Research Article

Optimum Design of Braced Steel Space Frames including Soil-Structure Interaction via Teaching-Learning-Based Optimization and Harmony Search Algorithms

Ayse T. Daloglu,1 Musa Artar,2 Korhan Ozgan,1 and Ali İ. Karakas1

1Department of Civil Engineering, Karadeniz Technical University, Trabzon, Turkey
2Department of Civil Engineering, Bayburt University, Bayburt, Turkey

Correspondence should be addressed to Korhan Ozgan; korhanozgan@yahoo.com

Received 19 August 2017; Revised 13 November 2017; Accepted 6 December 2017; Published 3 April 2018

Optimum design of braced steel space frames including soil-structure interaction is studied by using harmony search (HS) and teaching-learning-based optimization (TLBO) algorithms. A three-parameter elastic foundation model is used to incorporate the soil-structure interaction effect. A 10-storey braced steel space frame example taken from literature is investigated according to four different bracing types for the cases with/without soil-structure interaction. X, V, Z, and eccentric V-shaped bracing types are considered in the study. Optimum solutions of examples are carried out by a computer program coded in MATLAB interacting with SAP2000-OAPI for two-way data exchange. The stress constraints according to AISC-ASD (American Institute of Steel Construction-Allowable Stress Design), maximum lateral displacement constraints, interstorey drift constraints, and beam-to-column connection constraints are taken into consideration in the optimum design process. The parameters of the foundation model are calculated depending on soil surface displacements by using an iterative approach. The results obtained in the study show that bracing types and soil-structure interaction play very important roles in the optimum design of steel space frames. Finally, the techniques used in the optimum design seem to be quite suitable for practical applications.

1. Introduction

Optimum design of steel structures prevents excessive consumption of the steel material. Suitable cross sections must be selected automatically from a predefined list. Moreover, selected profiles should satisfy some required constraints such as stress, displacement, and geometric size. Metaheuristic search techniques are highly preferred for problems with discrete design variables. There are many metaheuristic techniques developed recently. Some of them are genetic algorithm, harmony search algorithm, tabu search algorithm, particle swarm optimization, ant colony algorithm, artificial bee colony algorithm, teaching-learning-based optimization, simulated annealing algorithm, bat-inspired algorithm, cuckoo search algorithm, and evolutionary structural optimization. In literature, there are many studies available for the optimum design of structures using these algorithms. For example, Daloglu and Armutcu [1] used the genetic algorithm method for the optimum design of plane steel frames. Kameshki and Saka [2] carried out the optimum design of nonlinear steel frames with semirigid connections using the genetic algorithm. Lee and Geem [3] developed a new structural optimization method based on the harmony search algorithm. Hayalioglu and Degertekin [4] applied genetic optimization on minimum cost design of steel frames with semirigid connections and column bases. Kelesoglu and Ulker [5] searched for multiobjective fuzzy optimization of space trusses by MS Excel. Degertekin [6] compared simulated annealing and genetic algorithms for the optimum design of nonlinear steel space frames. Esen and Ulker [7] optimized multistorey space steel frames considering the nonlinear material and geometrical properties. Saka [8] used the harmony search algorithm method to get the optimum design of steel sway frames.
in accordance with BS5950. Degertekin and Hayalioglu [9] applied the harmony search algorithm for minimum cost design of steel frames with semirigid connections and column bases. Hasancebi et al. [10] investigated non-deterministic search techniques in the optimum design of real-size steel frames. Hasançebi et al. [11] used the simulated annealing algorithm in structural optimization. Hasancebi et al. [12] investigated the optimum design of high-rise steel buildings using an evolutionary strategy integrated with parallel algorithm. Togan [13] used one of the latest stochastic methods, teaching-learning-based optimization, for design of planar steel frames. Aydogdu and Saka [14] used ant colony optimization for irregular steel frames including the elemental warping effect. Dede and Ayvaz [15] studied ant colony optimization on the optimum structural optimization problems using the teaching-learning-based optimization algorithm. Dede and Ayvaz [16] applied teaching-learning-based optimization on the optimum design of grillage structures with respect to LRFD-AISC. Hasancıbı and Çarbaş [17] prepared an extensive review study on mathematical and metaheuristic optimization techniques and carried out a detailed analysis for the most suitable solving method. Saka and Geem [18] applied the harmony search algorithm for minimum weight steel frames using a computer program developed in MATLAB [29] interacting with SAP2000-OAPI (open application programming interface) [30]. Suitable cross sections are automatically selected from a list including 128 W profiles taken from AISC (American Institute of Steel Construction). The frame model is subjected to wind loads according to ASCE7-05 [31] as well as dead, live, and snow loads. The analysis results are found to be quite consistent with the literature results. In this study, the vertical displacements on soil surfaces are also calculated. It is observed that minimum weights of space frames vary depending on the bracing type. Also, it can be concluded that incorporation of soil-structure interaction results in heavier steel weight.

