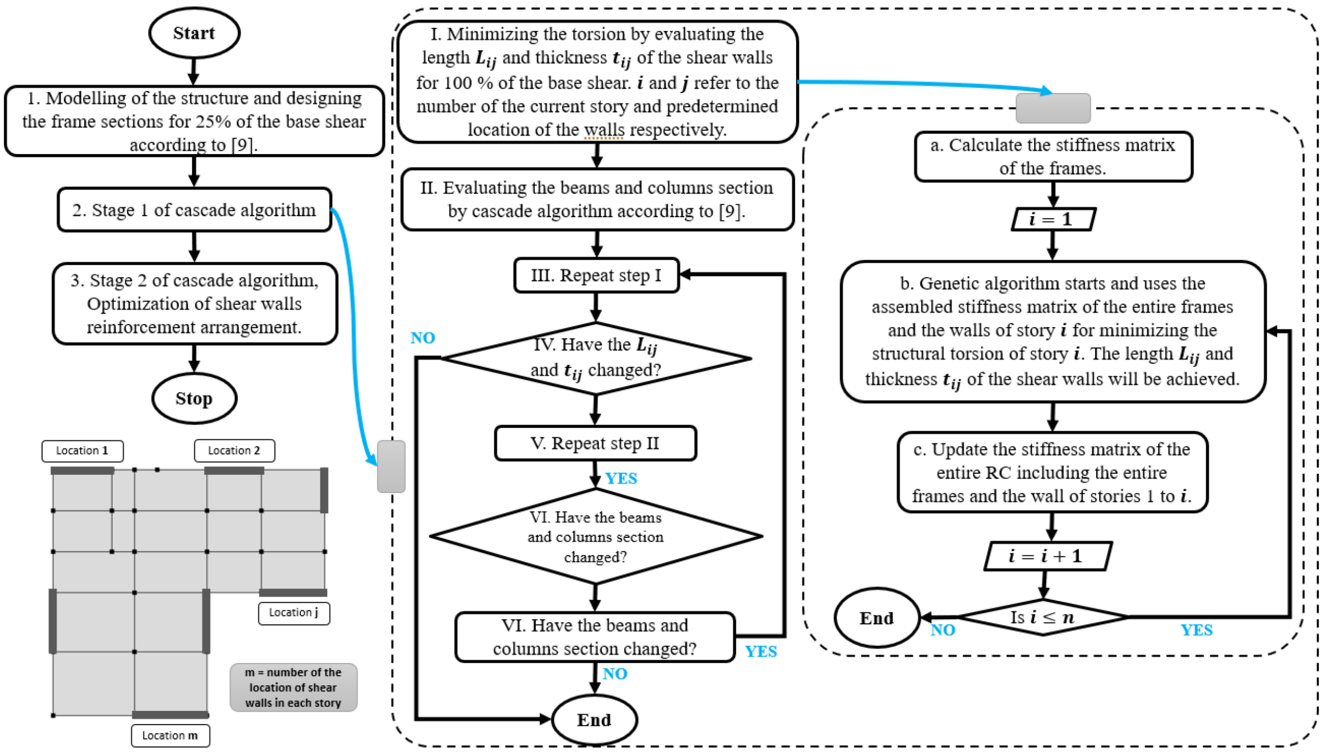


Fig. 2 The illustration of applied cascade algorithm for optimization of RC structure

3. Diameter and number of bars in upper sections of walls should be less than those in lower one.
4. Demand capacity ratio of walls should be equal or less than 1.

3 Numerical example

In the following, the effect of considered method on the 8-story RC structure as shown in Fig. 3 with the height of 3.5 m in each story is investigated. The data of earthquake and loading [30], and materials [31] are shown in Tables 1–3. The dark Gray thick lines show the locations of the walls. Table 4 shows the effective sections stiffness coefficient of elements [32].

At first, the optimum design of the frames under its considered constraints is performed according [17] so that it can resist at least 25% of the base shear. Table 5 and Table 6 are related to the analysis results of the structure at this stage, the maximum values of the drift are 0.0114 and 0.0086 exceeding the allowable drift and $\Delta_{max}/\Delta_{average}$ are 1.2838 and 1.2902 causing extreme torsional irregularity in X and Y direction, respectively. After determining the location of the shear walls by the designer, the first stage of the Cascade algorithm starts to design the shear walls story by story. The aim of this stage is to minimize the torsion of each story as an objective function, while meeting the considered constraints shown in Fig. 4. In the second stage of the Cascade algorithm, the optimum design of beams and columns of the RC frame in the presence of shear walls is carried out. The utilized method of this stage is introduced in [17]. The first and the second stages of the Cascade algorithm are repeated until the shear wall and frames sections are not changed and the convergence is achieved. Tables 7–17 show the analysis results of the whole structure after the convergence.

