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A research on optimum designs of steel frames including soil effects or semi rigid supports using Jaya algorithm

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Abstract. The effect of soil foundation plays active role in optimum design of steel space frames when included. However, its influence on design can be calculated after a long iterative procedure. So it requires longer computer time and more computational effort if it is done properly. The main purpose of this study is to investigate how these effects can be calculated in more practical way in a shorter time. The effects of semi-rigid column bases are taken into account in optimum design of steel space frames. This study is carried out by using JAYA algorithm which is a novel and practical method based on a single revision equation. The displacement, stress and geometric size constraints are considered in the optimum design. A computer program is coded in MATLAB to achieve corporation with SAP2000-OAPI (Open Application Programming Interface) for optimum solutions. Four different steel space frames including soil structure interaction taken from literature are investigated according to different semi-rigidly supported models depending on different rotational stiffness values. And the results obtained from analyses are compared with the results available in reference studies. The results of the study show that semi-rigidly supported systems in the range of appropriate rotational stiffness values offer practical solutions in a very short time. And close agreement is obtained with the studies on optimum design of steel space frames including soil effect underneath.

Keywords: JAYA algorithm, steel space frame, optimum design, soil effects, semi rigid column bases

1. Introduction

Optimum design of steel structures is one of the major areas of research in structural engineering. Low and high rise structures, long span bridges, various structural problems are solved by using many algorithm methods. The structure is considered to be connected to rigid supports first, but in recent years, more realistic designs are being investigated by considering soil-structure effect on the structure. However, the fact is that the several soil parameters should be calculated depending on foundation models (Vlasov, Pasternak, Winkler etc.) first to calculate the effect of soil-structure interaction on optimum design. For all these reasons the designs get more difficult and take longer time. The aim of this study is to obtain optimum design of steel space frames practically as if soil structure interaction included by using semi-rigidly supported systems instead of soil foundation.

Some of the algorithm methods for structural optimization problems in the literature can be listed as follows. Rajeev and Krishnamoorthy (1992) researched optimum designs of truss structure by using genetic algorithm. Erbatur *et al*. (2000) applied genetic algorithm for different steel structural problems such as plane and space truss systems. Kameshki and Saka (2001) investigated the effect of semi rigid connections on optimum design of steel frame via genetic algorithm. Also, Hayalioglu and Degertekin (2004) researched the effect of semi rigid connections on optimum designs of steel frames. Lee and Geem (2004) developed a powerful algorithm method called harmony search for structural problems. Kelesoglu and Ülker (2005) investigated optimum design of space truss systems. Hayalioglu and Degertekin (2005) researched the effects of semi-rigid connections and column bases on optimum design of steel frames. Togan and Daloglu (2006) applied a new approach on space truss structures using genetic algorithm. Degertekin (2007) compared optimum design results of steel space frames via two different metaherustic methods such as simulated annealing and genetic algorithm. Esen and Ülker (2008) researched multi storey structures including, nonlinear effect. Degertekin *et al*. (2008) compared optimum design of steel structures using tabu search and genetic algorithm. Degertekin *et al*. (2008) used a hybrid algorithm method on steel frames. Togan and Daloglu (2008) developed a new approach on genetic algorithm for structural problems. Hasançebi *et al.* (2009) researched different algorithm methods for optimization of real size pin jointed structures. Degertekin and Hayalioglu (2010) investigated the effects of semi-rigid connections and column bases on optimum designs of steel frames via harmony search algorithm. Togan *et al.* (2011) used harmony search for optimum design of steel truss problems. Rao *et al*. (2011) applied a new powerful algorithm method including teaching and learning operations. Togan (2012) applied TLBO (teaching learning based optimization) method on optimum design of steel frames. Aydogdu and Saka (2012) applied ACO (ant

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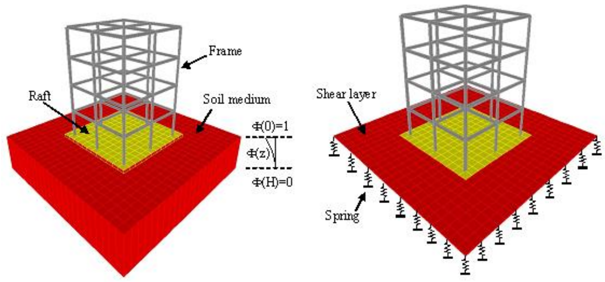
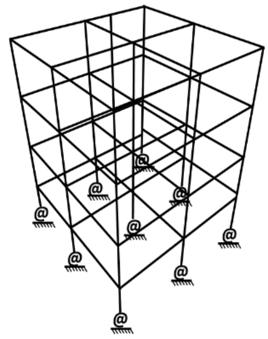
colony optimization) to determine elemental warping effect on optimum design of steel frames. Kaveh and Talatahari (2012) applied a hybrid algorithm method on optimum design. Saka and Geem (2013) investigated an extensive review on optimum design of steel frame. Rafiee *et al.* (2013) researched the semi rigid connections on optimum designs via Big Bang-Big Crunch method. Rao and Patel (2013) investigate an improved TLBO method on optimum designs. Hasançebi and Carbaş (2014) researched optimum design of steel frames via a novel metaheuristic method: bat inspired algorithm. Hadidi and Rafiee (2014) investigate optimum designs of semi rigid steel frames via an improved metaheuristic method. Artar and Daloglu (2015) applied genetic algorithm on optimization of steel frame with composite beams. Artar (2016) investigated earthquake effect on optimization of steel space structures via HS (harmony search) algorithm. Rao (2016) developed Jaya: A simple and new optimization algorithm for solving constrained and unconstrained optimization problems. Daloglu *et al*. (2016) investigated the effect of soil structure interaction on optimum design of steel space structures. Carbas (2016) used an enhanced firefly algorithm for optimization of steel frames in 2016. Karakas *et al*. (2016) researched optimum design of space truss Bridges Including Soil-Structure Interaction. Aydogdu (2017) researched the effects of seismic loading on optimization of reinforced concrete cantilever retaining walls. Aydogdu *et al.* (2017) used a new metaheuristic algorithm method: social spider optimization algorithm on optimum design of steel space frames. Degertekin *et al*. (2017) studied discrete and continuous design optimization of tower structures using Jaya Algorithm. Carbas (2017) studied Optimum structural design of spatial steel frames via biogeography-based optimization. Aydogdu *et al*. (2017) researched the effect of levy flight on the discrete optimum design of steel skeletal structures using metaheuristics. Dede (2018) studied on Jaya algorithm to solve single objective size optimization problem for steel grillage structures. Topal *et al*. (2018) studied buckling load optimization of laminated plates resting on Pasternak foundation using TLBO. Shallan *et al*. (2018) investigated a developed design optimization model for semi-rigid steel frames using teaching-learning-based optimization and genetic algorithms. Grzywinski *et al*. (2019) focused on optimization of the braced dome structures by using Jaya algorithm with frequency constraints. Shallan *et al*. (2019) researched design optimization of semi-rigid space steel frames with semi-rigid bases using biogeography-based optimization and genetic algorithms. Artar and Daloglu (2019) investigated optimum design of steel space truss towers under seismic effect using Jaya algorithm. Rao (2020) studied three metaphor-less simple algorithms for solving optimization problems.

As mentioned above, many studies have been carried out on optimum designs of steel space frames. In some of them, the only effect of semi-rigid connection on optimum designs has been investigated. Moreover, the effects of soil-structure interaction on optimum designs are investigated in some of these studies. Optimum design of steel skeletal structures including soil structure interaction depend on several soil parameters such as k (The modulus of subgrade reaction), $2t$ (soil shear parameter), γ (the vertical deformation profile within subsoil), E_s (modulus of elasticity of subsoil) and υ_s (Poisson's ratio of subsoil) can be obtained after a long iterative procedure. The main purpose of this study is to investigate how these effects can be calculated more practically by another approach such as semi-rigidly supported column bases according to different rotational stiffness values. So, in this study, a relationship between the effects of semi-rigid column bases and soil-structure interaction on optimum solution of steel space frames are researched. For this purpose, four different steel space frames including soil-structure interaction from literature have been examined with semi-rigid column bases considering different rotational stiffness. The results of the analysis show that there is a relationship between the optimum solutions of frames with semi-rigid column bases of different rotational stiffness and the optimum solutions of frames including soil-structure interaction. Fig.1a and 1b show the real and mathematical model of a steel space frame on elastic foundation (Daloglu *et al*. 2016). Fig.1c shows the semi rigidly supported system investigated in this study to predict the soil effect on optimum designs.



a)3D frame on elastic subsoil b) Mathematical model



c)Semi-rigidly supported system

Fig. 1. A space frame on elastic foundation

2. Technical background

The main objective in the optimum design problem is to approach the minimum steel weight in the design as defined below.

$$\min W = \sum_{k=1}^{ng} A_k \sum_{i=1}^{nk} \rho_i L_i \tag{1}$$

In this equation, W is steel frame weight, A is cross-sectional area, ρ is density of member, L length of member, i is member number, k group number, ng and nk total numbers.

