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Optimum design of steel space truss towers under seismic effect using Jaya algorithm

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Abstract. This study investigates optimum designs of steel space truss towers under seismic loading by using Jaya optimization algorithm. Turkish Earthquake Code (2007) specifications are applied on optimum designs of steel space truss towers under the seismic loading for different local site classes depending on different soil groups. The proposed novel algorithm does not have any algorithm-specific control parameters and depends only a simple revision equation. Therefore, it provides a practical solution for structural optimization problems. Optimum solutions of the different steel truss examples are carried out by selecting suitable W sections taken from American Institute of Steel Construction (AISC). In order to obtain optimum solutions, a computer program is coded in MATLAB in corporated with SAP2000-OAPI (Open Application Programming Interface). The stress and displacement constraints are applied on the design problems according to AISC-ASD (Allowable Stress Design) specifications. Firstly, a benchmark truss problem is examined to see the efficiency of Jaya optimization algorithm. Then, two different multi-element truss towers previously solved with other methods without seismic loading in literature are designed by the proposed algorithm. The first space tower is a 582-member space truss with the height of 80 m and the second space tower is a 942-member space truss of about 95 m height. The minimum optimum designs obtained with this novel algorithm for the case without seismic loading are lighter than the ones previously attained in the literature studies. The results obtained in the study show that Jaya algorithm is a practical and robust optimization method for structural optimization problems. Moreover, incorporation of the seismic loading causes significant increase in the minimum design weight.

Keywords: Jaya algorithm; steel space truss tower; optimum design; seismic loading; MATLAB-SAP2000 OAPI

1. Introduction

In recent years, we have witnessed several new algorithm methods developed for structural optimum designs. These new design algorithms generally based on metaheuristics. This is because metaheuristics is efficient in finding the optimum solution of discrete and/or mixed variable programming problems. Some of these metaheuristics are Genetic Algorithm (GA), Harmony Search (HS) Algorithm, Artificial Bee Colony (ABC) Algorithm, Ant Colony Algorithm (ACO), Cuckoo Search (CS) Algorithms, Biogeography-based optimization algorithm with Levy flight distribution (LFBBO), Firefly Algorithm (FFA), Teaching-Learning-Based Optimization Algorithm (TLBO), Social Spider Optimization (SSO), Bat Algorithm (BA) (Coello, 2002, Saka 2007, Lamberti and Pappalettere 2011, Saka and Dogan 2012, Saka and Geem 2013, Saka 2014, Kaveh 2016). One of the very recent addition to above mentioned metaheuristics is called Jaya developed by Rao (2016). This algorithm is quite practical and suitable for constrained design optimization problems (Rao and Waghmare 2017). Therefore, Jaya algorithm is selected to carry out the optimum solutions of steel truss tower. Some structural optimization studies in recent years can be listed as follows. Hasançebi and Erbatur (2002) researched on efficient use of simulated annealing in complex structural optimization problems. Kelesoglu and Ülker (2005) focused on multi-objective fuzzy optimization of space trusses by Ms-Excel. Toğan and Daloğlu (2008) investigated an improved genetic algorithm with initial population strategy and self-adaptive member grouping. Saka (2009) investigate optimum design of steel sway frames to BS5950 using harmony search algorithm. Hasançebi *et al*. (2009) studied performance evaluation of metaheuristic search techniques in the optimum design of real size pin jointed structures. Hasançebi *et al.* (2010) researched improving performance of simulated annealing in structural optimization. Aydoğdu and Saka (2012) used ant colony optimization of irregular steel frames including elemental warping effect. Degertekin (2012) researched optimum design of geometrically non-linear steel frames using artificial bee colony algorithm. Rao and Patel (2012) researched an elitist teaching-learning-based optimization algorithm for solving complex constrained optimization problems. Hasançebi and Çarbaş (2014) used bat inspired algorithm for discrete size optimization of steel frames. Hadidi and Rafiee (2014) researched harmony search based, improved particle swarm optimizer for minimum cost design of semi-rigid steel frames. Dede and Togan (2015) used a teaching learning based optimization for truss

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structures with frequency constraints. Artar and Daloglu (2015) studied optimum design of steel space frames with composite beams using genetic algorithm. Artar (2016a) researched optimum design of steel space frames under earthquake effect using harmony search. Artar (2016b) studied optimum design of braced steel frames via teaching learning based optimization. Artar (2016c) focused on a comparative study on optimum design of multi-element truss structures. Rao (2016) developed Jaya: A simple and new optimization algorithm for solving constrained and unconstrained optimization problems. Daloglu *et al.* (2016) researched optimum design of steel space frames including soil–structure interaction. Carbas (2016) studied design optimization of steel frames using an enhanced firefly algorithm. Rao *et al.* (2016) investigated dimensional optimization of a micro-channel heat sink using Jaya algorithm. Rao et al. (2016) researched surface grinding process optimization using Jaya Algorithm. Degertekin and Geem (2016) researched metaheuristic optimization in structural engineering. Rao and More (2017) studied design optimization and analysis of selected thermal devices using self-adaptive Jaya algorithm. Carbas (2017) focused on optimum structural design of spatial steel frames via biogeography-based optimization. Aydogdu *et al.* (2017) investigated effect of Levy Flight on the discrete optimum design of steel skeletal structures using metaheuristics.Aydogdu *et al.* (2017) studied optimum design of steel space structures using social spider optimization algorithm with spider jump technique. Degertekin *et al.* (2017) studied heat transfer search algorithm for sizing optimization of truss structures.

In this study, the weights of truss systems are minimized under the design constraints (stress and displacement) described in the steel design codes (AISC-ASD). Moreover, the optimum designs of steel space towers are studied with the proposed novel algorithm by adding seismic loading. The seismic zone 1 having the highest effective ground acceleration coefficient is selected as the seismic region. Seismic loading as defined in Turkish Earthquake Code (2007) specifications are imposed on steel space truss towers for different local site classes including different soil conditions. Thus, it is aimed to determine how the seismic loading affects the minimum weight of steel space truss towers. Furthermore, the other purpose is that the new algorithm method Jaya depending on a single revision equation is confirmed for its robustness and applicability in the optimum designs of steel structure. In this purpose, different truss problems are carried out with the proposed algorithm. First problem is a benchmark truss problem which is examined to see its efficiency. The other problems are a 582-member and a 942- member steel truss towers which are carried out for the cases without and with seismic loading in seismic zone 1 for different soil conditions according to Turkish Earthquake Code (2007) specifications. The results are compared with the results in literature. The optimum solutions are very close to the results available in literature but weight of the towers increase significantly when the seismic loading considered depending on the soil conditions. Furthermore, the results prove that Jaya algorithm is very suitable and practical method for structural optimum designs because it depends only a revision equation.

2. Optimum design problem

The optimum design of steel space truss is linear and discrete optimum design problem to obtain minimum steel weight which is defined as below;

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

In this equation, W is the weight of the system, 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.

