Optimum Design of Braced Steel Space Frames Using Teaching Learning Based Optimization

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Abstract- In this study, optimum design of braced steel space frames is obtained via a novel metaheuristic method, teaching learning based optimization. This algorithm method consists of the two basic phases. The first phase is called as teaching; In this phase, the knowledge interaction occurs between students and teacher. In the second phase, learning phase, the knowledge interaction occurs among students in the class. Optimum profiles are selected among 128 W taken from American Institute of Steel Construction (AISC). The constraints imposed on the frame example are stress constraints as stated in AISC-ASD specifications, geometric constraints and displacement constraints. To obtain optimum solutions, a program is coded in MATLAB programming to incorporate with SAP2000 - Open Application Programming Interface (OAPI). The results are compared through tables and figures. The results indicate that teaching learning based optimization method and MATLAB SAP2000 OAPI technique are applicable even for complex problems and present practical solutions.

Keywords Optimum design, teaching learning based optimization, braced steel space

1. Introduction

In this study, optimum design of a five story braced steel space frame is carried out. The cross sections for the structural members are selected from a list of 128 W profiles taken from AISC (American Institute of Steel Construction). A novel metaheuristic algorithm method, teaching learning based optimization method, is applied on analyses. A program was developed in MATLAB programming to interact with SAP2000-OAPI (Open Application Programming Interface) to get optimum solutions for X braced and unbraced cases of space frames. The stress constraints according to AISC-ASD specifications (American Institute of Steel Construction- Allowable stress design), geometric size (column-column and column-beam) constraints, top displacement and inter story drift constraints are applied to both solutions. The results are compared through tables and figures. The results obtained from the analysis show that teaching learning based optimization method and MATLAB SAP2000 OAPI technique are very applicable and robust for structural optimization of complex structures. Moreover, X braces provide a decrease in the minimum steel weight of space frames.

Teaching learning based optimum design is applied for the optimum design of structural systems as can be found in the literature. Rao et al. [1] studied teaching-learning-based optimization for constrained mechanical design optimization problems. Toğan [2] focused on optimum design of planar steel frames via this novel method. Rao and Patel [3] used this algorithm method for solving unconstrained optimization problems. Dede and Ayvaz [4] studied structural optimization by using teaching-learning-based optimization algorithm. Artar [5] studied optimum design of braced steel frames by using this algorithm method.

In this study, teaching learning based optimization is used for the optimum design of braced steel space frame. A program is developed in MATLAB [6] programming to interacted with SAP2000 [7] OAPI. The results evaluated are presented with the help of tables and figures. The results show that teaching learning based optimization method and MATLAB - SAP2000 OAPI technique is applicable and robust for even very complex structural optimization problems.

2. The Formulation of Optimum Design

The discrete optimum design for minimum weight of plane steel frames is calculated as below,

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

where W is the weight of the frame, A_k is cross-sectional area of group k, ρ_i and L_i are density and length of member i, ng is total number of groups, nk is the total number of members in group k.

$$\varphi(x) = W(x)\left(1 + P\sum_{i=1}^{m} c_i\right) \tag{2}$$

where P is a penalty constant, $\varphi(x)$ is objective function, c_i is constraint violations. The constraint violations are calculated as follows;

$$g_i(\mathrm{x}) > 0 \rightarrow c_i = g_i(\mathrm{x}) \tag{3}$$

$$g_i(\mathrm{x}) \leq 0 \rightarrow c_i = 0 \tag{4}$$

The stress constraints according to AISC-ASD [8] specifications (American Institute of Steel Construction-Allowable stress design) are applied.

Geometric size (column-column and column-beam) constraints, are determined as below,

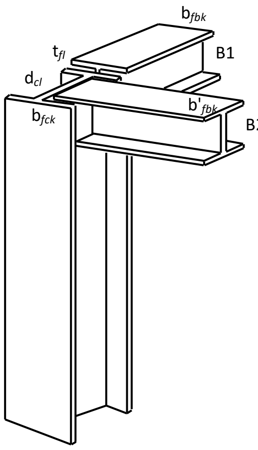


Fig. 1. Beam to column connection geometric constraints

Column-to-column geometric constraints are calculated as below,

$$g_n(x) = \frac{D_{un}}{D_{ln}} - 1 \leq 0 \qquad n = 2,\ldots,ns \tag{5}$$

where D_{un} is the depth of upper floor column, D_{ln} is the depth of lower floor column.