- Stress according to AISC-LRFD (2001) specifications, displacement and geometric constraints applied in the analyzes are listed below.

$$\text{for } \frac{P_u}{\phi P_n} \geq 0.2$$

$$g_{il}(x) = \left(\frac{P_u}{\phi P_n}\right)_{il} + \frac{8}{9}\left(\frac{M_{ux}}{\phi_b M_{nx}} + \frac{M_{uy}}{\phi_b M_{ny}}\right)_{il} - 1.0 \leq 0 \quad \begin{array}{l} i = 1,...,nm \\ l = 1,...,nl \end{array} \tag{2}$$

$$\text{for } \frac{P_u}{\phi P_n} < 0.2$$

$$g_{il}(x) = \left(\frac{P_u}{2\phi P_n}\right)_{il} + \left(\frac{M_{ux}}{\phi_b M_{nx}} + \frac{M_{uy}}{\phi_b M_{ny}}\right)_{il} - 1.0 \leq 0 \quad \begin{array}{l} i = 1,...,nm \\ l = 1,...,nl \end{array} \tag{3}$$

where P_u, M_{ux} and M_{uy} are the required axial strength, flexural strength about major axis and minor axis, respectively. P_n, M_{nx} and M_{ny} are the nominal strength, flexural strength about major axis and minor axis, respectively. ϕ and ϕ_b are resistance factors for compression-tension and flexure, respectively.

The nominal compressive strength is determined by the following equations.

$$P_n = A_g F_{cr} \tag{4}$$

$$\text{for } \lambda_c \leq 1.5 \qquad F_{cr} = \left(0.658^{\lambda_c^2}\right) F_y \tag{5}$$

$$\text{for } \lambda_c > 1.5 \qquad F_{cr} = \left(\frac{0.877}{\lambda_c^2}\right) F_y \tag{6}$$

$$\lambda_c = \frac{KL}{r\pi}\sqrt{\frac{F_y}{E}} \tag{7}$$

where F_{cr}, F_y are critical stress and yield stress of steel, A_g, L are cross-sectional area and length of member, K, λ_c are the effective length factor and slenderness ratio, E and r are the elastic modulus and governing radius of gyration.

- Maximum lateral displacement and inter-storey drift constraints are determined as below.

$$g_{jl}(x) = \frac{\delta_{jl}}{\delta_{ju}} - 1 \leq 0 \qquad \begin{array}{l} j = 1,...,m \\ l = 1,...,nl \end{array} \tag{8}$$

$$g_{jil}(x) = \frac{\Delta_{jil}}{\Delta_{ju}} - 1 \leq 0 \qquad \begin{array}{l} j = 1,...,ns \\ i = 1,...,nsc \\ l = 1,...,nl \end{array} \tag{9}$$

where δ_{jl} and δ_{ju} are the displacement and upper limit value for jth degree of freedom, Δ_{jil} and Δ_{ju} are the inter-storey drift and limit value for ith column in the jth storey, l and nl are load case and total number of load cases, m is the number of restricted displacements, ns and nsc is the number of storey and the number of columns in a storey.

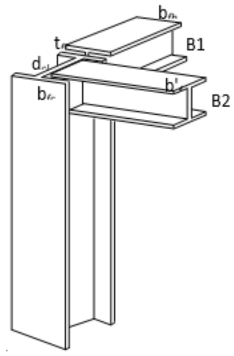


Fig. 2 The details of beam-column connection

- Geometric size constraints such as column to column and beam to column are determined by the following equations.

$$g_n(x) = \frac{D_{un}}{D_{ln}} - 1 \leq 0 \qquad n=2,\ldots,ns \tag{10}$$

$$g_{bf,i}(x) = \frac{b'_{fbk,i}}{d_{c,i} - 2t_{fl,i}} - 1 \leq 0 \qquad i= 1,\ldots,n_{bw} \tag{11}$$

$$g_{bb,i}(x) = \frac{b_{fbk,i}}{b_{fck,i}} - 1 \leq 0 \qquad i= 1,\ldots,n_{bf} \tag{12}$$

where D_{un} and $\underline{D_{ln}}$ are the depths of upper and lower floor columns, $b'_{fck,i}$ and $b_{fbk,i}$ are the flange widths of beams, $b_{fck,i}$, $d_{c,i}$ and $t_{fl,i}$ are the flange width, depth and flange thickness of the column as seen in Fig. 2.

Finally, the objective function $\varphi(x)$ is calculated as follows using the above mentioned information.

$$g_i(\mathrm{x}) > 0 \rightarrow c_i = g_i(\mathrm{x}) \tag{13}$$

$$g_i(\mathrm{x}) \leq 0 \rightarrow c_i = 0 \tag{14}$$

$$\varphi(x) = W(x)\left(1 + P\sum_{i=1}^{s} c_i\right) \tag{15}$$

where P, c_i and $\varphi(x)$ are a penalty constant, constraint violations and penalized objective function, respectively.

3. JAYA algorithm

JAYA algorithm is developed by Rao (2016). It is very simple and powerful for structural optimizations for constrained and unconstrained problems. This novel algorithm method was used to obtain optimum design in several studies [Rao 2016; Degertekin *et al.* 2017, Rao *et al.* 2016, Rao and More 2017, Rao *et al.* 2016). The solution vectors avoid the worst solution and try to reach best solution. So it is called as JAYA which means victory in Sanskrit word. This algorithm method is very simple because it is conducted only a single equation. In other words, JAYA does not require any algorithm-specific control parameters. Firstly, population size and number of design variables should be defined as below.

$$population = \begin{bmatrix} x_1^1 & x_2^1 & .. & x_{m-1}^1 & x_m^1 \\ x_1^2 & x_2^2 & .. & x_{m-1}^2 & x_m^2 \\ .. & .. & .. & .. & .. \\ x_1^{n-1} & x_2^{n-1} & .. & x_{m-1}^{n-1} & x_m^{n-1} \\ x_1^n & x_2^n & .. & x_{m-1}^n & x_m^n \end{bmatrix} \begin{matrix} \rightarrow f(x^1) \\ \rightarrow f(x^2) \\ \rightarrow .. \\ \rightarrow f(x^{n-1}) \\ \rightarrow f(x^n) \end{matrix} \tag{16}$$

where m is the number of design variables (j=1,2,……m), n is population size (candidate solutions, k=1,2…..n), $f(x^{1,2\ldots n})$ are objective function values of each solution vector. $f(x^{best})$ has the best value and $f(x^{worst})$ has the worst value in the population. At any iteration i^{th}, $x_{j,k,i}$ is the value of j^{th} variable for k^{th} solution vector. This value is modified as below,

$$x_{j,k,i}^{new} = x_{j,k,i} \underbrace{+r_{1,j,i}(x_{j,best,i} - |x_{j,k,i}|)}_{A} \underbrace{-r_{2,j,i}(x_{j,worst,i} - |x_{j,k,i}|)}_{B} \tag{17}$$

where $x_{j,best,i}$ and $x_{j,worst,i}$ is the j^{th} design variable in the best and worst solution vectors during i^{th} iteration. $x_{j,k,i}^{new}$ is modified value of $x_{j,k,i}$, $r_{1,j,i}$ and $r_{2,j,i}$ are random numbers in the range [0,1]. While term A in the Eq. (17) approaches to the best solution, term B avoids the worst solution. If the function value is provided by $x_{j,k,i}^{new}$ then it replaces $x_{j,k,i}$. The updated values become the input for the next iteration. In this study, a computer program is developed in MATLAB (2009) to interact with SAP2000 OAPI (2008). A flowchart of JAYA Algorithms is shown in Fig. 3.