2. Optimum Design Formulation

The optimum design problem of braced steel space frames is calculated as follows:

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

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

The stress constraints according to AISC-ASD [32] are defined as follows:

$$g_i(x) = \left[ \frac{f_s}{F_a} + \frac{C_{max} f_{bx}}{1 - \left( \frac{f_s}{F_a} \right) F_{bx,i}} \right] - 1.0 \leq 0, \quad i = 1, \ldots, nc,$$

$$g_i(x) = \left[ \frac{f_s}{0.60 F_y} + \frac{f_{bx}}{F_{bx,i}} \right] - 1.0 \leq 0, \quad i = 1, \ldots, nc.$$

If $(f_s/F_a) \leq 0.15$, instead of using (2), the stress constraint is calculated as follows:

$$g_i(x) = \left[ \frac{f_s}{F_a} + \frac{f_{bx}}{F_{bx,i}} \right] - 1.0 \leq 0, \quad i = 1, \ldots, nc,$$

where nc is the total number of members subjected to both axial compression and bending stresses, $f_s$ is the computed axial stress, $F_a$ is the allowable axial stress under axial compression force alone, $f_{bx}$ is the computed bending stress due to bending of the member about its major axis, $F_{bx,i}$ is the allowable compressive bending stress about major, $F_{ey}$ is the Euler stress, $F_y$ is the yield stress of the steel, and $C_{max}$ is a factor. It is calculated from $C_{max} = 0.6 - 0.4 (M1/M2)$ for the braced frame member without transverse loading between the ends and $C_{max} = 1 + \psi (f_s/F_a')$ for the braced frame member with transverse loading.

The effective length factors of columns in braced frames are calculated as follows [33]:

$$K = 3G_A G_B + 1.4 (G_A + G_B) + 0.64$$

$$3G_A G_B + 2.0 (G_A + G_B) + 1.28$$

where $G_A$ and $G_B$ are the relative stiffness factors at the 4th and 8th ends of columns.

The maximum lateral displacement and interstorey drift constraints are defined as follows:
\[ g_{jl}(x) = \frac{\delta_{jl}}{\delta_{ju}} - 1 \leq 0, \quad j = 1, \ldots, m, \quad l = 1, \ldots, nl, \tag{5} \]

where \( \delta_{jl} \) is the displacement of the \( j \)th degree of freedom under load case \( l \), \( \delta_{ju} \) is the displacement at the upper bound, \( m \) is the number of restricted displacements, and \( nl \) is the total number of loading cases.

\[ g_{jil}(x) = \frac{\Delta_{jil}}{\Delta_{jiu}} - 1 \leq 0, \quad j = 1, \ldots, ns, \quad i = 1, \ldots, nsc, \quad l = 1, \ldots, nl, \tag{6} \]

where \( \Delta_{jil} \) is the interstorey drift of the \( i \)th column in the \( j \)th storey under load case \( l \), \( \Delta_{jiu} \) is the limit value, \( ns \) is the number of storeys, and \( nsc \) is the number of columns in a storey.

The beam-to-column connection geometric constraint is determined as follows:

\[ g_{bj,i}(x) = \frac{b'_{bk,j}}{d_{cj} - 2t_{b,j}} - 1 \leq 0, \quad i = 1, \ldots, n_{bw}, \tag{7} \]
\[ g_{fb,j}(x) = \frac{b_{bk,j}}{b_{lk,j}} - 1 \leq 0, \quad i = 1, \ldots, n_{bf}, \]

where \( n_{bw} \) is the number of joints where beams are connected to the web of the column, \( b'_{bk,j} \) is the flange width of the beam, \( d_{cj} \) is the depth of the column, \( t_{b,j} \) is the flange thickness of the column, \( n_{bf} \) is the number of joints where beams are connected to the flange of the column, and \( b_{bk,j} \) and \( b_{lk,j} \) are flange widths of the beam and column, respectively (Figure 1).