The displacement and stress constraints according to AISC-ASD (1989) specifications are imposed on optimum design of steel space truss towers. The constraints are determined as below.

$$g_j(x) = \frac{\delta_{jl}}{\delta_{ju}} - 1 \le 0 \qquad j = 1, \ldots, n \tag{2}$$

$$g_m(x) = \frac{\sigma_m}{\sigma_{m,all}} - 1 \le 0 \qquad m = 1, \ldots, ne \tag{3}$$

where δ_{jl} and δ_{ju} are displacement of jth degree of freedom and upper bound, σ_m and $\sigma_{m,all}$ are the computed and allowable axial stresses for mth truss member, respectively.

The stress of the truss members is calculated according to AISC–ASD (1989) as below;

- The allowable stress is calculated for tension and compression members as below.

$$\sigma_{t,all} = 0.6 F_y \tag{4}$$

$$\lambda_m = \frac{K_m L_m}{r_m} \qquad m = 1, \ldots, ne \tag{5}$$

$$C_C = \sqrt{\frac{2\pi^2 E}{F_y}} \tag{6}$$

✓ for inelastic buckling ($\lambda_m < C_c$) ;

$$\sigma_{c,all} = \frac{\left[1 - \frac{\lambda_m^2}{2C_c^2}\right] F_y}{\frac{5}{3} + \frac{3\lambda_m}{8C_c} - \frac{\left(\lambda_m^3\right)}{8C_C^3}} \tag{7}$$

✓ for elastic buckling ($\lambda_m \ge C_c$) ;

$$\sigma_{c,all} = \frac{12\pi^2 E}{23\lambda_m^2} \tag{8}$$

where F_y is yield stress, r_m is minimum radius of gyration, K_m is the effective length factor (K=1), λ_m, C_c are the slenderness ratio and critical slenderness ratio parameter, respectively.

In addition to the constraints mentioned above, the areas of profiles for vertical members are restricted as below;

$$g_m(x) = \frac{A_{u,m}}{A_{l,m}} - 1 \le 0 \qquad m = 1,\dots,ne \tag{9}$$

where $A_{u,m}$ and $A_{l,m}$ are the section areas of upper profile and lower profile, respectively.

Metaheuristic algorithms deal with unconstrained optimization problems. However, almost all of the structural design problems are constrained optimization problems as mentioned in this section for the truss towers. One way is to transform the constrained optimum design problem into unconstrained problem by using penalty function. In this study the following function (Eq.10) is used to achieve this transformation.

$$\varphi(x) = W(x)\left(1 + P\sum_{i=1}^{s} c_i\right) \tag{10}$$

$$g_i(\mathrm{x}) > 0 \rightarrow c_i = g_i(\mathrm{x}) \tag{11}$$

$$g_i(\mathrm{x}) \le 0 \rightarrow c_i = 0 \tag{12}$$

where P a penalty constant, c_i is constraint violations and $\varphi(\mathrm{x})$ is penalized objective function.

3. Jaya algorithm

Jaya algorithm developed by Rao (2016) have been used by researchers for the optimum design since 2016 (Rao *et al.* 2016, Rao and More 2017, Rao and Waghmare 2017). This algorithm is quite suitable for structural problems because a simple revision equation is conducted and it does not need any control parameters for algorithm. Jaya is a Sanskrit word meaning “victory”. This novel algorithm method only needs common control parameters such as population size, number of generations and elite size to obtain optimum solutions although different algorithm methods also require different specific control parameters. Its basic aim is that the solution vectors avoid the worst solution and try to reach best solution. In the first process in Jaya, population size and number of design variables should be defined as below.

$$population = \begin{bmatrix} x_1^1 & x_2^1 & .. & x_{m-1}^1 & x_m^1 \\ x_1^2 & x_2^2 & .. & x_{m-1}^2 & x_m^2 \\ .. & .. & .. & .. & .. \\ x_1^{n-1} & x_2^{n-1} & .. & x_{m-1}^{n-1} & x_m^{n-1} \\ x_1^n & x_2^n & .. & x_{m-1}^n & x_m^n \end{bmatrix} \begin{matrix} \rightarrow f(x^1) \\ \rightarrow f(x^2) \\ \rightarrow .. \\ \rightarrow f(x^{n-1}) \\ \rightarrow f(x^n) \end{matrix} \tag{13}$$

where m is the number of design variables (j=1,2,……m), n is population size (candidate solutions, k=1,2…..n), $f(x^{1,2\dots n})$ 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 by the simple revision equation as follows,

$$x_{j,k,i}^{new} = x_{j,k,i} \underbrace{+ r_{1,j,i}\left(x_{j,best,i} - \left|x_{j,k,i}\right|\right)}_{A} \underbrace{- r_{2,j,i}\left(x_{j,worst,i} - \left|x_{j,k,i}\right|\right)}_{B} \tag{14}$$

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 the 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 the term A ($r_{1,j,i}(x_{j,best,i} - |x_{j,k,i}|)$) in the revision equation (Eq.14) shows the tendency of solution to go nearer to the best solution, the term B ($-r_{2,j,i}(x_{j,worst,i} - |x_{j,k,i}|)$) shows the ability of the solution to avoid the worst solution (Rao and Waghmare (2017). However, the term A does not show the tendency of solution to move closer to the best solution in case of $x_{j,k,i} < x_{j,best,i} < 0$. The similar problem can also be found in term B. Therefore, the absolute value of $x_{j,k,i}$ ($|x_{j,k,i}|$) uses instead of $x_{j,k,i}$. Thus, the use of absolute value further enhances the exploration ability of JAYA algorithm (Rao and Waghmare (2017). If $x_{j,k,i}^{new}$ gives a better function value, $x_{j,k,i}$ is replaced with $x_{j,k,i}^{new}$. At the end of the iterations, the modified function values are maintained and the next iteration is conducted with these values. The steps of the proposed algorithm method can be listed as follows.

1.Set up initial population

2.Calculate objective function value for each candidate solution vector in the population.

3.Modify each solution vector by the revision equation (Eq.14)

4.If the new vector gives a better solution, Replace the new solution vector with the previous solution vector.

5. Maintain the modified solution vectors and conduct the next iteration with the new population.

A computer program is developed in MATLAB to interact with SAP2000 OAPI. A flowchart of Jaya Algorithms is presented in Fig. 1.