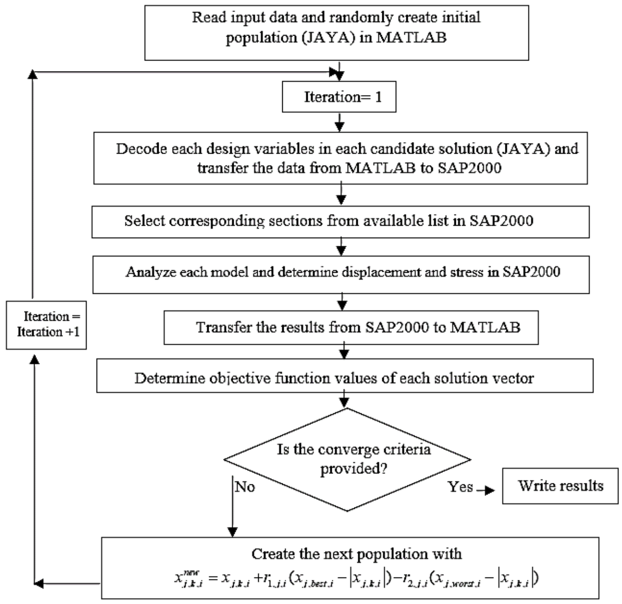


Fig. 3. Flowchart for the optimum design procedure of steel space frames

4. Design examples

Four different examples including soil-structure interaction in the literature are investigated in this study according to different rotational stiffness values by using JAYA algorithm. The effort is given to determine the equivalent rotational stiffness value range for each frame example. First example is a two story, 21-member irregular space frame which are carried out for pinned, semi-rigidly connected supports (50000 kNm/rad, 100000 kNm/rad, 200000 kNm/rad, 350000 kNm/rad) and fixed support. The second example is five-story, two-bay steel space frame which is performed for the cases with semi-rigidly connected supports (50000 kNm/rad, 100000 kNm/rad) and fixed support. Third example is four-storey, 84-member space frame which is solved for the cases with pin support, semi-rigidly connected supports (100000 kNm/rad, 150000 kNm/rad) and fixed support. The last example is a 20-story space frame which is investigated for the cases with pin support, semi-rigidly connected supports (50000 kNm/rad, 100000 kNm/rad) and fixed support. The purpose of so many trials for each example is that the steel space frame examples were designed according to different modulus of elasticity (E_s) and depth of soil stratum (H_s) in the literature. So a possible relationship between soil parameters (soil depth and modulus of elasticity) and rotational stiffness at the supports is investigated here in this study. A computer program was developed in MATLAB to achieve corporation with SAP2000-OAPI for optimum solutions. The suitable sections are selected from a predefined list of W profiles taken from AISC (American Institute of Steel Construction). In the all examples, material properties of steel are modulus of elasticity E=200 GPa, yield stress f_y=250 MPa, material density ρ=7.85 ton/m^3.

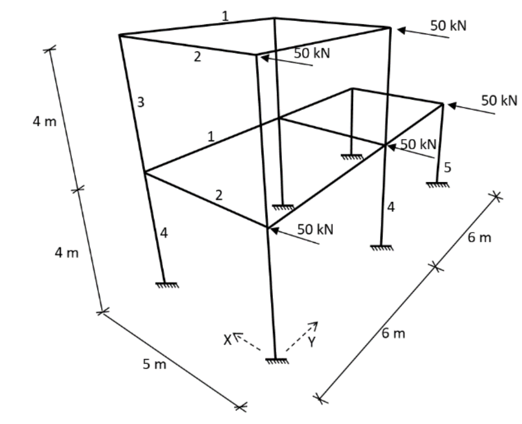
4.1 Two-storey, 21-member irregular space frame

This space frame was previously solved by Aydogdu (2010) according to ACO (Ant Colony Optimization) method. The frame was also solved by Daloglu *et al*. (2016) using Genetic Algorithm for the cases with and without subsoil effect. The optimum solutions including soil effect in Daloglu *et al.* (2016) were carried out for three different soil types such as loose, medium dense and stiff soil (modulus of elasticity of soil E_s= 20000 kN/m^2, 68950 kN/m^2 and 120000 kN/m^2). The depth of soil stratum H_s was considered for 20 m in the study (Daloglu *et al*. 2016) and Poisson’s ratio of the soil was taken as 0.25. Fig. 4 shows three dimensional view, plan view and semi rigidly supported model studied in this study.

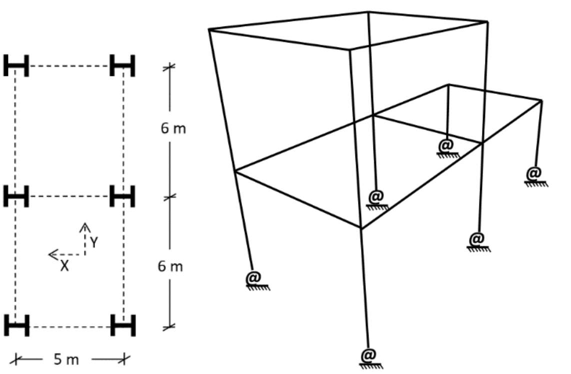
The members of steel space frame are divided to 5 group as shown in Fig. 4. Each beam is subjected to vertical dead load 20 kN/m in addition to the 50 kN wind loads shown in Fig.4. Maximum lateral displacement and inter-storey drift are restricted to 4 cm and 1.02 cm. Optimal solutions are given in Table 1 comparatively. Variations of optimum solutions with the iterations for all cases are given in Fig.5.

Table 1 Optimum solutions of the 21-member irregular space frames

Member Groups	Present study: JAYA Algorithm						Reference study: Daloglu et al.(2016) Genetic Algorithm				Reference study: Aydogdu (2010) Ant Colony Optimization
	Pin supported	Semi-rigidly connected support R_θ: rotational stiffness value, (kNm/rad)				Fixed support	with soil-structure interaction			Fix supported	Fix supported
		50000 kNm/rad	100000 kNm/rad	200000 kNm/rad	350000 kNm/rad		Soil,E_s= 20000 kN/m^2	Soil,E_s= 68950 kN/m^2	SoiL,E_s= 120000 kN/m^2		
1	W12X19	W12X26	W12X26	W12X26	W16X26	W16X26	W12X19	W14X26	W12X26	W14X26	W18X40
2	W24X68	W18X40	W18X35	W18X35	W18X35	W18X40	W21X50	W18X40	W18X40	W18X40	W14X22
3	W24X68	W18X50	W21X50	W18X50	W18X40	W18X40	W12X58	W14X48	W14X48	W14X48	W18X35
4	W27X94	W27X94	W21X62	W21X50	W21X50	W18X40	W14X61	W21X50	W21X50	W18X40	W18X46
5	W24X68	W14X30	W14X30	W12X30	W12X30	W12X30	W14X61	W16X36	W12X30	W12X30	W12X30
Minimum weight (kN)	80.92	65.56	56.23	53.34	51.09	50.65	63.078	55.515	54.73	52.483	48.68
Maximum top storey drift (cm)	1,51	1.95	1.95	1.93	1.92	1.96	1.939	1.893	1.857	2.031	1.82
Maximum inter-storey drift (cm)	0.99	1.014	1.00	0.96	0.90	1.011	1.019	1.018	1.013	1.017	0.95