The beam-to-column geometric constraints are calculated as below,

$$g_{bb,i}(x) = \frac{b_{fbk,i}}{b_{fck,i}} - 1 \leq 0 \qquad i = 1,\ldots,n_{bf} \tag{6}$$

where nbf is number of joints where beams are connected to the flange of column and are flange widths of the beam and column, respectively.

Displacement constraints are calculated as below,

$$g_{jl}(x) = \frac{\delta_{jl}}{\delta_{ju}} - 1 \leq 0 \qquad \begin{matrix} j = 1,\ldots,m \\ l = 1,\ldots,nl \end{matrix} \tag{9}$$

where δ_{jl} is the displacement of jth degree of freedom under load case l, δ_{ju} is the upper bound, m is the number of restricted displacements, nl is the total number of loading cases.

Inter-storey drift constraints are calculated as below,

$$g_{jil}(x) = \frac{\Delta_{jil}}{\Delta_{ju}} - 1 \leq 0 \qquad \begin{matrix} j = 1,\ldots,ns \\ i = 1,\ldots,nsc \\ l = 1,\ldots,nl \end{matrix} \tag{10}$$

where Δ_{jil} is the inter-storey drift of ith column in the jth storey under load case l, Δ_{ju} is the limit value, ns is the number of storey, nsc is the number of columns in a storey.

3. Teaching Learning Based Optimization

Teaching learning based optimization is a novel metaheuristic algorithm method which is developed by Rao et al. in 2011.This algorithm method has two basic phases. In the first phase which is called teaching, the knowledge interaction occurs between students and teacher. In the second phase, learning phase, the knowledge interaction occurs among students in the class. The sharing of information provides a better solution. The first class as solution vectors is randomly prepared in matrix form as below,

$$class(population) = \begin{bmatrix} x_1^1 & x_2^1 & .. & x_{n-1}^1 & x_n^1 \\ x_1^2 & x_2^2 & .. & x_{n-1}^2 & x_n^2 \\ .. & .. & .. & .. & .. \\ x_1^{S-1} & x_2^{S-1} & .. & x_{n-1}^{S-1} & x_n^{S-1} \\ x_1^S & x_2^S & .. & x_{n-1}^S & x_n^S \end{bmatrix} \begin{matrix} \rightarrow f(x^1) \\ \rightarrow f(x^2) \\ \rightarrow .. \\ \rightarrow f(x^{S-1}) \\ \rightarrow f(x^S) \end{matrix} \tag{11}$$

In here, each row in matrix indicates a student and it gives a solution vector. S is the number of students in class, n shows the number of design variables, $f(x^1), f(x^2)...f(x^S)$ are objective function value of each row in matrix form. In the class, the minimum objective function value represents the best information level. Thus, the student having the best objective value is assigned as the teacher of the class. The teacher shares his or her information with the other students as below,

$$x^{new,i} = x^i + r(x_{teacher} - T_F x_{mean}) \tag{12}$$

In here $x^{new,i}$ is the updated (new) student, x^i is the current (old) student, r is a random number in the range [0,1], TF, a teaching factor, is either 1 or 2. x_{mean} is the mean of the class is defined as $x_{mean} = (mean(x_1)....mean(x_S))$. If the new student has better information ($f(x^{new,i})$), the new student is replaced with the old student.

In the second step, learning step, the sharing of information occurs among students. Mentioned as below, if the new student has better information, it is replaced with the old student.

$$if\ f(x^i) < f(x^j) \ \Rightarrow \ x^{new,i} = x^i + r(x^i - x^j)$$
$$if\ f(x^i) > f(x^j) \ \Rightarrow \ x^{new,i} = x^i + r(x^j - x^i) \qquad (13)$$

The flowchart of processes in MATLAB-SAP2000 OAPI developed to get optimum solutions are shown as below,