4. The Information on seismic loading

Seismic loading is applied on optimum designs of steel space truss towers according to Turkish Earthquake Code (2007). Seismic loading is calculated as below.

$$\mathrm{A(T) = A_o\ I\ S(T)} \tag{15}$$

$$\mathrm{S_{ae}(T) = A(T)\,g} \tag{16}$$

$$\begin{aligned} \mathrm{S(T)} &= 1+1.5\frac{\mathrm{T}}{\mathrm{T_A}} && 0 \le \mathrm{T} \le \mathrm{T_A} \\ \mathrm{S(T)} &= 2.5 && \mathrm{T_A} \le \mathrm{T} \le \mathrm{T_B} \\ \mathrm{S(T)} &= 2.5\left(\frac{\mathrm{T_B}}{T}\right)^{0.8} && \mathrm{T_B} \le \mathrm{T} \end{aligned} \tag{17}$$

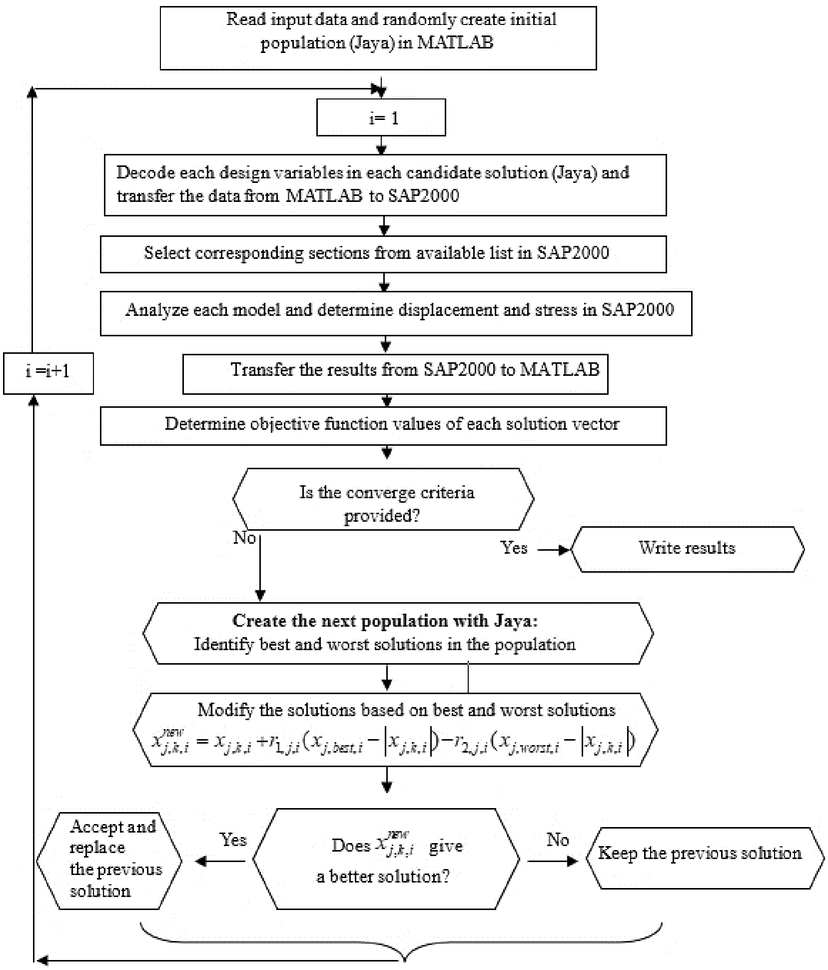


Fig. 1 Flowchart for the optimum design procedure of steel space frames

Table 1 Spectrum characteristic periods (T_A, T_B) (Turkish Earthquake Code 2007)

Local Site Class	T_A *(second)*	T_B *(second)*
Z1	0.10	0.30
Z2	0.15	0.40
Z3	0.15	0.60
Z4	0.20	0.90

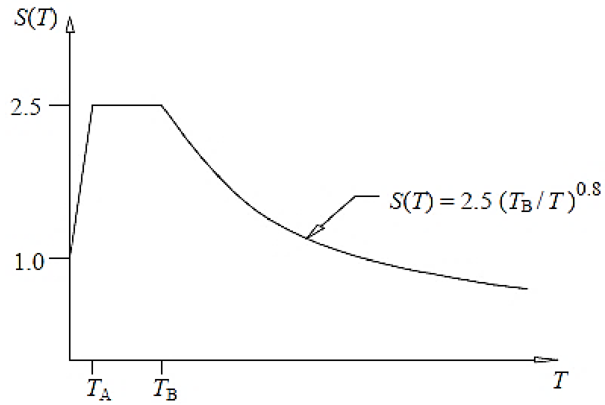


Fig. 2. The spectral coefficient, S(T) ((Turkish Earthquake Code 2007)

where T is natural period of structure, S_{ae} (T) is spectral acceleration, g is gravity, A(T) is the spectral acceleration coefficient, A_o, the effective ground acceleration coefficient, is 0.40, 0.30, 0.20 and 0.1 for seismic zones 1, 2, 3 and 4, respectively. I is the building importance factor (1.0-1.5). S(T) is the spectrum coefficient determined according to different local site classes (soil conditions) as shown in Fig.2. Table 1 presents local site classes indicating spectrum characteristic periods (T_A, T_B) and Table 2 gives information about the description of soil groups and local site classes.

R, structural system behavior factor is considered as 4 for steel space truss towers and (Turkish Earthquake Code 2007). The truss towers are considered in seismic zones 1 and A_o=0.4 is taken in the analyses. The optimum solutions. for the case with seismic loading are carried out for different local site classes (Z1, Z2, Z3 and Z4) mentioned above.

5. Design problems

Jaya Optimization Algorithm is used to design an engineering benchmark problem first to compare the performance of the proposed method. Then, optimum

Table 2 Soil Groups and local site classes (Turkish Earthquake Code 2007)

Soil Group	Description of Soil Group
(A)	1. Massive volcanic rocks, unweathered sound, metamorphic rocks, stiff, cemented sedimentary rocks 2. Very dense sand, gravel… 3. Hard clay and silty clay…
(B)	1. Soft volcanic rocks such as tuff and agglomerate, weathered cemented, sedimentary rocks with planes of discontinuity. 2. Dense sand, gravel... 3. Very stiff clay, silty clay…
(C)	1. Highly weathered soft metamorphic rocks and cemented sedimentary rocks with planes of discontinuity 2. Medium dense sand and gravel... 3. Stiff clay and silty clay.....
(D)	1. Soft, deep alluvial layers with high ground water level 2. Loose sand... 3. Soft clay and silty clay…..

Local Site Class	Soil Group and Topmost Soil Layer Thickness (h_1)
Z1	Group **(A)** soils Group **(B)** soils with $h1 \leq 15$ m
Z2	Group **(B)** soils with $h1 > 15$ m Group **(C)** soils with $h1 \leq 15$ m
Z3	Group **(C)** soils with 15 m $< h1 \leq 50$ m Group **(D)** soils with $h1 \leq 10$ m
Z4	Group **(C)** soils with $h1 > 50$ m Group **(D)** soils with $h1 > 10$ m

designs of two different multi-element space truss towers, a 582-member tower and a 942-member tower, are carried out for with and without seismic loading. Population size is selected as 20 in all three examples since population size was taken as 20 in the literature studies (Artar *et al.* 2017, Artar 2016c, Artar 2016d). Thus, optimum results obtained in this study are compared with the literature results to determine the robustness and applicability of Jaya algorithm.