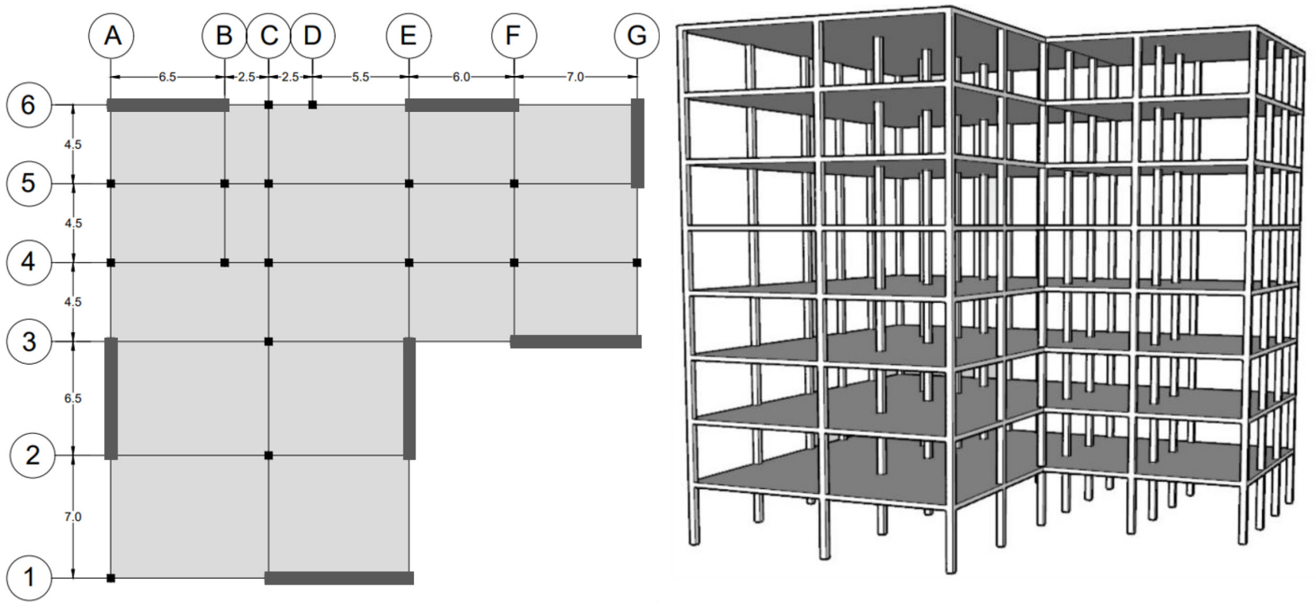


Fig. 3 The 10-story RC structure with the height of 3.5 m in each story

Table 1 Earthquake parameter

Base shear coefficient (C)	Building height exponent (K)
0.0704	1.13

Table 2 Loading

Load	(N, m)
Dead on stories	5.9 kN/m^2
Live on stories	2 kN/m^2
Dead on roof	6.4 kN/m^2
Live on roof	1.5 kN/m^2
Dead on perimeter beams	2.5 kN/m^2

Table 3 Material

Materials	Strength
Concrete	$f'_c = 28$ MPa
Steel of longitudinal bars	$f_y = 392.4$ MPa, $f_u = 588.6$ MPa
Steel of confinement bars	$f_y = 294$ MPa, $f_u = 490$ MPa

Table 4 The effective sections stiffness coefficient

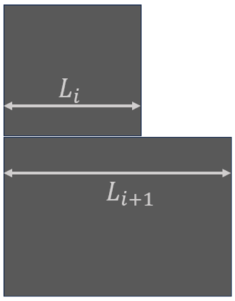
Reinforced concrete elements	Effective section stiffness coefficient	
	Cracked	Uncracked
Wall (In-plane)	0.35	0.7
Column	0.7	
Beam	0.35	

Table 5 Drift of the RC frame due to the 100% of base shear

	EX	EY
Story 1	0.0052	0.0042
Story 2	0.0101	0.0077
Story 3	0.0114	0.0084
Story 4	0.0111	0.0086
Story 5	0.0103	0.0083
Story 6	0.0086	0.0082
Story 7	0.0064	0.0082
Story 8	0.0039	0.0078

Table 6 Structural torsion of the RC frame due to the 100% of base shear

	Ratio					
	EX	EXN	EXP	EY	EYN	EYP
Story 1	1.1588	1.2620	1.0490	1.0519	1.0962	1.1919
Story 2	1.1850	1.2838	1.0794	1.0451	1.1050	1.1873
Story 3	1.1847	1.2813	1.0815	1.0756	1.0731	1.2155
Story 4	1.1801	1.2772	1.0765	1.0857	1.0634	1.2257
Story 5	1.1713	1.2688	1.0675	1.1031	1.0468	1.2433
Story 6	1.1436	1.2419	1.0395	1.0925	1.0594	1.2348
Story 7	1.1102	1.2120	1.0032	1.1387	1.0138	1.2799
Story 8	1.1139	1.2143	1.0082	1.1502	1.0011	1.2902



$L_i < 1.3 \times L_{i+1} \rightarrow ok$

Fig. 4 Sufficient length of two adjacent story walls not to create geometrical irregularity

Table 7 Drift of the RC frame due to the 100% of base shear after optimum design of the walls and frame

	EX	EY
Story 1	0.0002	0.0005
Story 2	0.0007	0.0012
Story 3	0.0012	0.0018
Story 4	0.0019	0.0023
Story 5	0.0023	0.0023
Story 6	0.0023	0.0022
Story 7	0.0021	0.0019
Story 8	0.0016	0.0016

Table 8 The structural torsion minimization after reaching the optimum walls and RC frame convergence