3. Three-Parameter Vlasov Elastic Foundation Model

The soil reaction exerted on a structure resting on a two-parameter elastic soil is expressed in

\[ q_z = kw - 2t\nabla^2w. \tag{8} \]

The reaction depends on the soil surface vertical displacement \( w \), soil reaction modulus \( k \), and soil shear parameter \( 2t \). These two soil parameters, \( k \) and \( 2t \), can be defined by

\[ k = \int_0^H \frac{E_s(1-v_s)}{(1+\nu_s)(1-2\nu_s)} \left( \frac{\partial \phi(z)}{\partial z} \right)^2 dz, \tag{9} \]
\[ 2t = \int_0^H G_s \phi(z)^2 dz, \]

in which \( H, \nu_s, \) and \( G_s \) are the depth, Poisson’s ratio, and shear modulus of the soil, respectively. In most of the classical two-parameter soil foundation models such as Pasternak, Hetenyi, and Vlasov models, the soil parameters are constants obtained by experimental tests or arbitrarily defined. However, it is highly difficult to determine these parameters experimentally. Therefore, Vallabhan and Daloglu [34] developed an additional parameter \( \gamma \) to characterize the vertical displacement profile within subsoil. They called this model including the third parameter \( \gamma \) as a three-parameter Vlasov model. This model eliminates the necessity of experimental tests to determine soil parameters since these values are determined iteratively in terms of the new parameter, \( \gamma \). The vertical deformation profile of the subsoil is described via a mode shape function as given in

\[ \phi(z) = \frac{\sin \gamma (1-(z/H))}{\sinh \gamma} \tag{10} \]

The boundary values of \( \phi(z) \) are assumed to be \( \phi(0) = 1 \) and \( \phi(H) = 0 \), as shown in Figure 2. The \( \gamma \) parameter can be calculated using

\[ \frac{\gamma^2}{H^2} = \frac{1-2\nu_s}{2(1-\nu_s)} \cdot \frac{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} (\nabla w)^2 dx dy}{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} w^2 dx dy}. \tag{11} \]

Equation (9) indicates that the soil parameters (\( k \) and \( 2t \)) are calculated based on the material properties and mode shape function (\( \phi(z) \)). Also, it is necessary to compute the \( \gamma \) parameter to calculate the mode shape function. It is necessary to know the soil vertical surface displacements obtained from the structural analysis to calculate the \( \gamma \) parameter. So, it can be stated that \( k, 2t, \phi, \gamma, \) and \( w \) are interdependent. That is why the analysis requires an iterative procedure. For this purpose, a computer program is coded in MATLAB interacting with SAP2000 structural analysis program via OAPI (open application programming interface) to perform this iterative procedure in the three-parameter foundation model.
Using the coded program, a soil model is generated such that the soil reaction modulus $k$ is represented by elastic area springs. The interaction between springs is taken into account using shell elements connecting the top of springs. The soil shell element with one degree of freedom at each node reflects only shear behavior of the soil. The soil surface vertical displacements are retrieved to compute a new vertical displacement. An iterative procedure is repeated until the convergence is fulfilled. Otherwise, the next iteration is performed, and the procedure is repeated until the convergence is fulfilled.

4. Optimization Algorithms

4.1. Harmony Search Algorithm. Harmony search (HS) algorithm method is developed by Lee and Geem [3] and mimics improvisation procedures of musical harmony. It consists of three basic procedures. Operations are conducted by the harmony memory (HM) matrix. In the first step, HM is randomly and automatically filled by the program coded in MATLAB. The form of harmony memory matrix is shown as follows:

$$
H = \begin{bmatrix}
    x_1^1 & x_2^1 & \cdots & x_{n-1}^1 & x_n^1 \\
    x_1^2 & x_2^2 & \cdots & x_{n-1}^2 & x_n^2 \\
    \vdots & \vdots & \cdots & \vdots & \vdots \\
    x_1^{HMS-1} & x_2^{HMS-1} & \cdots & x_{n-1}^{HMS-1} & x_n^{HMS-1} \\
    x_1^{HMS} & x_2^{HMS} & \cdots & x_{n-1}^{HMS} & x_n^{HMS}
\end{bmatrix} \rightarrow \phi(x^1) \rightarrow \phi(x^2) \rightarrow \ldots \rightarrow \phi(x^{HMS-1}) \rightarrow \phi(x^{HMS})
$$