5.1 Benchmark problem: 10-bar plane truss design

A 10-bar plane truss benchmark problem is designed to compare performance of the proposed optimization algorithm. Fig. 3 show the plane truss problem with 10 design variables. This problem was previously designed with different optimization algorithm methods by several researchers (Rajeev and Krishnamoorthy 1992, Li *et al.* 2009, Camp and Bichon 2004, Artar *et al.* 2017). The design variables are selected from the 42 different cross sections (1.62, 1.80, 1.99, 2.13, 2.38, 2.62, 2.63, 2.88, 2.93, 3.09, 3.13, 3.38, 3.47, 3.55, 3.63, 3.84, 3.87, 3.88, 4.18, 4.22, 4.49, 4.59, 4.80, 4.97, 5.12, 5.74, 7.22, 7.97, 11.50, 13.50, 13.90, 14.20, 15.50, 16.00, 16.90, 18.80, 19.90, 22.00, 22.90, 26.50, 30.00, 33.50 in^2). The modulus of elasticity is 10000 ksi, density of material is 0.1 lb/in^3 and the allowable stress for all members is ±25 ksi. The maximum limit displacement for x and y directions is 2 inches. Table 3.

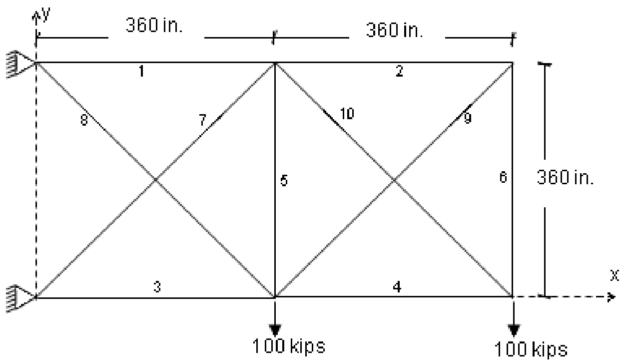


Fig. 3 10-bar plane truss

presents optimum design comparison of the benchmark problem. Fig 4. shows optimum design history of 10-bar plane truss.

It is observed from Table 3 that the optimum solutions of the proposed optimization algorithm are very similar with the ones of the literature studies. Moreover, the minimum steel weight is less than the others. The variation of minimum steel weight according to iteration number is shown in Fig.4. In this study, the analysis is performed for 200 iterations since the optimum solution was carried out for 200 iterations in the literature study of Artar *et al.* (2017). Optimum solution is practically obtained in 120 min. It indicates that the proposed optimization algorithm conducted only a single revision equation provides global solution without increasing solution time. Moreover, the maximum displacement value is calculated as 1.998 inches. This value is very near to allowable limit value. It shows that displacement constraints play very active role in the optimum solutions of the benchmark problem.

5.2 582-Member space truss tower

A 582-member space truss tower previously studied by Hasancebi *et al.* (2009) and Artar (2016c) using Particle Swarm Optimizer (PSO) and Harmony Search (HS) Algorithm. This tower is 80 m high and has 32 different element groups as seen in Fig.5. In this and the next example, optimum solutions are carried out with W profiles taken from American Institute of Steel Construction (AISC). The material properties of steel used in the towers are E (modulus of elasticity) = 203893.6 MPa and Fy (yield stress) = 253.1MPa. Loading information is as follows: lateral point loads of 5 kN is imposed to each point in x and y directions and a vertical load of -30 kN is imposed to each point in z directions.

In this study, in addition to these loads, seismic loads are added in the x and y directions according to different soil conditions in the first earthquake zone defined Turkish Earthquake Code (2007). Maximum drift is restricted to 8.00 cm. Optimum solutions are presented in Table 4 and optimum design histories for all solutions is given in Fig. 6. Fig. 6a shows the variation of minimum weight of the steel structure and Fig. 6b presents the variation of the first natural period of the steel structure according to iteration steps.

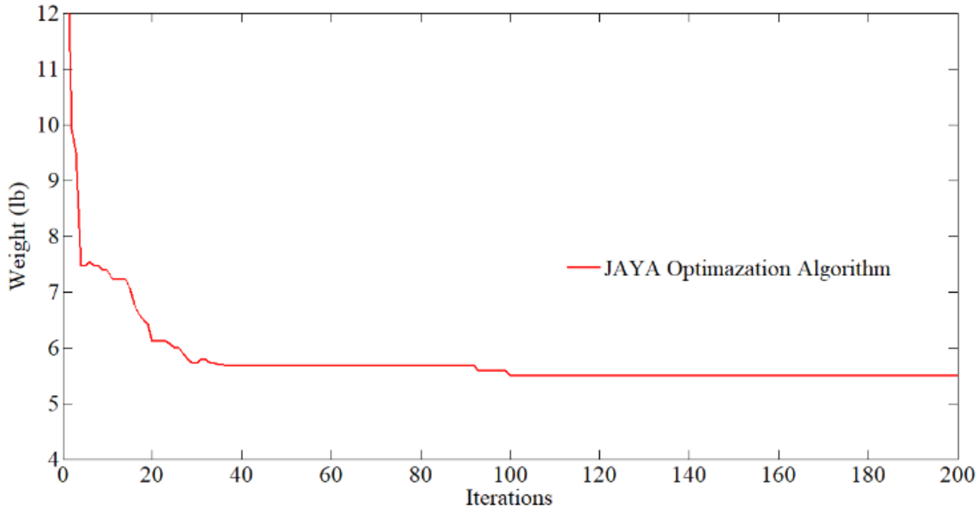


Fig. 4. Optimum design history of 10-bar plane truss

Table 3 Optimum design comparison of the benchmark problem

Design variables (in^2)	Rajeev and Krishnamoorthy (1992) Genetic Algorithm	Li *et al.* (2009) Heuristic Particle Swarm Optimization	Camp and Bichon (2004) Ant Colony Optimization	Artar *et al.* (2017) Teaching-Learning Based Optimization	Present study Jaya
1	33.50	30.00	33.50	33.50	33.50
2	1.62	1.62	1.62	1.62	1.62
3	22.00	22.90	22.90	22.90	22.90
4	15.50	13.50	14.20	14.20	15.50
5	1.62	1.62	1.62	1.62	1.62
6	1.62	1.62	1.62	1.62	1.62
7	19.90	26.50	22.90	22.90	22.00
8	14.20	7.97	7.97	7.97	7.97
9	2.62	1.80	1.62	1.62	1.62
10	19.90	22.00	22.00	22.00	22.00
Weight (lb)	5613.8	5531.9	5490.7	5490.7	5490.05