	Ratio					
	EX	EXN	EXP	EY	EYN	EYP
Story 1	1.037	1.1224	1.0511	1.1045	1.1468	1.0618
Story 2	1.1236	1.1991	1.0444	1.138	1.1945	1.081
Story 3	1.0685	1.145	1.0107	1.0937	1.1603	1.027
Story 4	1.0497	1.1251	1.028	1.0495	1.1288	1.0289
Story 5	1.0332	1.1091	1.0448	1.0153	1.1067	1.074
Story 6	1.0377	1.1145	1.0413	1.006	1.0955	1.1044
Story 7	1.0648	1.1451	1.0184	1.007	1.1008	1.1114
Story 8	1.0993	1.1883	1.0063	1.0283	1.0818	1.1346

Table 9 Optimum length and thickness of walls in X direction

	A-B-6		E-F-6		F-G-3		C-E-1	
	Length	Thickness	Length	Thickness	Length	Thickness	Length	Thickness
Story 1	6.5	0.158	6	0.295	4.3	0.179	8	0.159
Story 2	1.916	0.154	6	0.290	3.768	0.156	5.275	0.152
Story 3	1.904	0.153	4	0.285	3	0.154	4.5	0.151
Story 4	1.75	0.15	2.6	0.282	1.769	0.154	3.332	0.151
Story 5	1.75	0.15	1.75	0.15	1.769	0.154	3.332	0.151
Story 6	0.866	0.15	1.433	0.15	1.279	0.151	2.648	0.15
Story 7	0.866	0.15	1.162	0.15	0.85	0.15	1.737	0.15
Story 8	0.866	0.15	0.825	0.15	0.85	0.15	1.616	0.15

Table 10 Optimum length and thickness of walls in Y direction

	A-2-3		E-2-3		G-5-6	
	Length	Thickness	Length	Thickness	Length	Thickness
Story 1	3.887	0.297	2.514	0.299	4.5	0.22
Story 2	3.813	0.286	2.435	0.269	4.5	0.193
Story 3	3.5	0.281	2.056	0.191	3	0.191
Story 4	2.991	0.277	2.056	0.191	2.425	0.15
Story 5	2.991	0.156	2.056	0.191	1.825	0.15
Story 6	2.991	0.156	2.056	0.191	1.825	0.15
Story 7	2.991	0.156	2.056	0.191	1.825	0.15
Story 8	1.928	0.151	2.044	0.18	1.825	0.15

Table 11 Geometrical irregularity check

	$L_1 + L_2$	$(L_1 + L_2) \times 1.3$	Check the geometrical irregularity
Story 1	35.70098	46.41128	Ok
Story 2	27.70692	36.01899	Ok
Story 3	21.96026	28.54833	Ok
Story 4	16.92382	22.00097	Ok
Story 5	15.47384	20.11599	Ok
Story 6	13.0988	17.02844	Ok
Story 7	11.48745	14.93369	Ok
Story 8	9.954313	12.94061	Ok

Table 12 Pier *D*/*C* ratios of walls in X direction

	A-B-6				E-F-6				F-G-3				C-E-1			
	Pier *D*/*C* ratios for 100% of base shear		Pier *D*/*C* ratios for 50% of base shear		Pier *D*/*C* ratios for 100% of base shear		Pier *D*/*C* ratios for 50% of base shear		Pier *D*/*C* ratios for 100% of base shear		Pier *D*/*C* ratios for 50% of base shear		Pier *D*/*C* ratios for 100% of base shear		Pier *D*/*C* ratios for 50% of base shear	
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
Story 1	0.778	0.591	0.245	0.194	0.994	0.970	0.709	0.539	0.951	0.584	0.753	0.306	0.992	0.726	0.67	0.46
Story 2	0.573	0.554	0.277	0.191	0.927	0.980	0.468	0.576	0.786	0.473	0.24	0.179	0.907	0.739	0.575	0.464
Story 3	0.407	0.357	0.191	0.214	0.627	0.662	0.349	0.392	0.982	0.490	0.398	0.281	0.681	0.580	0.436	0.382
Story 4	0.412	0.500	0.224	0.426	0.571	0.879	0.308	0.65	0.921	0.431	0.421	0.294	0.527	0.520	0.325	0.363
Story 5	0.341	0.509	0.288	0.369	0.456	0.959	0.375	0.835	0.709	0.687	0.403	0.536	0.563	0.590	0.36	0.415
Story 6	0.416	0.453	0.356	0.247	0.452	0.969	0.436	0.702	0.907	0.916	0.935	0.91	0.564	0.680	0.491	0.568
Story 7	0.361	0.470	0.28	0.377	0.181	0.351	0.152	0.265	0.682	0.534	0.616	0.391	0.368	0.445	0.316	0.368
Story 8	0.147	0.273	0.13	0.223	0.258	0.322	0.204	0.241	0.613	0.393	0.509	0.238	0.480	0.503	0.422	0.315