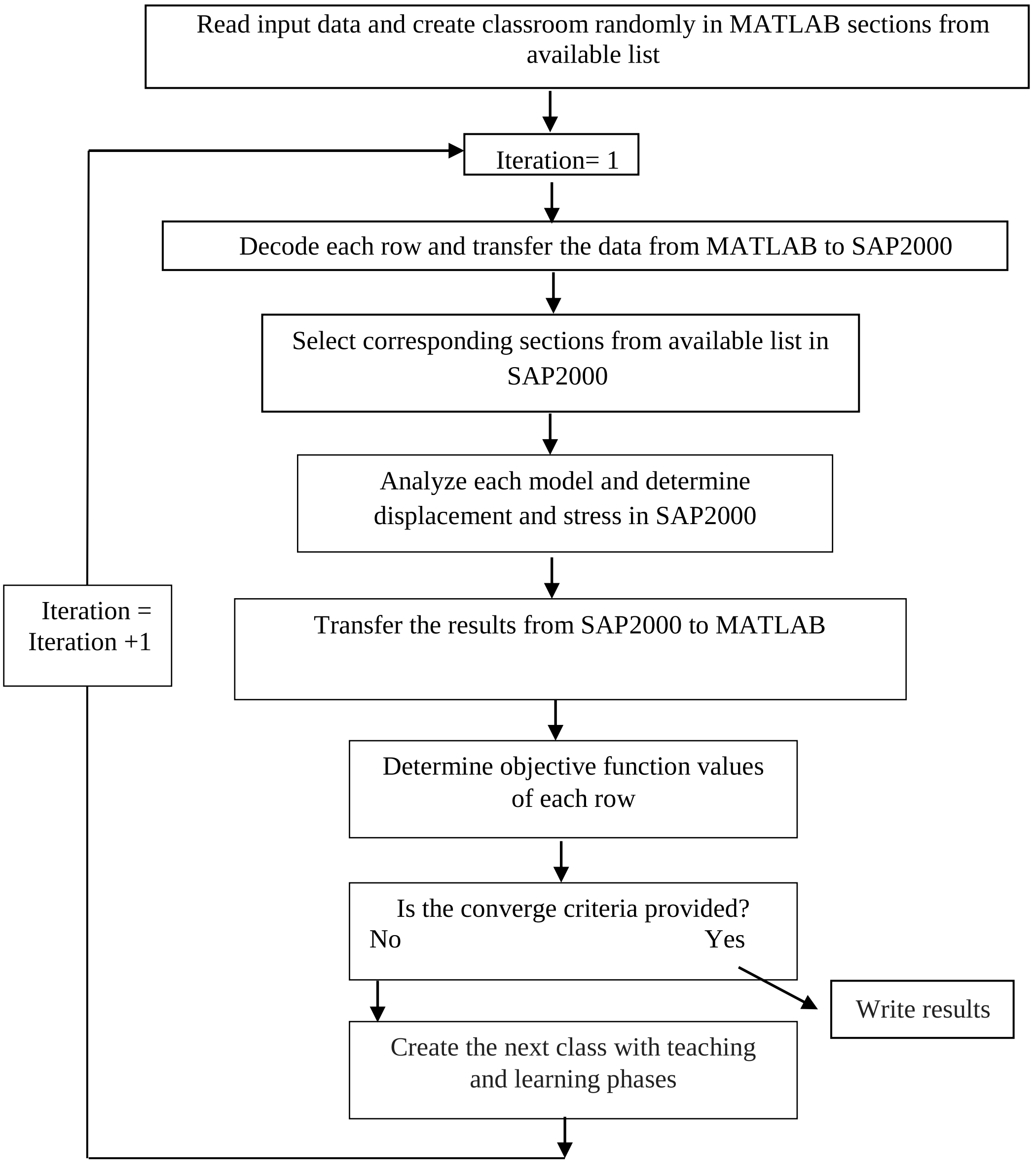


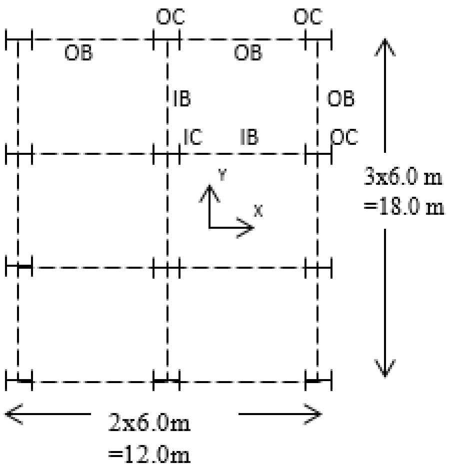
Fig. 2. Flowchart for the optimum design procedure of steel space frames