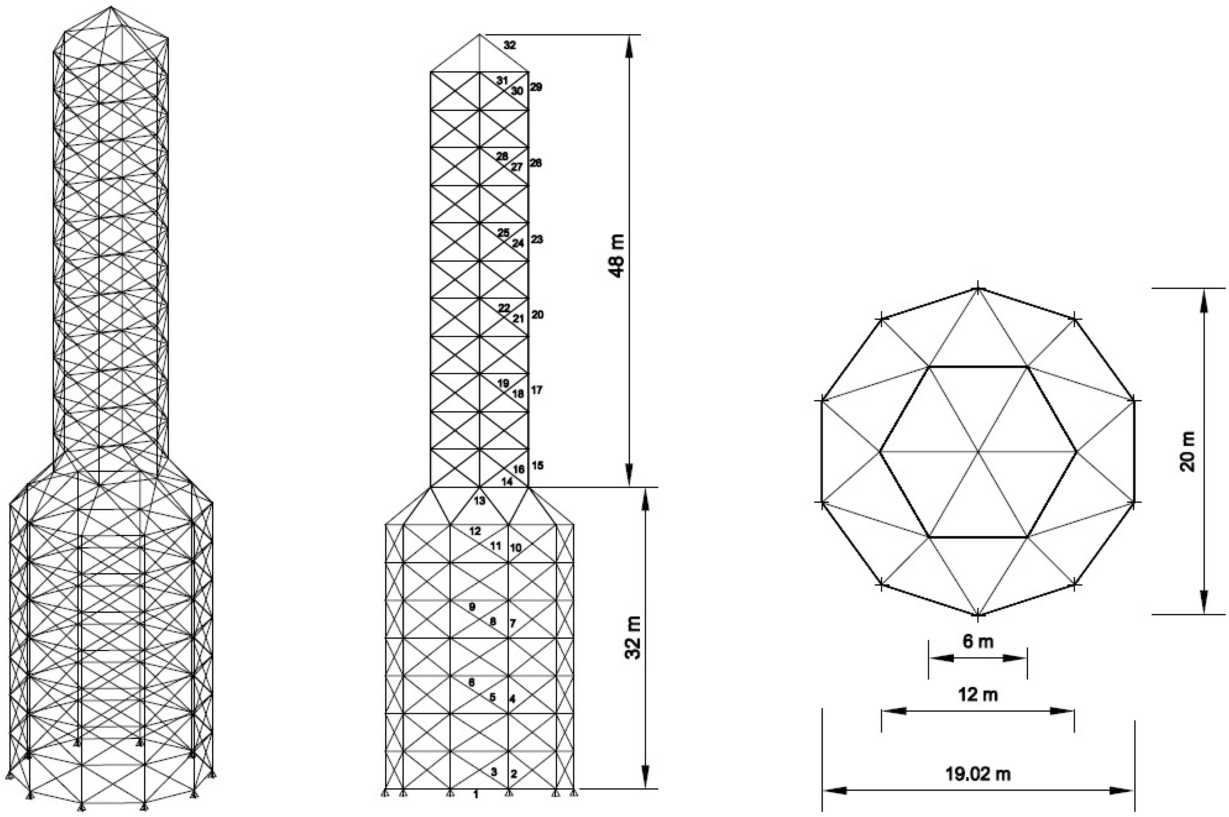
Note: 1 $in.^2$ = 6.452 cm^2 and 1lb = 4.45 N

As it is observed from Table 4 that the optimum results of the truss tower calculated in this study without incorporating seismic loading are similar to the ones available in literature. However, the minimum weight 1536.31 kN is 5.3% and 2.7% lighter than the minimum weights of Hasancebi *et al.* (2009) and Artar (2016c) determining with PSO and HS algorithms. Jaya algorithm provides a better solution for this example. Moreover, the table proves that consideration of seismic loading increases the structural weight significantly. The minimum weights of the truss tower under seismic loading are 1752.25 kN, 1833.29 kN, 1859.73 kN and 1952.17 kN for the four different local site classes Z1, Z2, Z3 and Z4, respectively.

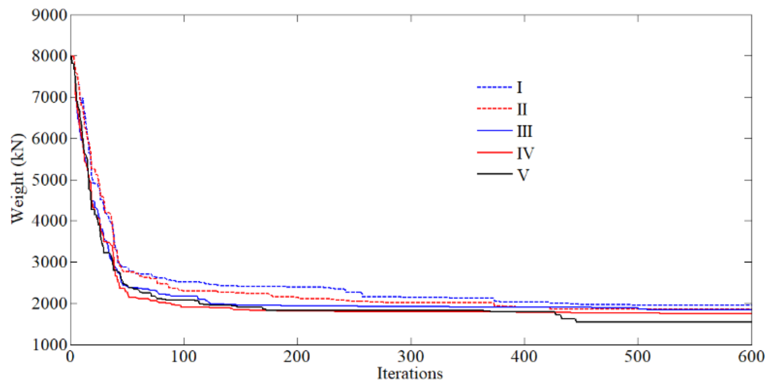
As seen in Table 2 and Table 3, Z1 shows strong soil conditions while Z4 indicates poor soil conditions. Therefore, the minimum weights for the cases with seismic loading according to Z1, Z2, Z3 and Z4 are nearly 14%, 19%, 21% and 27 % heavier than the minimum weight 1536.31 kN determined for the case without seismic loading. The first natural periods for the cases with seismic loading (Z1, Z2, Z3 and Z4) are calculated as 0.431 s, 0.425 s, 0.424 s and 0.396 s. Optimum solution is obtained in 360 min. It is observed from Table 4 that maximum drift values in all solutions are very close to the upper limit of displacement. As expected, it is apparent that the displacement constraints also play very active role in optimum designs of the truss tower.

5.3 942-Member space truss tower

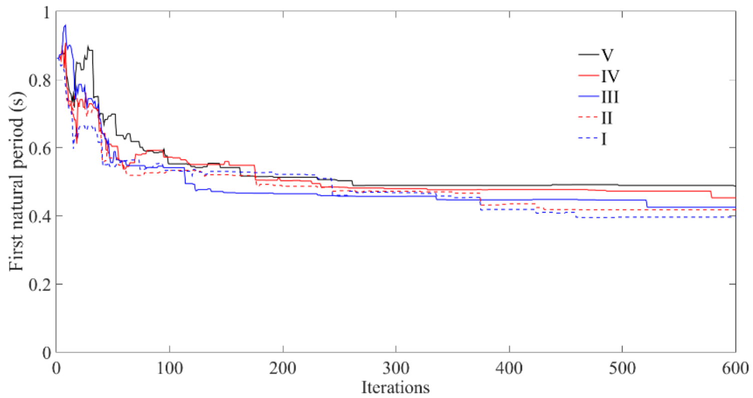
A 942-member space truss tower previously investigated by Hasançebi and Erbatur (2002), Hasançebi (2008), Hasançebi *et al.* (2013) and Artar (2016d) without seismic loading effect using various methods like Simulated Annealing (SA), Evolution Strategies (ES), Bat-inspired (BI) and Teaching-Learning Based Optimization (TLBO). 942-member space truss tower is 95.1 m high and its members are collected to 59 different groups as shown in



a) 3d view b) side view c) top view



a) The variation of minimum weight



b) The variation of first natural period

I, II, III and IV are optimum solutions under seismic loading for four different local site classes Z4, Z3, Z2 and Z1, respectively. V is optimum solutions without seismic loading.