Table 13 Pier *D*/*C* ratios of walls in Y direction

	A-2-3				E-2-3				G-5-6			
	Pier *D*/*C* ratios for 100% of base shear		Pier *D*/*C* ratios for 50% of base shear		Pier *D*/*C* ratios for 100% of base shear		Pier *D*/*C* ratios for 50% of base shear		Pier *D*/*C* ratios for 100% of base shear		Pier *D*/*C* ratios for 50% of base shear	
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
Story 1	0.704	0.553	0.495	0.426	0.939	0.479	0.623	0.266	0.77	0.371	0.733	0.312
Story 2	0.481	0.551	0.329	0.454	0.757	0.342	0.539	0.236	0.859	0.373	0.521	0.25
Story 3	0.527	0.550	0.309	0.431	0.821	0.409	0.443	0.328	0.929	0.441	0.541	0.309
Story 4	0.457	0.582	0.289	0.563	0.628	0.493	0.336	0.401	0.806	0.503	0.386	0.383
Story 5	0.349	0.762	0.326	0.653	0.362	0.506	0.324	0.442	0.428	0.72	0.374	0.58
Story 6	0.441	0.833	0.432	0.669	0.457	0.574	0.399	0.482	0.648	0.993	0.602	0.869
Story 7	0.433	0.773	0.41	0.645	0.371	0.529	0.317	0.452	0.477	0.512	0.349	0.367
Story 8	0.476	0.652	0.417	0.508	0.424	0.581	0.349	0.461	0.513	0.591	0.414	0.407

Table 14 Double layers rebar arrangement in X direction

	A-B-6		E-F-6		F-G-3		C-E-1	
	Diameter and spacing	Ratio of reinforcement percent	Diameter and spacing	Ratio of reinforcement percent	Diameter and spacing	Ratio of reinforcement percent	Diameter and spacing	Ratio of reinforcement percent
Story 1	Φ16@130mm	1.958	Φ25@90mm	3.698	Φ16@130mm	1.728	Φ16@90mm	2.81
Story 2	Φ16@130mm	2.009	Φ25@90mm	3.761	Φ16@130mm	1.983	Φ16@90mm	2.94
Story 3	Φ16@130mm	2.022	Φ25@90mm	3.827	Φ16@130mm	2.009	Φ16@90mm	2.959
Story 4	Φ16@130mm	2.062	Φ25@90mm	3.868	Φ16@130mm	2.009	Φ16@90mm	2.959
Story 5	Φ16@130mm	2.062	Φ16@90mm	2.979	Φ16@130mm	2.009	Φ16@90mm	2.959
Story 6	Φ16@130mm	2.062	Φ16@90mm	2.979	Φ16@130mm	2.049	Φ16@90mm	2.979
Story 7	Φ16@130mm	2.062	Φ16@90mm	2.979	Φ16@130mm	2.062	Φ16@90mm	2.979
Story 8	Φ16@130mm	2.062	Φ12@90mm	1.676	Φ16@130mm	2.062	Φ16@90mm	2.979

Table 15 Double layers rebar arrangement in Y direction

	A-2-3		E-2-3		G-5-6	
	Diameter and spacing	Ratio of reinforcement percent	Diameter and spacing	Ratio of reinforcement percent	Diameter and spacing	Ratio of reinforcement percent
Story 1	Φ25@90mm	3.673	Φ16@90mm	1.494	Φ16@90mm	2.81
Story 2	Φ25@90mm	3.814	Φ16@90mm	1.661	Φ16@90mm	2.94
Story 3	Φ25@90mm	3.882	Φ16@90mm	2.339	Φ16@90mm	2.959
Story 4	Φ25@90mm	3.938	Φ16@90mm	2.339	Φ16@90mm	2.959
Story 5	Φ16@90mm	2.864	Φ16@90mm	2.339	Φ16@90mm	2.959
Story 6	Φ16@90mm	2.864	Φ16@90mm	2.339	Φ16@90mm	2.979
Story 7	Φ16@90mm	2.864	Φ16@90mm	2.339	Φ16@90mm	2.979
Story 8	Φ16@90mm	2.959	Φ16@90mm	2.482	Φ16@90mm	2.979

Table 16 The optimum design of columns sections according to [17] with the unit being in meter (m)

Position of column	story 1		story 2		story 3		story 4		story 5		story 6		story 7		story 8	
	Width	Depth	Width	Depth	Width	Depth	Width	Depth	Width	Depth	Width	Depth	Width	Depth	Width	Depth
1 – *A*	0.6	0.4	0.6	0.4	0.6	0.4	0.6	0.4	0.6	0.4	0.6	0.4	0.6	0.4	0.6	0.4
1 – *C*	0.6	0.4	0.6	0.4	0.6	0.4	0.6	0.4	0.6	0.4	0.6	0.4	0.6	0.4	0.6	0.4
1 – *E*	0.4	0.55	0.4	0.55	0.4	0.55	0.4	0.55	0.4	0.5	0.4	0.5	0.4	0.5	0.3	0.45
2 – *A*	0.4	0.45	0.4	0.45	0.4	0.45	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
2 – *C*	0.6	0.5	0.5	0.45	0.5	0.45	0.5	0.45	0.5	0.45	0.5	0.45	0.5	0.45	0.5	0.45
2 – *E*	0.8	0.5	0.8	0.5	0.8	0.5	0.8	0.5	0.8	0.5	0.8	0.5	0.8	0.5	0.8	0.45
3 – *A*	0.6	0.5	0.6	0.5	0.6	0.5	0.6	0.5	0.6	0.5	0.6	0.5	0.6	0.5	0.6	0.45
3 – *C*	0.6	0.5	0.6	0.5	0.6	0.5	0.6	0.5	0.6	0.5	0.6	0.5	0.6	0.5	0.5	0.45
3 – *E*	0.5	0.4	0.5	0.4	0.5	0.4	0.5	0.4	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4
3 – *F*	0.5	0.4	0.5	0.4	0.5	0.4	0.5	0.4	0.5	0.4	0.5	0.4	0.5	0.4	0.5	0.4
3 – *G*	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
4 – *A*	0.6	0.4	0.6	0.4	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
4 – *B*	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
4 – *C*	0.6	0.4	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
4 – *E*	0.5	0.4	0.4	0.4	0.5	0.4	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
4 – *F*	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
4 – *G*	0.6	0.4	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
5 – *A*	0.6	0.4	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
5 – *B*	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
5 – *C*	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
5 – *E*	0.4	0.45	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
5 – *F*	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
5 – *G*	0.6	0.45	0.6	0.45	0.4	0.45	0.4	0.45	0.4	0.45	0.4	0.4	0.4	0.4	0.4	0.4
6 – *A*	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
6 – *B*	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
6 – *C*	0.6	0.4	0.6	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
6 – *D*	0.5	0.4	0.5	0.4	0.5	0.4	0.5	0.4	0.5	0.4	0.5	0.4	0.5	0.4	0.4	0.4
6 – *E*	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
6 – *F*	0.5	0.4	0.5	0.4	0.5	0.4	0.5	0.4	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4
6 – *G*	0.4	0.45	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4