4. Design Example

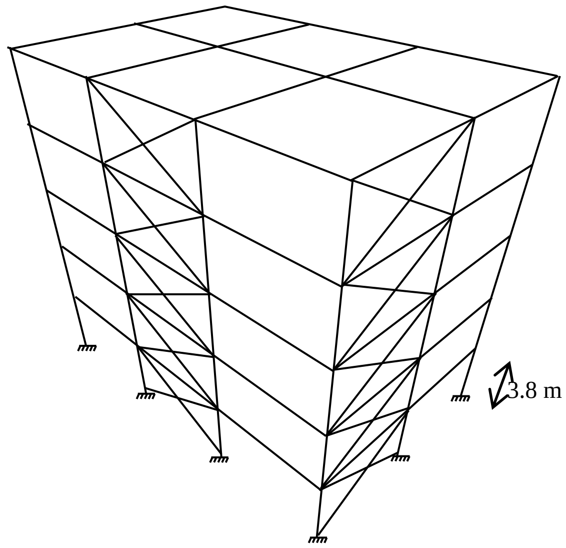
A 5-storey braced and unbraced steel space frame is shown Fig.3. Moreover, in this figure the plan view, braced space frame and unbraced frame views are presented.

All members are collected in 19 groups as given in Table 1. According to ASCE7-05 [9], dead load (2.80 kN/m2) and live load (2.39 kN/m2) are applied. Wind load is exposed in X direction according to TS498 [10] as wind speed 30m/s. The top displacement and inter story drifts are restricted to 4.75 cm (H/400) and 0.95 cm (h/400), respectively. Optimum cross sections are selected from a specified list including 128 W taken from AISC. The material properties are E=200 GPa, fy=250 MPa and ρ=7.85 ton/m3. Optimum solutions for both cases are also given Table 2. Fig 4 presents the both optimum solutions with iteration steps.

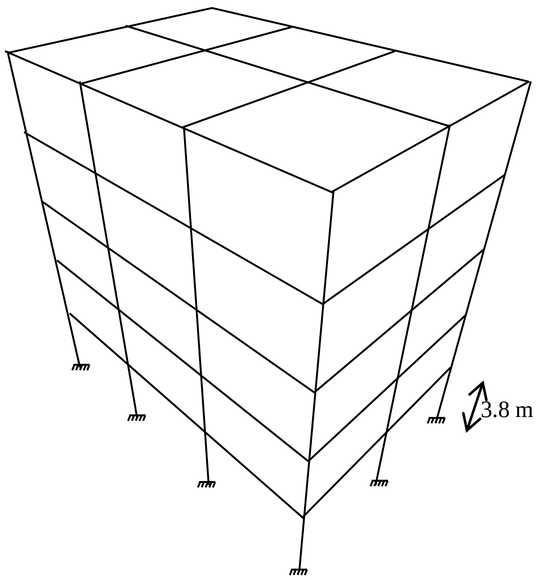
As it is observed from Table 2 that the minimum weight of unbraced steel space frame is 504.79 kN. On the other hand, the minimum weight of X braced steel space frame is 377.18 kN. It is nearly %25 lighter. Also, significant reduction is observed in cross sections. Moreover, in the solution of unbraced frame, the maximum lateral (top) displacement and inter storey drift values are 2.03 cm and 0.62 cm, respectively. These values are more than the values in X braced steel frame.



a). Plan view



b) braced fraame



c) unbraced frame

Fig. 3. A 5-storey braced and unbraced steel space frame

Table 1. Group member numbers

Floors	Outer column	Inner column	Outer beam		Inner beam		X Braced
			X direction	Y direction	X direction	Y direction	
1	1	2	7	8	9	10	19
2,3	3	4	11	12	13	14	19
4,5	5	6	15	16	17	18	19