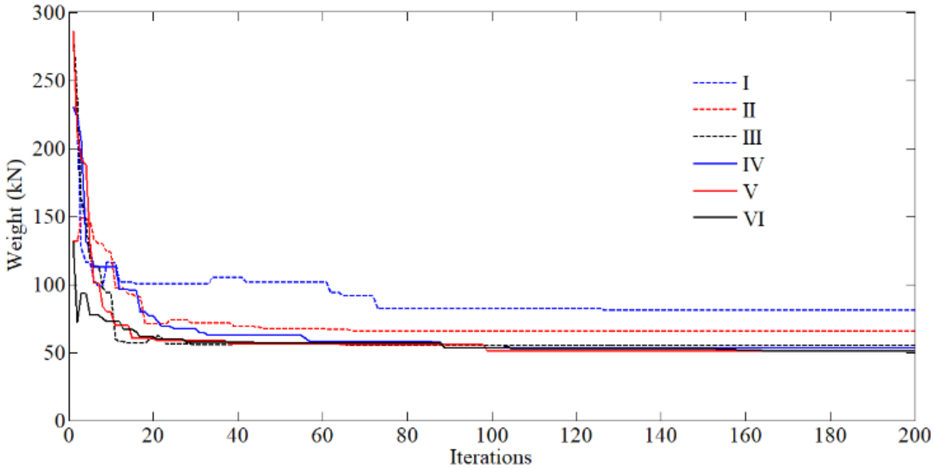
(a) 3D view



(b) Plan view (c) Semi-rigidly supported

Fig. 4 Two-storey, 21-member irregular space frame

In this study, several independent runs are carried out to get the best optimum solutions. While the solutions including soil-structure interaction in study by Daloglu *et al* (2016) are completed in 240 minutes, it can only be done around 65 minutes in this study. Moreover, as shown in Table 1, inter-storey drift in two solutions are very close to the limit value 1.02 m. Accordingly, it can be said that the constraints play active role in the optimum solutions. It is observed from the table that the minimum steel weight calculated as 50.65 kN for the case of fixed support model in other words without soil effect. The value is very close to the ones obtained from previous studies (52.483 kN and 48.68 kN) (Daloglu *et al*. 2016, Aydogdu 2010). Furthermore, according to Tablo 1, the minimum steel weights of space frames including soil effect for E_s= 20000 kN/m^2 at Hs=20 m is 63.078 kN stated in literature (Daloglu *et al*. 2016). This value is very close to 65.56 kN calculated in this study for the case of semi-rigid connected support having rotational stiffness value of 50000 kNm/rad. Therefore, it can be considered that the effect of loose soil (E_s= 20000 kN/m^2) on optimum designs of space frame can be determined by using the semi-rigidly connected support (R_θ= 50000 kNm/rad). This similarity is also observed in Tablo 1. In other words, the optimum solutions of medium dense soil (E_s= 68950 kN/m^2) and stiff soil (E_s= 120000 kN/m^2) are very close to the minimum values of semi-rigid connected support (R_θ=100000 kNm/rad and R_θ=200000 kNm/rad), respectively. Much higher value of optimum weight is obtained for pin supported case being 80.92 kN as



I: Pinned support, II: Semi-rigidly connected support; R_θ=50000kNm/rad, III: Semi-rigidly connected support; R_θ=100000kNm/rad, IV: Semi-rigidly connected support; R_θ=200000kNm/rad, V: Semi-rigidly connected support; R_θ=350000kNm/rad, VI: Fixed support. (R_θ: rotational stiffness)

Fig. 5 Variations of optimum solutions with iteration number for all cases

stated in Table 1 which can be considered as overdesigned remaining on the safe side. The results are encouraging but more results are necessary to reach a safe and sound decision. Following examples are examined for this purpose.

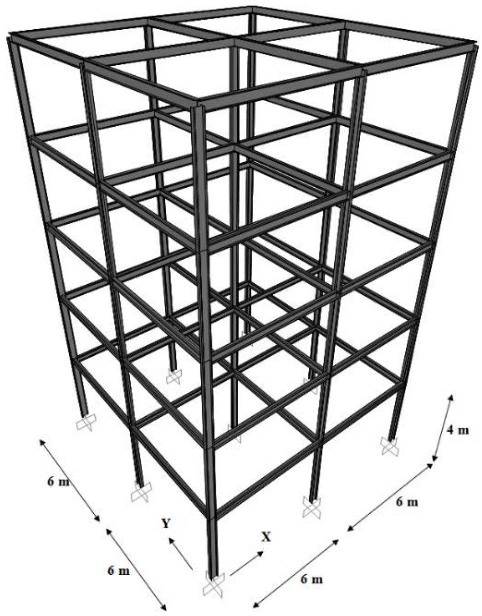
4.2 Five-story, two-bay steel space frame

3D view, plan and semi-rigid supported model of the steel space frame are presented in Fig. 6.

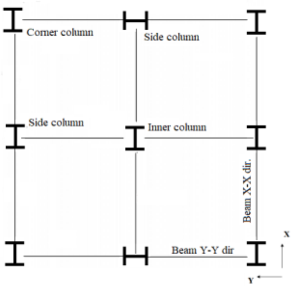
This space frame was previously solved by Aydogdu (2010) according to Harmony search (HS) algorithm method for the fixed supported case. The frame was also studied by Daloglu *et al*. (2015) using Genetic Algorithm for considering subsoil effect. The optimum designs of steel space frames including soil-structure interaction were carried out for two different soil types (loose (E_s= 20000 kN/m^2) and medium dense (68950 kN/m^2) taking depth of soil stratum as H_s= 20 m. Poisson's ratio of the soil was considered as 0.25. The members of steel space frame are collected in 11 groups as seen in Table 2. The space frame is subjected to dead loads (D=2.88 kN/m^2), live loads (L=2.39 kN/m^2), snow load (S=0.755 kN/m^2) and wind speed is 105 mph (65 m/s) according to ASCE 7-05 (2005). The loading combinations are considered as 1.2D + 1.6L + 0.5S; 1.2D + 0.5L +1.6S; 1.2D + 1.6W+ 0.5L + 0.5S where W is the wind load. Maximum lateral displacement and inter-storey drift are restricted to 6.67 cm and 1.33 cm (height /300), respectively. Optimum solutions are presented in Table 3 comparatively. Also, Fig.7 shows the variations of optimum solutions with iteration number for all cases.

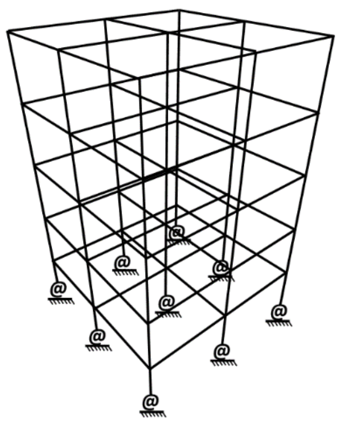
Table 2 Member grouping of the steel space frame

Storey number	Group number				
	Beam X–X dir.	Beam Y–Y dir.	Corner column	Side column	Inner column
1	1	2	9	10	11
2, 3	1	2	6	7	8
4, 5	1	2	3	4	5



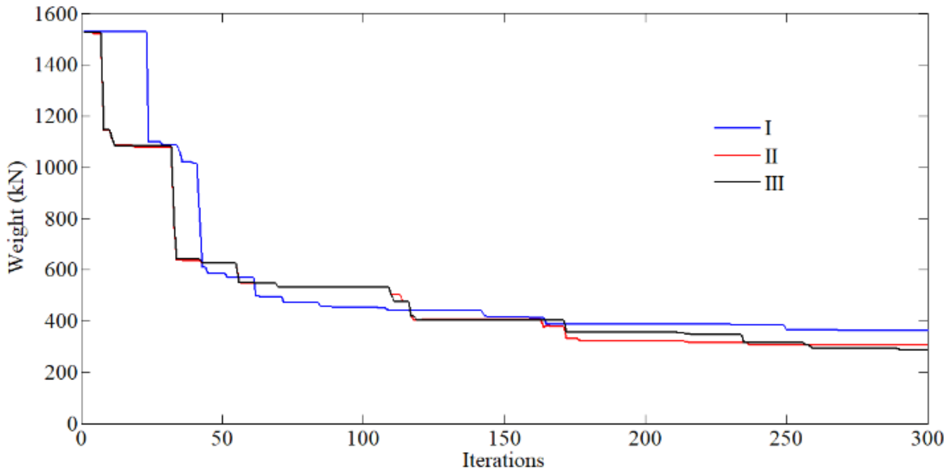
(a) 3D view





(b) plan view (c) semi-rigidly supported model

Fig. 6 Five-story, two-bay steel space frame



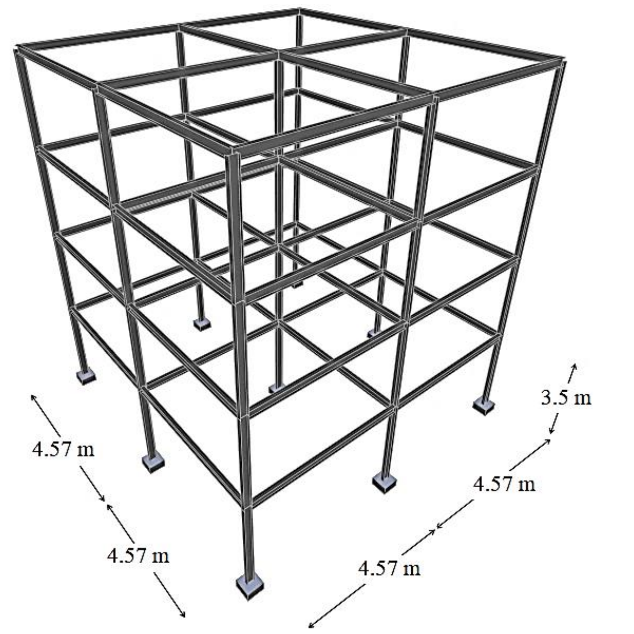
I: Semi-rigid connected support; R_θ=50000kNm/rad, II: Semi-rigidly connected support; R_θ=100000kNm/rad, III: Fixed support. (R_θ: rotational stiffness value)