Fig. 6. Optimum design histories for all solutions

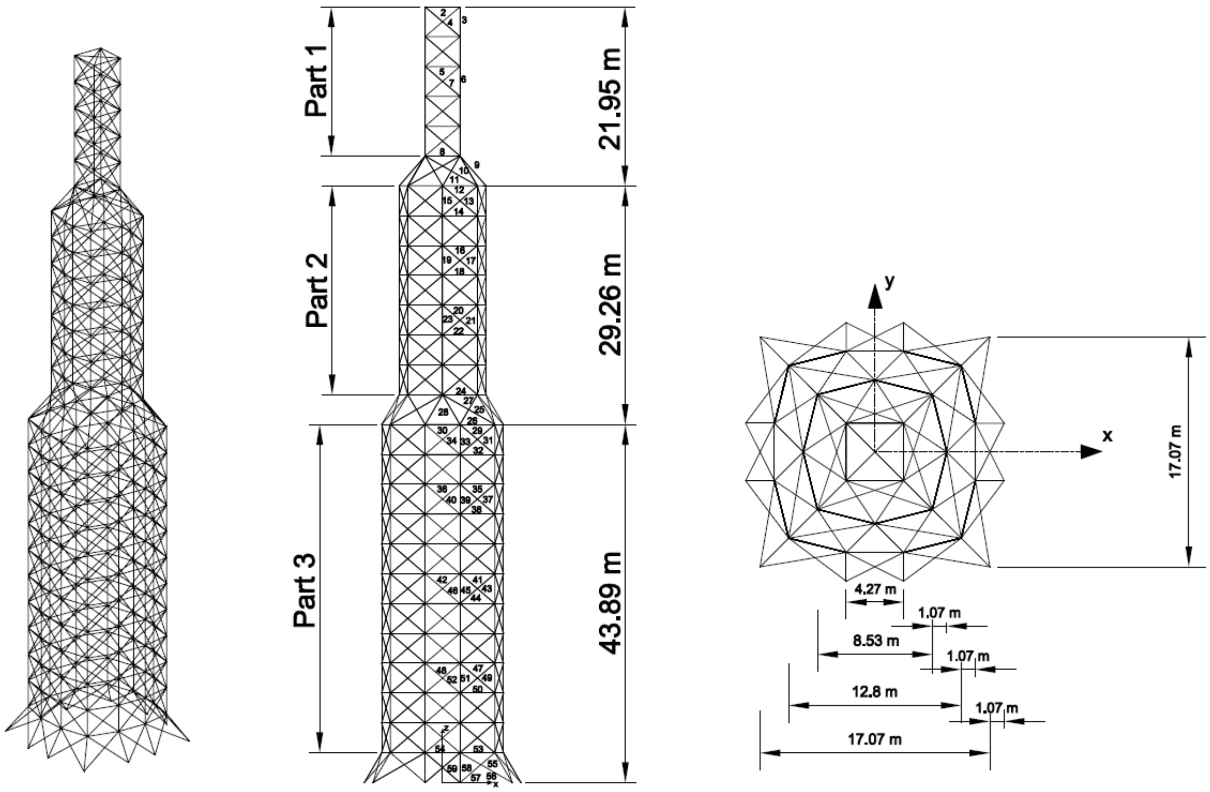
Table 4 Optimum design results

Group number	Literature results Without seismic loading (Hasancebi *et al.*2009) PSO algorithm	Literature results Without seismic loading (Artar 2016c) HS algorithm	Present study without seismic loading (Jaya Algorithm)	Present study with seismic loading (Jaya Algorithm) According to Local Site Classes Z1	Z2	Z3	Z4
1	W8X21	W10X12	W6X12	W12X16	W10X15	W8X10	W12X14
2	W12X79	W30X108	W12X152	W12X152	W12X152	W27X161	W14X311
3	W8X24	W8X10	W8X10	W10X12	W8X13	W5X16	W6X15
4	W10X60	W16X67	W12X152	W12X152	W12X152	W12X152	W12X152
5	W8X24	W8X15	W8X10	W8X10	W6X15	W8X13	W6X15
6	W8X21	W6X20	W8X10	W8X10	W8X10	W8X10	W8X10
7	W8X48	W16X50	W10X60	W12X152	W10X100	W12X152	W12X152
8	W8X24	W6X20	W8X10	W10X15	W8X10	W10X15	W10X17
9	W8X21	W10X15	W8X13	W8X13	W6X12	W8X10	W8X13
10	W10X45	W16X31	W10X39	W12X87	W10X39	W12X58	W10X54
11	W8X24	W5X16	W8X15	W12X14	W6X12	W8X10	W12X14
12	W10X68	W10X68	W16X31	W10X112	W10X112	W16X77	W14X99
13	W14X74	W16X67	W10X68	W18X86	W12X152	W12X152	W18X130
14	W8X48	W18X106	W14X48	W21X57	W14X61	W21X68	W14X48
15	W18X76	W16X100	W12X152	W12X152	W12X152	W12X152	W12X152
16	W8X31	W12X19	W8X13	W10X12	W10X30	W8X13	W8X13
17	W8X21	W16X89	W12X152	W12X152	W12X152	W12X152	W12X152
18	W16X67	W12X19	W10X12	W12X14	W8X13	W10X17	W10X12
19	W8X24	W12X35	W10X12	W10X12	W10X12	W8X10	W8X10
20	W8X21	W16X50	W12X152	W12X96	W12X152	W12X106	W10X45
21	W8X40	W6X15	W10X15	W5X16	W10X15	W6X15	W10X15
22	W8X24	W14X30	W10X15	W8X10	W8X10	W10X15	W8X10
23	W8X21	W14X30	W14X43	W10X54	W10X39	W8X40	W8X40
24	W10X22	W8X10	W10X15	W10X12	W8X10	W5X16	W8X13
25	W8X24	W18X46	W12X14	W10X12	W10X12	W12X14	W8X10
26	W8X21	W14X22	W12X30	W10X15	W6X12	W6X20	W6X20
27	W8X21	W12X26	W10X15	W8X10	W8X10	W8X10	W8X10
28	W8X24	W10X39	W8X10	W10X12	W10X12	W10X12	W8X10
29	W8X21	W10X15	W6X12	W10X12	W6X12	W6X12	W6X12
30	W8X21	W8X13	W12X14	W8X10	W8X10	W8X10	W8X10
31	W8X24	W8X31	W10X15	W8X10	W12X14	W8X10	W8X13
32	W8X24	W16X26	W10X15	W8X10	W8X10	W8X13	W8X13
Max disp. cm	-	7.66	7.995	7.992	7.996	7.958	7.974
Total weight kN	1618.8	1579.8	1536.31	1752.25	1833.29	1859.73	1952.17
First natural period (s)	-	-	0.538	0.431	0.425	0.424	0.396

Fig. 7. The loading information is as follows: the vertical loads in the z direction are -13.344 kN, -26.688 kN and -40.032 kN at each node in the first, second and third sections, respectively.