Table 2. Optimum solutions of both cases

Group no	X braced	unbraced
1	W8X35	W30X148
2	W18X55	W44X285
3	W8X31	W18X65
4	W12X40	W18X55
5	W8X24	W12X65
6	W8X24	W16X45
7	W3X26	W8X24
8	W3X26	W6X20
9	W12X35	W8X31
10	W14X34	W8X31
11	W8X24	W12X30
12	W8X24	W8X24
13	W10X33	W16X45
14	W14X34	W14X34
15	W8X24	W12X26
16	W12X26	W6X20
17	W18X40	W21X50
18	W14X34	W8X31
19	W12X14	-
Weight (kN)	377.18	504.79
Max.lateral disp. cm	1.63	2.03
Max.inter storey drift cm	0.38	0.62

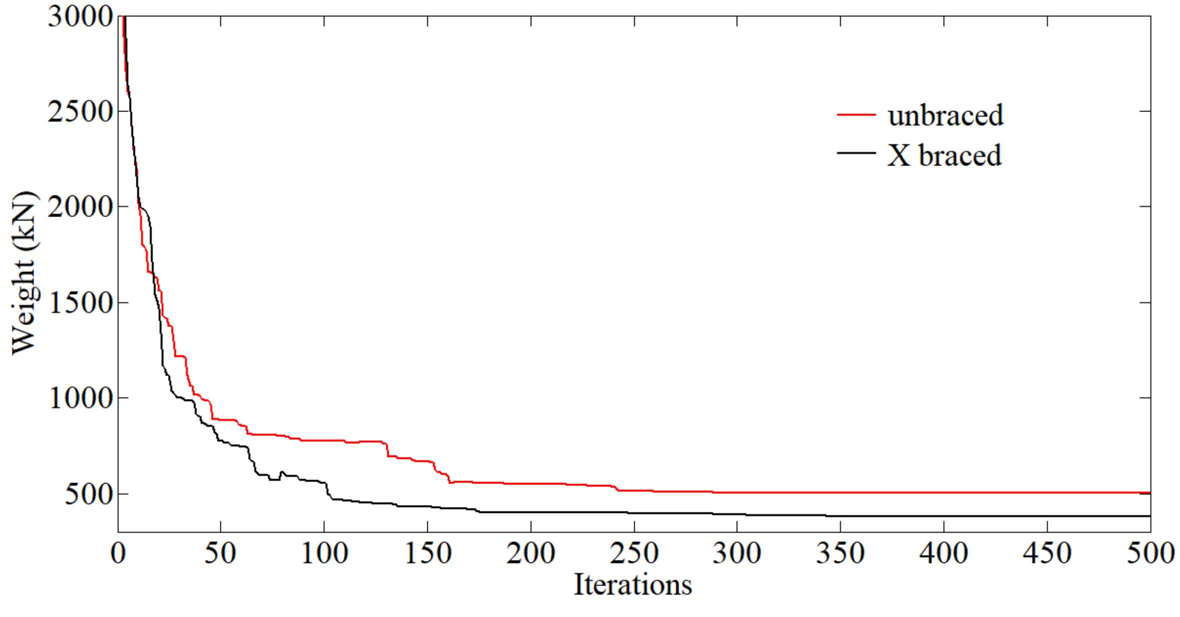


Fig. 4. Optimum solutions with iteration steps

5. Conclusions

This study presents optimum structural design of a five story steel space frame for X-braced and unbraced cases. The cross sections of structural members are selected from 128 W profiles taken from AISC (American Institute of Steel Construction). A new metaheuristic algorithm method, teaching learning based optimization method is used in the analyses. To obtain optimum solution, a program was coded in MATLAB programming to incorporate with SAP2000 OAPI (Open Application Programming Interface) simultaneously. The stress constraints according to AISC-ASD (American Institute of Steel Construction- Allowable stress design), geometric size (column-column and column-beam) constraints, top displacement and inter story drift constraints are applied to both solutions. According to optimum solutions, the minimum weight of X-braced steel frame is nearly %25 lighter than the minimum weight of unbraced frame. The results also show that teaching learning based optimization method and MATLAB SAP2000 OAPI technique are applicable and robust on structural optimization.

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