(12)

where $x_j^i$ is the $i$th design variable of the $j$th solution vector, $n$ is the total number of design variables, $\phi(x^i)$ is the $j$th objective function value, and HMS (harmony memory size) indicates a specified number of solutions. In the harmony memory matrix, each row presents design variables.

In the second step, the objective function values ($\phi(x^1), \phi(x^2), \ldots, \phi(x^{HMS-1}), \phi(x^{HMS})$) of solution vectors in the harmony memory matrix are determined. In the third step, a new solution vector ($x^{nh} = [x_1^{nh}, x_2^{nh}, \ldots, x_n^{nh}]$) is prepared by selecting each design variable from either the harmony memory matrix or the entire section list $X_d$. Harmony memory consideration rate (HMCR) is applied as follows:

$$
x_i^{nh} \in \{x_1^1, x_2^1, \ldots, x_i^{HMS}\} \text{ with probability of HMCR}
$$

$$
x_i^{nh} \in X_d \text{ with probability of } (1 - \text{HMCR}).
$$

(13)

Also, the new value of the design variable selected from the harmony memory matrix is checked whether this value should be pitch adjusted or not depending on the pitch adjustment ratio (PAR). This decision is determined as follows:

$$
\begin{align*}
\text{Yes, with probability of PAR} \\
\text{No, with probability of } 1 - \text{PAR}.
\end{align*}
$$

(14)

Detailed information about the HS algorithm can be found in the literature [3, 8, 9, 23].

4.2. Teaching-Learning-Based Optimization. Teaching-learning-based optimization (TLBO) was developed by Rao et al. [35]. This method mimics teaching and learning processes between a teacher and students in classroom. The person having the highest information in the class is selected as a teacher. The teacher gives his/her information to the other
people (students) in the class. These procedures provide suitable solutions in structural optimizations. The teaching-learning-based optimization method consists of two basic steps such as teaching and learning. In the first step, the teaching step, the first population (class) is randomly filled in steps such as teaching and learning. In the first step, the learning-based optimization method consists of two basic suitable solutions in structural optimizations. The teaching-people (students) in the class. These procedures provide suitable solutions in structural optimizations. The teaching-learning-based optimization method consists of two basic steps such as teaching and learning. In the first step, the teaching step, the first population (class) is randomly filled in steps such as teaching and learning. In the first step, the learning-based optimization method consists of two basic suitable solutions in structural optimizations. The teaching-people (students) in the class. These procedures provide suitable solutions in structural optimizations. The teaching-learning-based optimization method consists of two basic steps such as teaching and learning. In the first step, the teaching step, the first population (class) is randomly filled in steps such as teaching and learning. In the first step, the learning-based optimization method consists of two basic suitable solutions in structural optimizations.

$$\begin{bmatrix} x_1^1 & x_2^1 & \cdots & x_{n-1}^1 & x_n^1 \\ x_1^2 & x_2^2 & \cdots & x_{n-1}^2 & x_n^2 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ x_1^{S-1} & x_2^{S-1} & \cdots & x_{n-1}^{S-1} & x_n^{S-1} \\ x_1^S & x_2^S & \cdots & x_{n-1}^S & x_n^S \end{bmatrix} \rightarrow f(x^1) \rightarrow f(x^2) \rightarrow \vdots \rightarrow f(x^{S-1}) \rightarrow f(x^S)$$