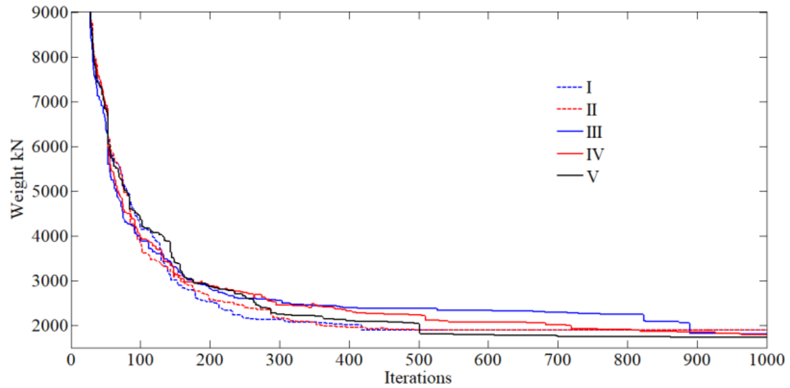
The lateral loads in the y direction are 4.448 kN at all nodes of the tower and the lateral loads in the x direction are 6.672 kN and 4.448 kN at each node on the left and right sides of the tower, respectively. The maximum displacement in any direction is restricted to 38.1 cm. In this study, in addition to these loads, seismic loads are added in the x and y directions according to various soil conditions in the first earthquake zone defined Turkish Earthquake Code (2007). Optimum solutions are presented in Table 5 and optimum design histories for all solutions are given in Fig. 8. Fig. 8a shows the variation of minimum weight of the steel structure and Fig. 8b presents the variation of the first natural period of the steel structure according to iteration steps.

As it is seen from Table 5 that the profiles in optimum solution of the truss tower determined in the present study are very similar to the results of literature studies for the case without seismic loading. Moreover, the minimum weight is calculated in this study as 1582.22 kN which is nearly 6.7%, 6.2%, 6.19% and 5.18% lighter than the

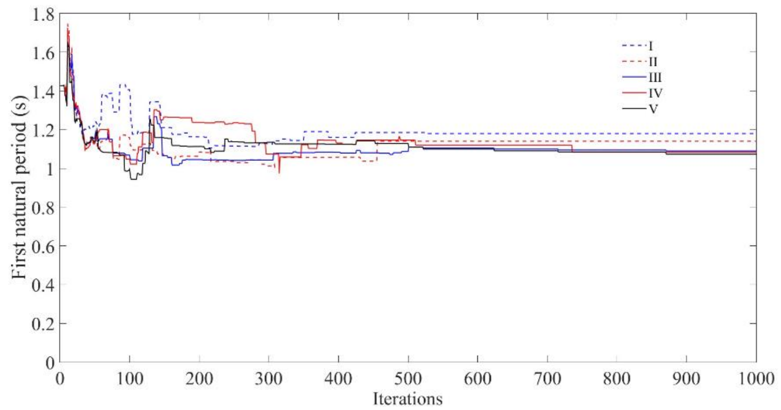


a) 3d view b) side view c) top view

Fig. 7 942-Member space truss tower



(a) The variation of minimum weight



(b) The variaition of first natural period

I, II, III and IV are optimum solutions under seismic loading for four different local site classes Z4, Z3, Z2 and Z1, respectively. V is optimum solutions without seismic loading