Table 17 The optimum design of square beam sections according to [17], the units being in meter (m)

Position of beam	story 1	story 2	story 3	story 4	story 5	story 6	story 7	story 8
1 – 2 – *A*	0.45	0.45	0.4	0.4	0.4	0.4	0.4	0.4
2 – 3 – *A*	0.45	0.45	0.4	0.4	0.4	0.4	0.4	0.4
3 – 4 – *A*	0.45	0.45	0.35	0.35	0.4	0.35	0.35	0.4
4 – 5 – *A*	0.45	0.45	0.4	0.4	0.4	0.4	0.4	0.4
5 – 6 – *A*	0.45	0.45	0.35	0.35	0.35	0.35	0.35	0.4
4 – 5 – *B*	0.4	0.4	0.45	0.4	0.4	0.45	0.4	0.4
5 – 6 – *B*	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
1 – 2 – *C*	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
2 – 3 – *C*	0.35	0.4	0.35	0.35	0.35	0.35	0.35	0.4
3 – 4 – *C*	0.35	0.4	0.35	0.35	0.35	0.35	0.35	0.3

Table 17 The optimum design of square beam sections according to [17], the units being in meter (m) (continued)

Position of beam	story 1	story 2	story 3	story 4	story 5	story 6	story 7	story 8
4 – 5 – *C*	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
5 – 6 – *C*	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
1 – 2 – *E*	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.3
2 – 3 – *E*	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.3
3 – 4 – *E*	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.3
4 – 5 – *E*	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
5 – 6 – *E*	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
3 – 4 – *F*	0.35	0.3	0.35	0.35	0.35	0.35	0.35	0.3
4 – 5 – *F*	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.3
5 – 6 – *F*	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.3
3 – 4 – *G*	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
4 – 5 – *G*	0.35	0.3	0.35	0.4	0.4	0.35	0.35	0.4
5 – 6 – *G*	0.35	0.3	0.35	0.35	0.35	0.35	0.35	0.4
1 – *A* – *C*	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.45
1 – *C* – *E*	0.4	0.4	0.4	0.4	0.4	0.5	0.45	0.45
2 – *A* – *C*	0.4	0.45	0.45	0.4	0.4	0.4	0.4	0.45
2 – *C* – *E*	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5
3 – *A* – *C*	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.3
3 – *C* – *E*	0.4	0.55	0.5	0.5	0.5	0.5	0.5	0.5
3 – *E* – *F*	0.35	0.35	0.4	0.4	0.4	0.4	0.35	0.4
3 – *F* – *G*	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
4 – *A* – *B*	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.3
4 – *B* – *C*	0.35	0.35	0.4	0.4	0.4	0.4	0.35	0.3
4 – *C* – *E*	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.3
4 – *E* – *F*	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.3
4 – *F* – *G*	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
5 – *A* – *B*	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.3
5 – *B* – *C*	0.35	0.35	0.4	0.35	0.35	0.35	0.35	0.3
5 – *C* – *E*	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.3
5 – *E* – *F*	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.3
5 – *F* – *G*	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.35
6 – *A* – *B*	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.3
6 – *B* – *C*	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.3
6 – *C* – *D*	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.35
6 – *D* – *E*	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.3
6 – *E* – *F*	0.35	0.35	0.4	0.45	0.4	0.4	0.35	0.3
6 – *F* – *G*	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.3
6 – *A* – *B*	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.3

According to Table 8, Maximum torsion is decreased to 1.1991 and 1.945 in x and y direction, respectively that are less than 1.2 by applying optimum shear walls. According to Fig. 4, Table 9 and Table 10, the length and thickness of walls are evaluated so that the geometrical irregularity goes not occur. As can be seen, the Tables 7–13 show the power of this cascade algorithm reducing the structural torsion to less than 1.2. Fig. 5 shows the optimum wall section of G-5-6 story 1 and G-5-6 story 3. Also, the overview of all optimum walls applied to the structures are illustrated in Fig. 6.