Fig. 7 Variations of optimum solutions according to iteration steps for all cases

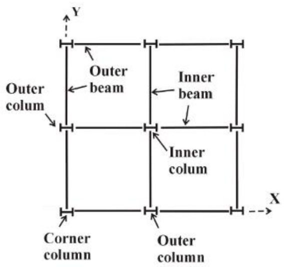
Table 3 Optimum solutions of the five-story, two-bay steel space frame

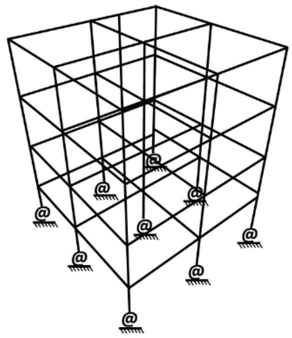
Group members	Present study: JAYA Algorithm			Reference study: Daloglu *et al.* (2015) Genetic Algorithm		Reference study: Aydogdu (2010) Harmony Search Algorithm
	Semi-rigidly connected support R_θ: rotational stiffness value, (kNm/rad)		Fixed support	with soil-structure interaction		Fix supported
	50000 kNm/rad	100000 kNm/rad		Soil,E_s= 20000 kN/m^2	Soil,E_s= 68950 kN/m^2	
1	W12X26	W14X26	W16X26	W8x28	W8x28	W21x44
2	W10X26	W10X26	W10X26	W8x31	W8x31	W12x26
3	W12X26	W8X21	W8X24	W10x33	W14x30	W8x24
4	W27X94	W18X76	W14X68	W14x61	W14x61	W8x24
5	W10X33	W12X26	W8X24	W14x53	W12x45	W14x30
6	W16X31	W14X43	W10X39	W12x35	W14x34	W12x26
7	W30X148	W18X76	W27X94	W18x76	W18x76	W14x48
8	W18X35	W24X68	W21X50	W36x194	W27x161	W24x62
9	W27X94	W18X76	W12X53	W14x61	W18x35	W16x36
10	W36X194	W30X148	W27X94	W36x194	W27x94	W14x48
11	W24X68	W24X68	W21X50	W36x194	W36x194	W30x99
Minimum weight (kN)	355.60	304.89	288.11	350.87	310.90	278.196
Maximum top storey drift (cm)	4.76	4.45	4.38	4.50	4.88	4.837
Maximum inter-storey drift (cm)	1.32	1.17	1.15	1.19	1.33	1.33

It is observed from Table 3 that inter-storey drift constraints are very close to the upper limit value 1.33 m. Therefore, this situation proves that the constraints are very dominant in optimum designs of steel space frames. Moreover, the minimum steel weight is calculated as 288.11 kN for fixed supported frame in other words for the case without soil effect. This value is 3.4% heavier than the result obtained from literature (278.196 kN) (Aydogdu 2010). This is a normal situation that may be encountered in the optimum solutions of a structure problem with different algorithm methods. In other words, different algorithm methods are constantly proposed and it is not possible for each newly developed algorithm to design more economical optimum solution for each problem. As seen in Table 3, the minimum steel weights of space frames in this study is calculated as 355.60 kN for semi-rigid connected support having R_θ = 50000 kNm/rad. This value is very close to the minimum weight of frame for the case with soil effect for E_s= 20000 kN/m^2. It is nearly 1.4% heavier than 350.87 kN defined for the loose soil (E_s= 20000 kN/m^2). It is observed from Table 3 that the minimum steel weights of space frames are found as 304.89 kN for semi-rigid connected



a) 3d view





b) plan view c) semi-rigidly supported model

Fig. 8. 4-storey, 84-member space frame

support having R_θ = 100000 kNm/rad. This value is about 1.9% lighter than the results of the case with soil effect for medium dense soil (E_s= 68950 kN/m^2). In other words, these results confirm the results found in the previous question. However, first two examples are studied constant depth of soil stratum, H_s=20 m. Next frame is examined according to various soil depths (H_s).

4.3 Four-storey, 84-member space frame

The steel space frame shown in Fig.8 was previously searched by Degertekin *et al.* (2008) using Tabu Search (TS) algorithm. The steel frame was also studied by Daloglu *et al.* (2016) using Genetic Algorithm for the cases with and without considering soil effect. The optimum solutions containing soil-structure interaction in Daloglu *et al.* (2016) were investigated for medium dense soil (Es= 68950 kN/m^2) according to different soil depths such as H_s= 5 m, H_s=10 m and H_s=15 m. Poisson's ratio of the soil was taken as 0.25 . Fig. 8 presents three dimensional view, plan view and semi rigidly supported model considered in this study.

Table 4 Member grouping of the steel space frame

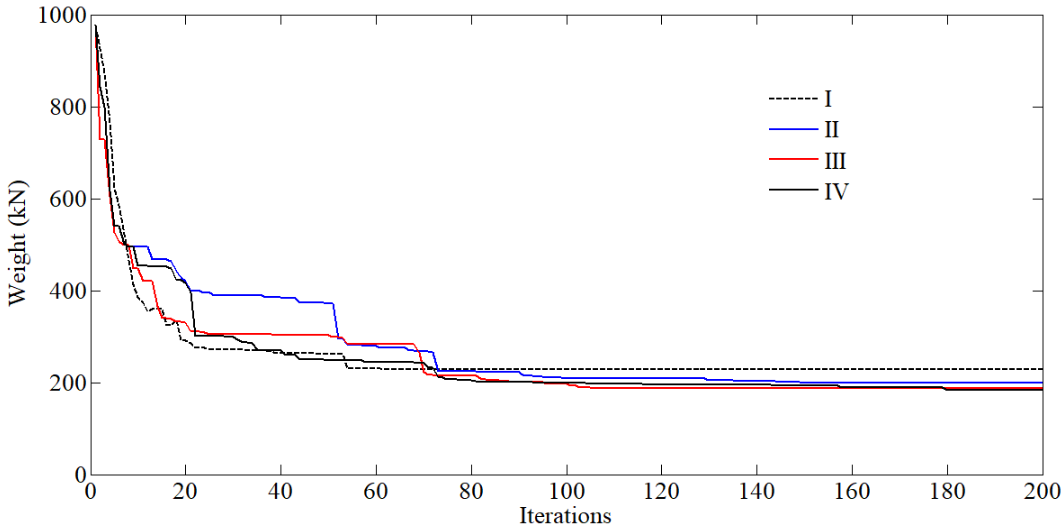
Storey number	Group number				
	Outer beam	Inner beam	Corner column	Outer column	Inner column
1	2	4	6	8	10
2	2	4	6	8	10
3	2	4	6	8	10
4	1	3	5	7	9

The members of the space frames are collected in 10 groups as seen in Table 4. The steel space frame is exposed to dead load (D=3.84 kN/m^2), live load (L=2.40 kN/m^2), roof live load (Lr=2.40 kN/m^2) and wind pressure according to the equation ($p=C_eC_qq_sI_w$, where p, C_e, C_q, q_s and I_w are wind pressure, factor coefficient (combined height, exposure and guest), pressure coefficient, wind stagnation pressure and wind importance factor, respectively. C_q is 0.8 and 0.5 for windward and leeward faces, respectively. q_s is 0.785 kN/m^2, I_w is 1. The wind loads (W) are considered in the x-direction. Load combinations are as; 1.4D; 1.2D + 1.6L + 0.5L_r; 1.2D + 1.6L_r + 0.5L ; 1.2D + 1.3W + 0.5L_r + 0.5L. The maximum lateral displacement and inter-story drifts constraints are 3.50 cm and 1.17 cm, respectively. Optimum solutions are given in Table 5 together with literature solutions. Also, Fig.9 shows the variations of optimum solutions according to iteration steps for all cases.