Fig. 8. Optimum design histories for all solutions

Table 5 Optimum design results

Group number	Literature studies (Without seismic loading): Hasançebi and Erbatur (2002),SA	Hasançebi (2008), ESs	Hasançebi *et al*. (2013), BI	Artar(2016d) TLBO	Present study without seismic loading (Jaya Algorithm)	Present study with seismic loading (Jaya Algorithm) According to Local Site Classes: Z1	Z2	Z3	Z4
1	W6X9	W6X9	W6X9	W12X14	W12X14	W12X14	W12X14	W12X14	W12X30
2	W6X9	W8X10	W6X9	W6X9	W8X15	W5X16	W12X22	W8X21	W8X21
3	W6X9	W6X9	W6X9	W8X15	W4X13	W4X13	W4X13	W10X15	W6X9
4	W6X15	W6X15	W6X15	W6X9	W6X9	W6X9	W6X9	W10X15	W10X15
5	W6X9	W6X9	W6X9	W12X14	W4X13	W4X13	W6X9	W10X15	W12X14
6	W6X15	W6X15	W6X15	W8X15	W10X15	W10X15	W4X13	W10X15	W8X21
7	W6X15	W6X15	W6X15	W6X9	W12X14	W12X14	W12X14	W8X15	W12X14
8	W6X9	W6X9	W6X9	W6X9	W6X9	W6X9	W6X9	W6X9	W6X9
9	W6X20	W6X20	W6X20	W8X15	W10X15	W10X15	W12X19	W10X15	W12X26
10	W8X24	W6X25	W8X24	W5X16	W6X9	W12X14	W12X16	W12X14	W6X20
11	W6X15	W6X15	W6X15	W14X22	W12X14	W12X14	W10X15	W12X14	W12X14
12	W6X9	W6X9	W6X9	W10X15	W4X13	W4X13	W4X13	W10X15	W4X13
13	W6X20	W6X20	W6X20	W8X21	W12X26	W12X35	W12X35	W10X15	W12X26
14	W6X15	W6X15	W6X15	W6X9	W6X9	W6X9	W12X14	W6X9	W6X15
15	W4X13	W4X13	W4X13	W12X14	W6X9	W12X14	W10X15	W6X9	W6X9
16	W6X9	W6X9	W6X9	W10X30	W6X9	W4X13	W6X9	W6X15	W6X9
17	W8X28	W8X28	W8X28	W12X30	W12X30	W18X40	W18X40	W14X26	W16X40
18	W6X15	W6X15	W6X15	W12X14	W6X9	W6X9	W6X9	W12X19	W10X15
19	W6X15	W6X15	W5X16	W12X14	W12X16	W12X16	W12X16	W14X22	W14X22
20	W6X9	W6X9	W6X9	W14X26	W4X13	W4X13	W4X13	W10X15	W10X15
21	W8X35	W8X35	W8X35	W14X38	W21X44	W24X117	W24X55	W18X50	W21X83
22	W6X20	W6X20	W6X20	W8X15	W8X15	W12X14	W10X15	W12X14	W12X14
23	W6X25	W8X24	W8X24	W12X14	W14X26	W14X26	W12X16	W14X34	W18X35
24	W8X35	W10X45	W8X35	W12X30	W8X24	W8X24	W8X21	W10X22	W8X24
25	W10X49	W8X58	W10X49	W18X55	W24X55	W30X191	W24X55	W24X68	W24X94
26	W8X31	W8X31	W8X31	W8X35	W12X14	W12X14	W12X14	W10X15	W12X14
27	W6X15	W6X15	W6X15	W8X21	W6X9	W4X13	W4X13	W8X15	W6X9
28	W8X24	W8X24	W8X24	W12X14	W10X15	W10X15	W10X15	W5X16	W12X14
29	W14X26	W6X25	W8X24	W12X45	W12X26	W10X30	W10X30	W16X31	W14X34
30	W8X21	W10X22	W8X21	W10X30	W16X26	W14X30	W12X35	W14X30	W12X35
31	W12X87	W14X90	W27X84	W18X86	W27X84	W30X191	W40X149	W24X68	W30X191
32	W6X20	W6X20	W6X20	W8X21	W6X9	W6X9	W10X15	W6X15	W6X15
33	W6X20	W6X15	W5X19	W12X14	W4X13	W4X13	W6X9	W6X15	W6X9
34	W6X15	W6X15	W6X15	W4X13	W12X14	W8X15	W8X15	W12X14	W12X14
35	W6X9	W6X9	W6X9	W6X9	W6X9	W4X13	W4X13	W8X21	W4X13
36	W6X9	W6X9	W6X9	W6X9	W6X9	W12X14	W12X14	W6X9	W12X14
37	W14X99	W14X99	W14X99	W21X101	W30X108	W36X194	W40X277	W44X285	W40X277
38	W8X24	W8X24	W8X24	W12X14	W10X15	W12X14	W12X14	W16X26	W12X14
39	W6X15	W6X15	W6X15	W12X19	W8X21	W8X21	W8X24	W8X21	W6X20
40	W6X20	W6X20	W6X20	W6X9	W6X9	W12X14	W10X15	W10X15	W10X15
41	W6X9	W6X9	W6X9	W6X9	W8X15	W6X9	W8X15	W6X15	W8X15
42	W6X9	W8X10	W6X9	W6X9	W10X15	W4X13	W6X9	W10X15	W4X13
43	W24X131	W24X131	W24X131	W21X132	W33X221	W44X285	W44X285	W44X285	W44X285
44	W8X31	W8X31	W8X31	W10X22	W12X14	W10X15	W12X14	W10X15	W6X15
45	W6X15	W6X15	W6X15	W12X26	W16X26	W10X30	W10X30	W16X31	W10X22
46	W8X24	W8X24	W8X24	W12X14	W12X14	W6X9	W4X13	W6X15	W12X14
47	W4X13	W4X13	W4X13	W6X15	W6X9	W6X9	W6X9	W8X21	W12X14
48	W6X9	W6X9	W6X9	W12X14	W10X15	W10X15	W10X15	W8X15	W10X15
49	W14X145	W14X145	W14X145	W30X148	W44X285	W44X285	W44X285	W44X285	W44X285
50	W8X31	W8X31	W8X31	W8X24	W12X14	W12X14	W12X14	W10X15	W6X20
51	W8X28	W12X30	W8X28	W12X30	W10X33	W8X21	W8X28	W10X22	W8X15
52	W8X24	W8X24	W8X24	W12X14	W12X14	W12X14	W8X15	W10X15	W12X14
53	W10X60	W12X65	W12X65	W10X100	W16X100	W12X65	W18X86	W24X62	W16X40
54	W24X68	W21X73	W21X73	W14X145	W12X65	W8X40	W12X65	W16X31	W14X38
55	W14X132	W14X132	W14X132	W40X183	W44X285	W44X285	W44X285	W44X285	W44X285
56	W8X35	W8X31	W8X31	W12X65	W12X14	W4X13	W6X9	W10X15	W6X9
57	W12X79	W12X72	W12X72	W12X53	W14X43	W21X62	W21X50	W21X62	W10X88
58	W8X24	W8X28	W8X28	W14X22	W12X14	W8X21	W10X49	W8X24	W12X14
59	W8X35	W8X31	W8X31	W16X45	W12X65	W10X22	W6X15	W12X40	W14X22
Weight kN	1689.42	1681.79	1680.07	1664.41 148.5608 148.5608	1582.22	1784.77	1805.39	1890.21	1893.88
First natural period (s)	-	-	-	-	1.073	1.083	1.096	1.149	1.185
Max.disp. cm					20.09	20.25	21.74	22.89	20.89

literature results of Hasançebi and Erbatur (2002), Hasançebi (2008), Hasançebi *et al.* (2013) and Artar (2016d). Jaya algorithm presents very good results here as in the previous example. Table 5 also shows that the seismic loading causes an important increase in the minimum weight. The minimum weights of the truss tower under seismic loading are calculated as 1784.77 kN, 1805.39 kN, 1890.21 kN and 1893.88 kN for the four different local site classes Z1, Z2, Z3 and Z4, respectively. These values are 12.7%, 14.1%, 19.5% and 19.7% heavier than the minimum weight 1582.22 kN calculated for the case without seismic loading. According to the results, seismic loading depending on the soil conditions (local site classes) result with an important increase in the minimum weight of steel space truss tower. However, the rates of increase in the minimum steel weight because of seismic loading are slightly different from the values determined in the first example. Optimum solution is obtained in 420 min.

Also, it is seen from Table 5 that the stress constraints are very important determinant in optimum designs rather than displacement constraints because maximum drift values are far below the upper limit of displacement. The first natural periods for the cases with seismic loading for Z1, Z2, Z3 and Z4 are calculated as 1.083 s, 1.096 s, 1.149 s and 1.185 s, respectively.

6. Conclusions

In this study, optimum designs of steel space truss towers under seismic loading are carried out by using Jaya optimization algorithm. This proposed novel optimization algorithm is very practical because it does not have any algorithm-specific control parameters and it depends only a simple revision equation. The benchmark problem solved in the present study proves that Jaya algorithm presents practically optimum solution without local optimum. Moreover, two different truss towers taken from literature are carried out with lighter designs by using Jaya algorithm. Optimum designs of the steel towers are also carried out for the seismic loading for different local site classes depending on different soil groups according to Turkish Earthquake Code (2007) specifications. The stress and displacement constraints are applied according to AISC-ASD specifications. In the first tower, a 582-member steel space truss system is carried out the case without and with seismic loading depending local site classes (soil conditions) such as Z1, Z2, Z3 and Z4 defined in Turkish Earthquake Code (2007) specifications. Z1 shows strong soil conditions while Z4 indicates poor soil conditions. Therefore, the minimum weights for the cases with seismic loading according to Z1, Z2, Z3 and Z4 are nearly 14%, 19%, 21% and 27 % heavier than the minimum weight 1536.31 kN determined for the case without seismic loading. The increase rates are nearly 12.7%, 14.1%, 19.5% and 19.7% for the 942-member steel truss tower. Considerable increases on the steel weight are observed when the optimum designs are performed under seismic loading. It shows that soil conditions are quite effective for optimum designs of steel truss towers. Moreover, the displacement constraints play active role in optimum solutions in the first two examples while the stress constraints are determinative in the third example.

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