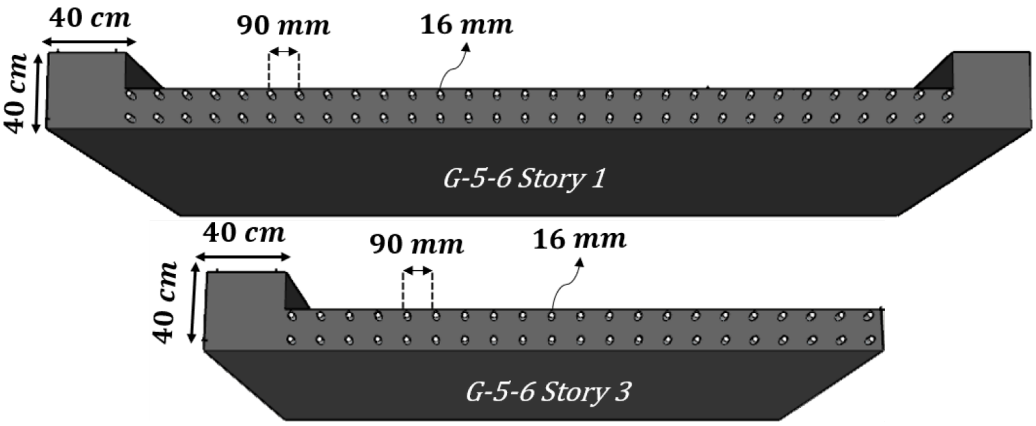


Fig. 5 Optimum wall rebar arrangement in G-5-6 story 1 and story 3

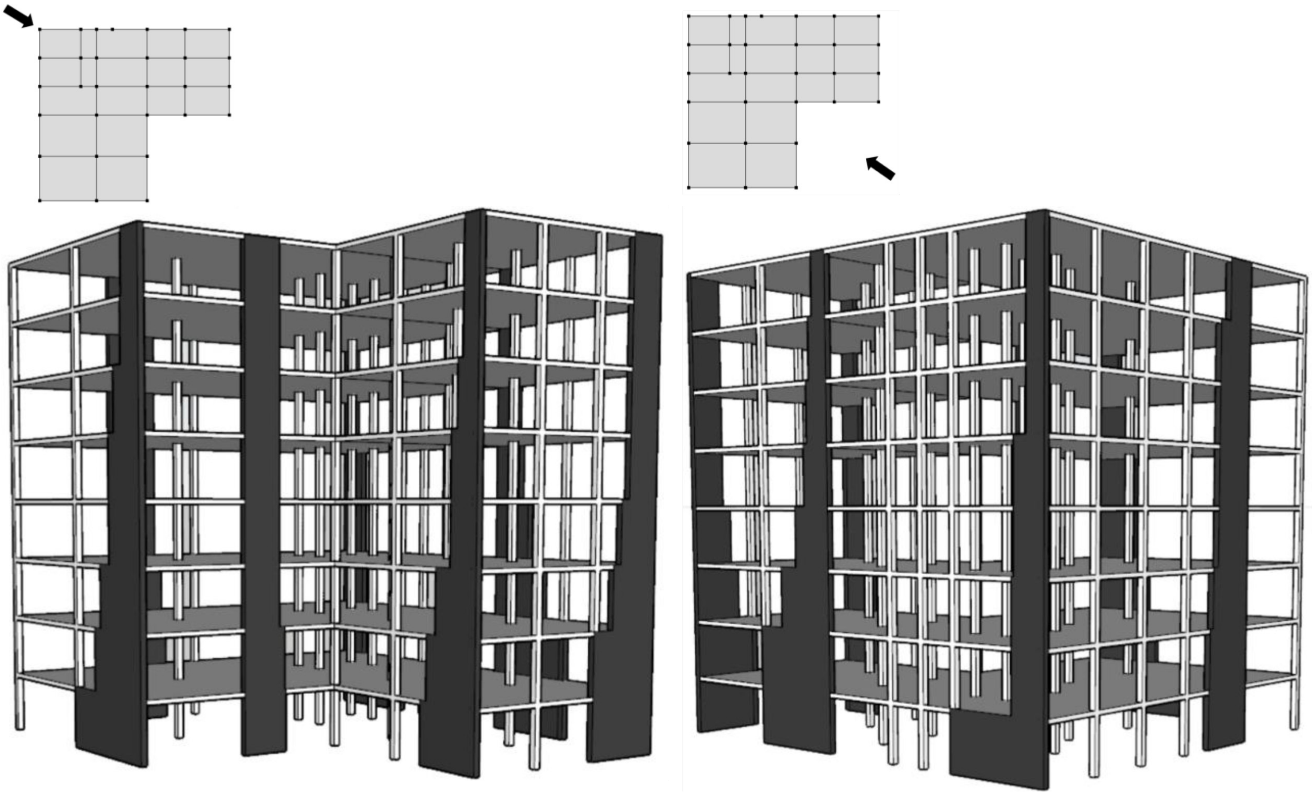


Fig. 6 The outline of the optimum walls

Though in this paper the Cascade algorithm is used for optimization, however, other single and hybrid algorithms can also be utilized [33–36]. Some additional requirement such as reliability can also be included [37–40].

4 Conclusions

The present paper has introduced a new cascade algorithm of optimization for minimizing the torsion of each story of the RC structures as fitness function while satisfying the corresponding constraints. The first stage of this algorithm uses the assembled matrix of the frames and condensed stiffness matrix of shear walls. The length and thickness of the shear walls whose location are according to the decision of designer are used as design variables. In the next stage, the optimization of rebar arrangements according to the required rebar area is performed. The efficiency of this method is shown by the 3-dimentional large-scale concrete structure as a numerical example. As shown in the results, the length and thickness of the shear walls minimize the torsion of each story so that the maximum torsion in the entire structure reduces from 1.2838 and 1.2902 to 1.1991 and 1.1945 in X and Y direction, respectively less than 1.2. Using the Cascade algorithm reduces the computational time and achieves higher accuracy.