In this study, the minimum steel weight is obtained as 183.21 kN for fixed support. This value is very close to the ones obtained by other studies for the case without soil effect (Daloglu *et al.* 2016, Degertekin *et al.* 2008). In the first two examples, the effect of medium dense soil (E_s= 68950 kN/m^2) on optimum design of space frame could be estimated approximately for the depth of the soil stratum H_s=20 m by using the semi-rigidly connected support (R_θ = 100000 kNm/rad). It is observed from Table 5 that the minimum weight of steel space frame with semi-rigidly connected support having rotational stiffness value of 150000 kNm/rad is 187.14 kN. This value is very close to the minimum weight defined by Daloglu *et al.* (2016) for H_s = 5 m. So it can be said that as the depth of the soil stratum decreases, the effect of soil foundation on design decreases. It also indicates that the result of semi-rigidly connected support model gets closer to the result for fixed supported case. The minimum steel weights calculated by Daloglu *et al.* (2016) for H_s = 10 m and H_s = 15 m are 193.45 kN and 195.71 kN, respectively. These values are nearly 3% and 1.9% lighter than the minimum steel weight (199.52 kN) obtained in this study for the case of semi-rigidly connected support having rotational stiffness value of 100000 kNm/rad. The optimum weight of 229.17 kN obtained for pin supported frame is quite high compare to all other cases which can be considered as an uneconomical representation but remains on the safe side. It is evident in this example that the reduction in the depth of soil stratum considered in optimization leads to an increase in the rotational stiffness of the support. Next example is studied to investigate how a thick soil layer affect the design, and to see the relationship with the rotational stiffness needed.

Table 5 Optimum solutions of the 84-member space frame

Group members	Present study: JAYA Algorithm				Reference study: Daloglu *et al.* (2016) Genetic Algorithm				Reference study: Degertekin *et al.* (2008) Tabu Seach
	Pin supported	Semi-rigid connected support R_θ: rotational stiffness value, (kNm/rad) 100000 kNm/rad	150000 kNm/rad	Fix supported	with soil -structure interaction Hs=5 (m)	Hs=10 (m)	Hs=15 (m)	Fix supported	Fix supported
1	W12X26	W10X26	W8X28	W10X26	W12X40	W16X31	W12X35	W16X31	W21X44
2	W14X30	W10X26	W16X31	W10X26	W12X35	W18X35	W18X35	W16X31	W14X30
3	W14X26	W12X35	W12X19	W12X19	W14X34	W14X34	W12X26	W14X26	W14X30
4	W21X50	W18X35	W14X43	W16X26	W16X26	W16X26	W16X26	W14X30	W14X30
5	W12X26	W12X58	W10X33	W10X26	W12X45	W12X72	W12X72	W10X26	W12X45
6	W24X68	W18X35	W16X31	W14X30	W16X40	W16X40	W18X50	W18X40	W14X43
7	W14X30	W10X39	W12X40	W12X26	W12X45	W14X48	W10X39	W16X40	W14X43
8	W27X94	W27X94	W21X62	W30X108	W14X30	W18X40	W14X38	W24X68	W14X43
9	W10X22	W14X30	W14X26	W14X26	W14X48	W12X50	W16X36	W16X26	W10X33
10	W21X50	W16X40	W21X62	W18X35	W30X108	W27X94	W27X94	W16X36	W14X33
Minimum weight (kN)	229.17	199.52	187.14	183.21	188.06	193.45	195.71	184.33	182.83
Maximum top storey drift (cm)	3.30	3.34	3.25	3.31	3.35	3.15	3.32	3.32	3.50
Maximum inter-storey drift (cm)	0.78	0.93	0.91	0.94	1.04	0.99	1.02	1.05	1.17

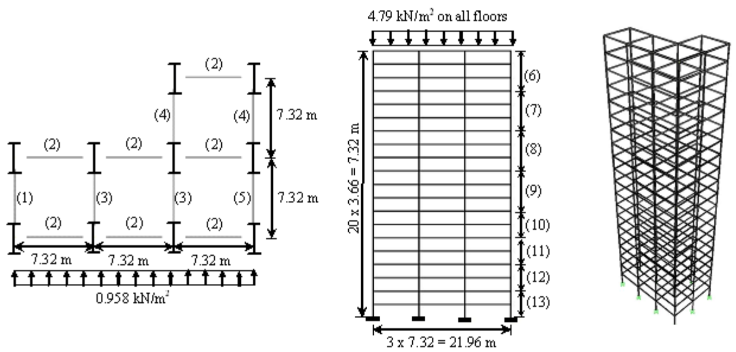


I: Pin support, II: Semi-rigid connected support; R_θ=100000kNm/rad,
III: Semi-rigid connected support; R_θ=150000kNm/rad, IV: Fixed support. (R_θ: rotational stiffness value)

Fig. 9 Variations of optimum solutions according to iteration steps for all cases

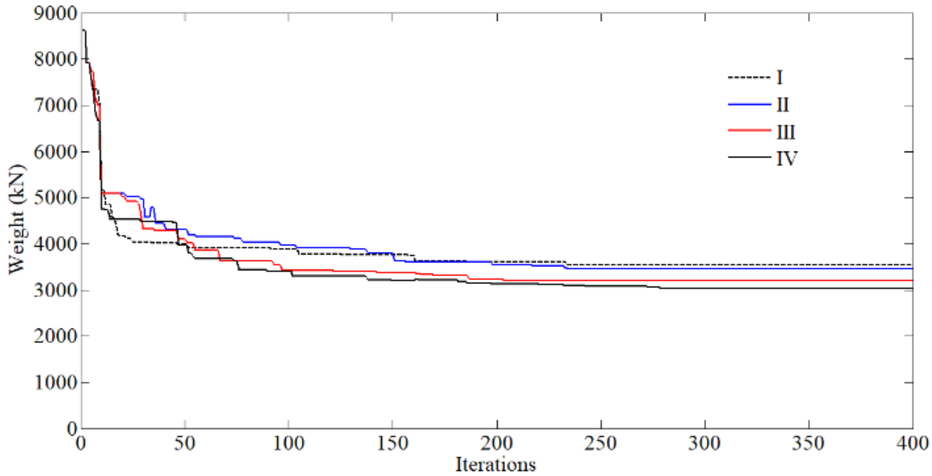
4.4 20-storey, 460-member space frame

The 20-storey, 460-member space frame was previously studied by Aydogdu and Saka (2012) using ACO (Ant Colony Optimization) and Aydogdu (2010) using Harmony Search (HS) algorithm. The same frame was solved by Daloglu *et al*. (2016) using Harmony Search (HS) algorithm for the cases with and without soil. Fig. 10 shows three dimensional view, plan view and semi rigidly supported model studied in this study.



a) plan view b) side view c) semi-rigidly supported model

Fig. 10 Plan, side and semi-rigidly supported model views of 20-story space frame



I: Pin support, II: Semi-rigid connected support; R_θ=50000kNm/rad,
III: Semi-rigid connected support; R_θ=100000kNm/rad, IV: Fixed support. (R_θ: rotational stiffness value)

Fig. 11 Variations of optimum solutions according to iteration steps for all cases

The optimum 1solutions including soil effect in Daloglu *et al*. (2016) was carried out for medium dense soil (E_s=68950 kN/m^2). Poisson's ratio of the soil was taken as 0.25 and the depth of soil stratum H_s was considered as 30 m in the study Daloglu *et al*. (2016). Loading information (Vertical loads on all floors: 4.79 kN/m^2 and wind load: 0.958 kN/m^2) and the member groups are presented in Fig. 10. Maximum lateral displacement and inter-storey drift are restricted to 24.40 and 1.22 cm, respectively. Optimum solutions are presented in Table 6 together with literature results. Fig.11 gives the variations of optimum solutions according to iteration steps for all cases.

In this study, several independent runs are performed to obtain the best optimum solutions. While the optimum solutions including soil-structure interaction in literature study Daloglu *et al.* (2016) are completed in 1200 minutes, it can only be carried out nearly 220 minutes in this study. As seen in Table 6 inter-storey drift in the all solutions are very close to the upper limit value (1.22 cm). As in the previous examples, these constraints are very dominant in the optimizations. Moreover, it is observed from the table that the minimum weight is 3051.17 kN for fixed support in this study. This value and selected profiles are parallel to available ones in literature (Daloglu *et al*. 2016, Aydogdu and Saka 2012, Aydogdu 2010). As shown in Table 1, the minimum steel weight including soil-structure interaction for Es=68950 kN/m^2 and the depth of soil stratum H_s=30 m is 3684.42 kN in the study by Daloglu *et al.* (2016). The value is nearly 13%, 5.7% and 4.2% heavier than the optimum solutions for the cases of semi-rigidly connected support models (R_θ=100000 kNm/rad, R_θ=50000 kNm/rad) and pin supported model, respectively. In other words, when the depth of soil stratum to the rock foundation is high, the optimum weight increases considerably and even the pin supported representation remains on the unsafe side.