References

[1] Kaveh, A., Mahdavi, V. R. "Colliding bodies optimization: a novel meta-heuristic method", Computers & Structures, 139, pp. 18–27, 2014. https://doi.org/10.1016/j.compstruc.2014.04.005

[2] Kaveh, A., Mahdavi, V. R. "Colliding bodies optimization: extensions and applications", Springer, 2015. ISBN 978-3-319-19658-9 https://doi.org/10.1007/978-3-319-19659-6

[3] Kaveh, A., Ilchi Ghazaan, M. "Enhanced colliding bodies algorithm for truss optimization with frequency constraints", Journal of Computing in Civil Engineering, 29(6), 04014104, 2015. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000445

[4] Kaveh, A., Ilchi Ghazaan, M. "A new meta-heuristic algorithm: vibrating particles system", Scientia Iranica, 24(2), pp. 551–566, 2017. https://doi.org/10.24200/SCI.2017.2417

[5] Kaveh, A., Ilchi Ghazaan, M. "Vibrating particles system algorithm for truss optimization with multiple natural frequency constraints", Acta Mechanica, 228, pp. 307–322, 2017. https://doi.org/10.1007/s00707-016-1725-z

[6] Kaveh, A., Seddighian, M. R., Ghanadpour, E. "Black Hole Mechanics Optimization: a novel meta-heuristic algorithm", Asian Journal of Civil Engineering, 21, pp. 1129–1149, 2020. https://doi.org/10.1007/s42107-020-00282-8

[7] Kaveh, A. Shakouri Mahmoud Abady, A. "Harmony search algorithm for optimum design of slab formwork", Iranian Journal of Science and Technology, 34(B4), pp. 335–351, 2010.

[8] Kaveh, A., Behnam, A. F. "Charged system search algorithm for the optimum cost design of reinforced concrete cantilever retaining walls", Arabian Journal for Science and Engineering, 38, pp. 563–570, 2013. https://doi.org/10.1007/s13369-012-0332-0

[9] Kaveh, A., Behnam, A. F. "Design optimization of reinforced concrete 3D structures considering frequency constraints via a charged system search", Scientia Iranica, 20(3), pp. 387–396, 2013. https://doi.org/10.1016/j.scient.2012.11.017

[10] Kaveh, A. "Advances in metaheuristic algorithms for optimal design of structures", Springer, 2017. ISBN 978-3-319-83459-7 https://doi.org/10.1007/978-3-319-46173-1

[11] Kaveh, A. "Applications of metaheuristic optimization algorithms in civil engineering", Springer, 2017. ISBN 978-3-319-48011-4 https://doi.org/10.1007/978-3-319-48012-1

[12] Kaveh, A, Zaerreza, A, Hosseini, S. M. "Shuffled shepherd optimization method simplified for reducing the parameter dependency", Iranian Journal of Science and Technology, Transactions of Civil Engineering, 45, pp. 1397–1411, 2021. https://doi.org/10.1007/s40996-020-00428-3

[13] Kaveh, A., Zaerreza, A., Hosseini S. M. "An enhanced shuffled Shepherd Optimization Algorithm for optimal design of large-scale space structures", Engineering with Computers, 38, pp. 1505–1526, 2022. https://doi.org/10.1007/s00366-021-01292-z

[14] Boulaouad, A., Amour, A. "A displacement-based seismic design for reinforced concrete structures", KSCE Journal of Civil Engineering, 15(3), pp. 507–516, 2011. https://doi.org/10.1007/s12205-011-1009-z

[15] Kaveh, A. "Cost and CO_2 emission optimization of reinforced concrete frames using enhanced colliding bodies optimization algorithm", In: Applications of Metaheuristic Optimization Algorithms in Civil Engineering, Springer, 2017, pp. 319–350. ISBN 978-3-319-48011-4 https://doi.org/10.1007/978-3-319-48012-1_17

[16] Liu, J., Li, S., Xu, C., Wu, Z., Ao, N., Chen, Y. F. "Automatic and optimal rebar layout in reinforced concrete structure by decomposed optimization algorithms", Automation in Construction, 126, 103655, 2021. https://doi.org/10.1016/j.autcon.2021.103655

[17] Salimi, P, Rahimi Boderabady, H. A., Kaveh, A. "Optimal Design of Reinforced Concrete Frame Structures Using Cascade Optimization Method", Periodica Polytechnica Civil Engineering, 66(4), pp. 1220–1233, 2022. https://doi.org/10.3311/PPci.20868

[18] Atabay, Ş. "Cost optimization of three-dimensional beamless reinforced concrete shear-wall systems via genetic algorithm", Expert Systems with Applications, 36(2), pp. 3555–3561, 2009. https://doi.org/10.1016/j.eswa.2008.02.004

[19] Kaveh, A., Zakian, P. "Optimal seismic design of reinforced concrete shear wall-frame structures", KSCE Journal of Civil Engineering, 18, pp. 2181-2190, 2014. https://doi.org/10.1007/s12205-014-0640-x

[20] Nikzad, H., Yoshitomi, S. "Structural optimization method for 3D reinforced concrete building structure with shear wall", World Academy of Science, Engineering and Technology International Journal of Civil and Environmental Engineering, 11(9), pp. 1352–1358, 2017. https://doi.org/10.1999/1307-6892/10008455

[21] Kaveh, A., Farhadmanesh, M. "Optimal Seismic Design of Steel Plate Shear Walls Using Metaheuristic Algorithms", Periodica Polytechnica Civil Engineering, 63(1), pp. 1-17, 2019. https://doi.org/10.3311/PPci.12119

[22] Talatahari, S., Rabiei, M. "Shear wall layout optimization of tall buildings using Quantum Charged System Search", Frontiers of Structural and Civil Engineering, 14, pp. 1131–1151, 2020. https://doi.org/10.1007/s11709-020-0660-1

[23] Patidar, M., Jamle, S. "Optimization of stability of multistoried structure by changing grades of concrete in shear wall member", Journal of Xi'an University of Architecture and Technology, 12(4), pp. 2479–2797, 2020. https://doi.org/10.37896/JXAT12.04/979

[24] Lou, H., Gao, B., Jin, F., Wan, Y., Wang, Y. "Shear wall layout optimization strategy for high-rise buildings based on conceptual design and data-driven tabu search", Computers and Structures, 250, 106546, 2021. https://doi.org/10.1016/j.compstruc.2021.106546

[25] Lou, H. P., Ye, J., Jin, F. L., Gao, B. Q., Wan, Y. Y., Quan, G. "A practical shear wall layout optimization framework for the design of high-rise buildings", Structures, 34, pp. 3172–3195, 2021. https://doi.org/10.1016/j.istruc.2021.09.038

[26] Kaveh, A., Biabani Hamedani, K., Zaerreza, A. "A set theoretical shuffled shepherd optimization algorithm for optimal design of cantilever retaining wall structures", Engineering with Computers, 37, pp. 3265–3282, 2021. https://doi.org/10.1007/s00366-020-00999-9

[27] Kaveh, A., Akbari, H., Hosseini, S. M. "Plasma generation optimization for optimal design of reinforced concrete cantilever retaining wall structures", Iranian Journal of Science and Technology, Transactions of Civil Engineering, 46, pp. 1177–1200, 2022. https://doi.org/10.1007/s40996-020-00566-8

[28] Lou, H., Xiao, Z., Wan, Y., Quan, G., Jin, F., Gao, B., Lu, H. "Size optimization design of members for shear wall high-rise buildings", Journal of Building Engineering, 61, 105292, 2022. https://doi.org/10.1016/j.jobe.2022.105292

[29] Abualreesh, A. M., Tuken, A., Albidah, A., Siddiqui, N. A. "Reliability-based optimization of shear walls in RC shear wall-frame buildings subjected to earthquake loading", Case Studies in Construction Materials, 16, e00978, 2022. https://doi.org/10.1016/j.cscm.2022.e00978

[30] American Society of Civil Engineers "Minimum design loads and associated criteria for buildings and other structures", American Society of Civil Engineers, 2017.

[31] ACI Committee "Building code requirements for structural concrete (ACI 318-11)", American Concrete Institute, 2011.

[32] ACI "ACI 318-19 and ACI 318R-19: Building Code Requirements for Structural Concrete and Commentary", American Concrete Institute, Farmington Hills, MI, USA, 2019.

[33] Kaveh, A., Izadifard, R. A., Mottaghi, L. "Optimal design of planar RC frames considering CO_2 emissions using ECBO, EVPS and PSO metaheuristic algorithms", Journal of Building Engineering, 28, 101014, 2020. https://doi.org/10.1016/j.jobe.2019.101014

[34] Kaveh, A., Mirzaei, B., Jafarvand, A. "An improved magnetic charged system search for optimization of truss structures with continuous and discrete variables", Applied Soft Computing, 28, pp. 400–410, 2015. https://doi.org/10.1016/j.asoc.2014.11.056

[35] Kaveh, A., Talatahari, S. "Hybrid charged system search and particle swarm optimization for engineering design problems", Engineering Computations, 28(4), pp. 423–440, 2011. https://doi.org/10.1108/02644401111131876

[36] Kaveh, A., Talatahari, S. "An enhanced charged system search for configuration optimization using the concept of fields of forces", Structural and Multidisciplinary Optimization, 43, pp. 339–351, 2011. https://doi.org/10.1007/s00158-010-0571-1

[37] Harrach, D., Habashneh, M., Movahedi Rad, M. "Reliability-based numerical analysis of glulam beams reinforced by CFRP plate", Scientifi Reports, 12, 13587, 2022. https://doi.org/10.1038/s41598-022-17751-6

[38] Szép, J., Habashneh, M., Lógó, J., Movahedi Rad, M. "Reliability assessment of reinforced concrete beams under elevated temperatures: a probabilistic approach using finite element and physical models", Sustainability, 15, 6077, 2023. https://doi.org/10.3390/su15076077

[39] Khaleel Ibrahim, S., Movahedi Rad, M. "Limited optimal plastic behavior of RC beams strengthened by carbon fiber polymers using reliability-based design", Polymers, 15, 569, 2023. https://doi.org/10.3390/polym15030569

[40] Movahedi Rad, M. "A Review of Elasto-Plastic Shakedown Analysis with Limited Plastic Deformations and Displacements", Periodica Polytechnica Civil Engineering, 62(3), pp. 812–817, 2018. https://doi.org/10.3311/PPci.11696