5. Summary and conclusions

It is clear that soil effect plays very active roles in optimum design of steel space frames but soil parameters are required in the analyses and its optimum solutions can be carried out after an iterative process and computational effort. This study investigates a practical way for optimum design of steel space frames containing soil foundation effect by using semi-rigidly supported models depending on rotational stiffness values. A novel stochastic search method JAYA is selected to carry out the optimum solutions. The displacement, stress and geometric size constraints are

Table 6 Optimum solutions of 20-story space frame

Group members	Present study:JAYA Algorithm					Reference study: Daloglu *et al.* (2016) Harmony Searh (HS) Algorithm	Reference study: Aydogdu and Saka (2012) ACO	Reference study: Aydogdu (2010) HS
	Pin supported	Semi-rigid connected support R_θ: rotational stiffness value, (kNm/rad) 50000 kNm/rad	100000 kNm/rad	Fix supported	with soil - structure interaction Soil, E_s=68950 kN/m^2	Fix supported	Fix supported	Fix supported
1	W27X84	W40X149	W30X124	W30X99	W30X90	W27X129	W24X62	W27X84
2	W16X50	W10X60	W18X50	W18X46	W21X57	W16X50	W12X190	W18X55
3	W40X167	W18X55	W27X84	W27X84	W36X150	W24X68	W30X132	W27X84
4	W21X44	W30X90	W21X44	W16X57	W18X55	W21X50	W18X46	W24X68
5	W18X46	W18X55	W16X50	W16X57	W21X44	W21X50	W21X44	W18X60
6	W10X60	W21X101	W12X87	W18X76	W30X99	W10X60	W12X136	W27X84
7	W14X82	W21X101	W12X96	W18X76	W30X99	W18X97	W14X159	W30X90
8	W24X94	W30X108	W24X76	W24X76	W30X108	W27X84	W14X159	W30X90
9	W40X167	W30X108	W30X99	W40X149	W30X148	W36X150	W24X176	W30X90
10	W40X221	W40X149	W33X221	W40X149	W40X149	W44X224	W30X211	W30X108
11	W44X224	W44X198	W44X224	W40X149	W40X199	W44X224	W30X211	W30X116
12	W44X224	W44X224	W44X224	W40X221	W44X248	W44X224	W30X211	W40X149
13	W44X224	W44X224	W44X224	W40X249	W44X285	W44X224	W33X221	W40X183
Minimum weight (kN)	3530.42	3472.03	3199.46	3051.17	3684.42	3221.16	3191.15	2943.811
Maximum top storey drift (cm)	19.44	21.06	24.29	24.36	21.69	23.45	17.9	19.64
Maximum inter-storey drift (cm)	1.22	1.18	1.22	1.22	1.22	1.21	1.13	1.21

taken into account in the optimum designs. To be able to do all the operations practically, a computer program is developed in MATLAB interacted with SAP2000-OAPI. Four different steel space frames including soil effect taken from literature are solved according to different semi-rigidly supported models depending on the rotational stiffness values. The results obtained are listed below.

- In the first example, six different optimum solutions are carried out for pin supported model, semi-rigidly supported models (R_θ=50000 kNm/rad, R_θ=100000 kNm/rad, R_θ=200000 kNm/rad, R_θ=350000 kNm/rad) and fixed supported model. The results are compared with the literature results of the optimum solutions including soil effect (three different soil types such as loose (E_s=20000 kN/m^2), medium dense (E_s=68950 kN/m^2) and stiff soil (E_s=120000 kN/m^2) for the depth of soil stratum H_s=20 m.
- To confirm the result of first example and to observe the change in the rotational stiffness of the supports, the second, third and fourth examples from literature are studied according to the cases of various rotational stiffness values for semi-rigidly connected support models.
- It is evident in these examples that a reduction in the depth of soil stratum considered in optimization leads to an increase in the value of rotational stiffness of the semi-rigidly connected supports. But as the depth of soil layer increases the value of rotational stiffness decreases for moderately thick soil layers.
- Pin supported frame model remains on the safe but uneconomical side for moderately thick soil layers. But even the pin supported model remains on the unsafe side for high values of soil layer thickness. So a complete analysis of the frame on deep elastic foundation can be advised for high rise buildings without any simplification.
- Computational time and effort were significantly reduced with the approach suggested here.

References

AISC-LRFD (2001), Manual of Steel Construction-Load and Resistance Factor Design. American Institute of Steel Construction, Chicago, USA.

ASCE 7-05 (2005), Minimum Design Loads for Building and Other Structures, New York, USA.

Artar, M. and Daloglu, A.T. (2015), "Optimum design of steel space frames with composite beams using genetic algorithm", *Steel Compos. Struct.,* **19**(2), 503-519. https://doi.org/ 10.12989/ scs. 2015.19.2.503.

Artar, M. (2016), "Optimum design of steel space frames under earthquake effect using harmony search", *Struct. Eng. Mech.,*

58(3), 597-612. https://doi.org/10.12989/sem.2016.58.3.597.

Artar, M. and Daloglu, A.T. (2019), "Optimum design of steel space truss towers under seismic effect using Jaya algorithm", *Struct. Eng. Mech.,* **71**(1),1-12. https://doi.org/10.12989/sem.2019.71.1.001.

Aydoğdu, I. and Saka, M.P. (2012), "Ant colony optimization of irregular steel frames including elemental warping effect", *Adv. Eng. Softw.,* **44**(1), 150-169. https://doi.org/10.1016/j.advengsoft.2011.05.029.

Aydogdu, I. (2017), "Cost optimization of reinforced concrete cantilever retaining walls under seismic loading using a biogeography-based optimization algorithm with Levy flights", *Eng. Optimiz.* **49**(3), 381-400. https://doi.org/10.1080/0305215X.2016.1191837.

Aydogdu, I., Efe, P. Yetkin, M. and Akin., A. (2017), "Optimum design of steel space structures using social spider optimization algorithm with spider jump technique", *Struct. Eng. Mech.,* **62**(3), 259-272. https://doi.org/10.12989/sem.2017.62.3.259.

Aydogdu, I, Carbas, S. and Akin., A. (2017), "Effect of Levy Flight on the discrete optimum design of steel skeletal structures using metaheuristics", *Steel Compos. Struct.,* **24**(1), 93-112. https://doi.org/10.12989/scs.2017.24.1.093.

Aydogdu I. (2010), Optimum design of 3-d irregular steel frames using ant colony optimization and harmony search algorithms. Ph.D. Dissertation, Middle East Technical University, Ankara, Turkey.

Carbas S. (2016), "Design optimization of steel frames using an enhanced firefly algorithm", *Eng. Optimiz.,* **48**(12), 2007-2025. https://doi.org/10.1080/0305215X.2016.1145217.

Carbas, S. (2017), "Optimum structural design of spatial steel frames via biogeography-based optimization", *Neural Comput. Appl.,* **28**(6),1525-1539. https://doi.org/10.1007/s00521-015-2167-6.

Daloglu, A.T, Artar, M., Ozgan, K. and Karakas A.I. (2016), "Optimum design of steel space frames including soil-structure interaction", *Struct. Multidiscip. O.,* **54**(1), 117–131. https://doi.org/10.1007/s00158-016-1401-x.

Daloğlu, A., Artar, M., Ozgan K. and Karakas, A.I. (2015), "Optimum design of space steel frames on elastic ground with GA" *XIX. National Mechanical Congress*, Karadeniz Technical University, Trabzon, Turkey, August.

Dede, T. (2018), "Jaya algorithm to solve single objective size optimization problem for steel grillage structures", *Steel Compos. Struct.*, **26**(2), 163-170. https://doi.org/10.12989/scs.2018.25.2.163.

Degertekin, S.O. (2007), "A comparison of simulated annealing and genetic algorithm for optimum design of nonlinear steel space frames", *Struct. Multidiscip. O.*, **34**(4), 347-359. https://doi.org/10.1007/s00158-007-0096-4.

Değertekin, S.O., Saka, M.P. and Hayalioglu, M.S. (2008), "Optimal load and resistance factor design of geometrically nonlinear steel space frames via tabu search and genetic algorithm", *Eng. Struct.*, **30**(1), 197-205. https://doi.org/10.1016/j.engstruct.2007.03.014.

Degertekin, S.O., Hayalioglu, M.S. and Ulker, M. (2008), "A hybrid-tabu simulated annealing heuristic algirthm for optimum design of steel frames", *Steel Compos. Struct.*, **8**(6), 475-490. https://doi.org/10.12989/scs.2008.8.6.475.

Degertekin, S.O. and Hayalioglu, M.S. (2010), "Harmony search algorithm for minimum cost design of steel frames with semi-rigid connections and column bases", *Struct. Multidiscip. O.*, **42**(5), 755-768.https://doi.org/10.1007/s00158-010-0533-7.

Degertekin, S.O., Lamberti L. and Ugur I.B. (2017), "Discrete and continuous design optimization of tower structures using the Jaya algorithm", ICADET'17, *2. International Conference on Advanced Engineering Technologies Bayburt*, Turkey, September.

Erbatur, F., Hasancebi, O., Tutuncu, I. and Kılıc, H. (2000), "Optimal design of planar and space structures with genetic algorithms", *Comput. Struct.,* **75**(2), 209-224. https://doi.org/ 10.1016/S0045-7949(99)00084-X.

Esen, Y. and Ülker, M. (2008), "Optimization of multi storey space steel frames, materially and geometrically properties non-linear", *J. Fac. Eng. Arch. Gazi Univ*., **23**(2), 485-494.

Grzywinski, M., Dede, T. and Ozdemir, Y.I. (2019), "Optimization of the braced dome structures by using Jaya algorithm with frequency constraints", *Steel Compos. Struct*., **30**(1), 47-55. https://doi.org/10.12989/scs.2019.30.1.047.

Hadidi, A. and Rafiee, A. (2014), "Harmony search based, improved Particle Swarm Optimizer for minimum cost design of semi-rigid steel frames", *Struct. Eng. Mech., Int. J.*, **50**(3), 323-347.https://doi.org/10.12989/sem.2014.50.3.323.

Hasançebi, O., Çarbaş, S., Doğan, E., Erdal, F. and Saka, M.P. (2009) "Performance evaluation of metaheuristic search techniques in the optimum design of real size pin jointed structures", *Comput. Struct.,* **87**(5-6), 284-302. https://doi.org/10.1016/j.compstruc.2009.01.002.

Hasançebi, O. and Çarbaş, S. (2014) "Bat inspired algorithm for discrete size optimization of steel frames", *Adv. Eng. Softw.,* **67**, 173-185.https://doi.org/10.1016/j.advengsoft.2013.10.003.

Hayalioglu, M.S. and Degertekin, S.O. (2004), "Genetic algorithm based optimum design of non-linear steel frames with semi-rigid connections", *Steel Compos. Struct*., **4**(6), 453-469.

Hayalioglu, M.S. and Degertekin, S.O. (2005), "Minimum cost design of steel frames with semi-rigid connections and column bases via genetic optimization", *Comput. Struct*., **83**(21-22), 1849-1863.https://doi.org/10.1016/j.compstruc.2005.02.009.

Kameshki, E.S. and Saka, M.P. (2001), "Genetic algorithm based optimum bracing design of non-swaying tall plane frames", J. Constr. Steel Res., **57**(10), 1081-1097. https://doi.org/10.1016/S0143-974X(01)00017-7.

Karakas, A.I., Artar, M. Ozgan, K. and Daloglu, A.T. (2016), Optimum design of space truss bridges including soil-structure interaction, ICENS, *International Conference on Engineering and Natural Sciences*, Sarajevo, May.

Kaveh, A. and Talatahari, S. (2012), "A hybrid CSS and PSO algorithm for optimal design of structures", *Struct. Eng. Mech.,* **42**(6), 783-797.https://doi.org/10.12989/sem.2012.42.6.783.

Kelesoglu, O., and Ülker, M. (2005), "Multi-objective fuzzy optimization of space trusses by Ms-Excel", *Adv. Eng. Softw.,* **36**(8), 549-553.https://doi.org/10.1016/j.advengsoft.2005.02.001.

Lee, K.S. and Geem, Z.W. (2004), "A new structural optimization method based on the harmony search algorithm", *Comput. Struct*., **82**, 781-798. https://doi.org/10.1016/j.compstruc.2004.01.002.

MATLAB (2009), *The Language of Technical Computing*. The Mathworks, Natick, MA, U.S.A.

Rafiee, A., Talatahari, S. and Hadidi, A. (2013), "Optimum design of steel frames with semi-rigid connections using Big Bang-Big Crunch method", *Steel Compos. Struct*., **14**(5), 431-451. https://doi.org/10.12989/scs.2013.14.5.431.

Rajeev, S. and Krishnamoorthy, C.S. (1992), "Discrete optimization of structures using genetic algorithms", *J. Struct. Eng., ASCE*, **118**(5), 1233-1250. https://doi.org/10.1061/(ASCE)0733-9445(1992)118:5(1233)

Rao, R.V., Savsani, V.J. and Vakharia, D.P. (2011), "Teaching-learning-based optimization: A novel method for constrained mechanical design optimization problems", *Computer-Aided Design,* **43**(3), 303-315. https://doi.org/10.1016/j.cad.2010.12.015.

Rao, R.V. and Patel, V. (2013), "An improved teaching-learning-based optimization algorithm for solving unconstrained optimization problems", *Scientia Iranica,* **20**(3), 710-720. https://doi.org/10.1016/j.scient.2012.12.005.

Rao, R.V. (2016), "Jaya: A simple and new optimization algorithm for solving constrained and unconstrained optimization

problems", *J. Industrial Eng. Comput.,* **7**(1), 19-34. https://doi.org/10.5267/j.ijiec.2015.8.004.
Rao, R.V., More, K.C., Taler, J. and Ocłon., P. (2016), "Dimensional optimization of a micro-channel heat sink using Jaya algorithm", *Appl. Therm. Eng.,* **103**, 572–582. https://doi.org/10.1016/j.applthermaleng.2016.04.135.
Rao, R.V., Rai, D.P. and Balic, J. (2016), "Surface grinding process optimization using Jaya Algorithm", *Comput. Intelligence Data Mining,* **2**, 487-495. https://doi.org/10.1007/978-81-322-2731-1_46.
Rao, R.V., and More, K.C. (2017), "Design optimization and analysis of selected thermal devices using self-adaptive Jaya algorithm", *Energy Conversion Management,* **140,** 24–35. https://doi.org/10.1016/j.enconman.2017.02.068.
Rao, R.V. (2020), "Rao algorithms: Three metaphor-less simple algorithms for solving optimization problems", *J. Industrial Eng. Comput.*, **11**(1), 107-130. https://doi.org/ 10.5267/j.ijiec.2019.6.002.
Saka, M.P. and Geem, Z.W. (2013), "Mathematical and Metaheuristic applications in design optimization of steel frame structures: an extensive review", *Math. Problems Eng.,* **2013**, 1–33. https://doi.org/10.1155/2013/271031.
SAP2000. 2008. Integrated finite elements analysis and design of structures. Computers and Structures, Inc. Berkeley.
Shallan, O., Maaly, H.M., Sagiroglu, M. and Hamdy, O. (2019), "Design optimization of semi-rigid space steel frames with semi-rigid bases using biogeography-based optimization and genetic algorithms", *Struct. Eng. Mech.,* **70**(2), 221-231. https://doi.org/10.12989/sem.2019.70.2.221.
Shallan, O., Maaly, H.M. and Hamdy, O. (2018), "A developed design optimization model for semi-rigid steel frames using teaching-learning-based optimization and genetic algorithms", *Struct. Eng. Mech*., **66**(2), 173-183. https://doi.org/10.12989/sem.2018.66.2.173.
Togan, V. and Daloglu, A.T. (2006), "Optimization of 3d trusses with adaptive approach in genetic algorithms", *Eng. Struct*., **28**(7), 1019-1027.https://doi.org/10.1016/j.engstruct.2005.11.007
Toğan, V. and Daloğlu, A.T. (2008), "An improved genetic algorithm with initial population strategy and self-adaptive member grouping", *Comput. Struct.,* **86**(11-12): 1204-1218. https://doi.org/10.1016/j.compstruc.2007.11.006.
Togan, V., Daloglu, A.T. and Karadeniz, H. (2011), "Optimization of trusses under uncertainties with harmony search", *Struct. Eng. Mech.,* **37**(5), 543-560. https://doi.org/10.12989/sem.2011.37.5.543.
Togan, V. (2012), "Design of planar steel frames using teaching–learning based optimization", *Eng. Struct*., **34**, 225-232. https://doi.org/10.1016/j.engstruct.2011.08.035.
Topal, U., Trung, V.D., Dede, T. and Nazarimofrad, E. (2018), "Buckling load optimization of laminated plates resting on Pasternak foundation using TLBO", *Struct. Eng. Mech.,* **67**(6), 617-628. https://doi.org/10.12989/sem.2018.67.6.617.

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