(15)

where each row represents a student and gives a design solution, $S$ is the population size (the number of students), $n$ is the number of design variables, and $f(x^{i-1}, \ldots)$ is the unconstrained objective function value of each student in the class. The student in a class having the best information is selected as a teacher of the class. His or her objective function value is the minimum in the class. The information update of students in the class is carried out with the help of the teacher as follows:

$$x_{new}^j = x^j + r(x_{teacher} - T_F x_{mean}),$$

(16)

where $x_{new}^j$ is the new student, $x^j$ is the current student, $r$ is a random number in the range $[0,1]$, and $T_F$, a teaching factor, is either 1 or 2. $x_{mean}$ is the mean of the class defined as $x_{mean} = (\text{mean}(x_1) \ldots \text{mean}(x_S))$. If the new student has better information ($f(x_{new}^j)$), the new student is replaced with the current student. In the second step, the learning step, information is shared between students. This step is similar to the first step. If the new student presents a better information, he/she is replaced with the current student. The information update of students in the class is carried out as follows:

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

$$\text{if } f(x^j) > f(x^i) \Rightarrow x_{new}^j = x^j + r(x^j - x^i).$$

(17)

The detailed information about the TLBO algorithm can be obtained from [13, 15, 16, 20, 24, 35]. The flowchart of processes in MATLAB-SAP2000 OAPI developed to get optimum solutions is presented in Figure 3.

### 5. Design Example

A 10-storey braced steel space frame example taken from literature [36] is studied considering four different types of
bracing such as X, V, Z, and eccentric V. The behavior of the frame is investigated with and without considering the effect of soil-structure interaction. The frame example is exposed to wind loads according to ASCE7-05 [31] in addition to dead, live, and snow loads. Optimum cross sections are practically selected from a predefined list of 128 W profiles taken from AISC. The stress constraints according to AISC-ASD [32], maximum lateral displacement constraint (H/400), interstorey drift constraint (h/400), and beam-to-column geometric constraints are subjected to the optimum design of the braced steel space frames. In the analyses, the steel modulus of elasticity, $E$, and yield stress, $F_y$, are taken as

Table 1: Gravity loading on beams of roof and floors [36].

<table>
<thead>
<tr>
<th>Beam type</th>
<th>Outer span beams (kN/m)</th>
<th>Inner span beams (kN/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long span floor beams</td>
<td>9.79</td>
<td>19.59</td>
</tr>
<tr>
<td>Short span floor beams</td>
<td>8.04</td>
<td>16.07</td>
</tr>
<tr>
<td>Long span roof beams</td>
<td>6.75</td>
<td>13.50</td>
</tr>
<tr>
<td>Short span floor beams</td>
<td>5.54</td>
<td>11.07</td>
</tr>
</tbody>
</table>

Table 2: Wind loads calculated for the 10-storey braced frame [36].

<table>
<thead>
<tr>
<th>Floor</th>
<th>$X$-direction</th>
<th>$Y$-direction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Distributed windward force (kN/m)</td>
<td>Distributed leeward force (kN/m)</td>
</tr>
<tr>
<td>1</td>
<td>2.33</td>
<td>2.32</td>
</tr>
<tr>
<td>2</td>
<td>2.66</td>
<td>2.32</td>
</tr>
<tr>
<td>3</td>
<td>2.99</td>
<td>2.32</td>
</tr>
<tr>
<td>4</td>
<td>3.24</td>
<td>2.32</td>
</tr>
<tr>
<td>5</td>
<td>3.46</td>
<td>2.32</td>
</tr>
<tr>
<td>6</td>
<td>3.64</td>
<td>2.32</td>
</tr>
<tr>
<td>7</td>
<td>3.81</td>
<td>2.32</td>
</tr>
<tr>
<td>8</td>
<td>3.95</td>
<td>2.32</td>
</tr>
<tr>
<td>9</td>
<td>4.09</td>
<td>2.32</td>
</tr>
<tr>
<td>10</td>
<td>2.11</td>
<td>1.16</td>
</tr>
</tbody>
</table>

Figure 4: Typical plane view of a 10-storey steel frame.

Figure 5: Three dimensional view of a V-braced frame.

Figure 6: 2D view of the X-braced steel space frame without and with soil-structure interaction. (a) The case without soil-structure interaction. (b) The case with soil-structure interaction.
Table 3: Optimum results of the X-braced space frame.

<table>
<thead>
<tr>
<th>Storeys</th>
<th>Member groups</th>
<th>Literature research, Hasancebi [36]</th>
<th>TLBO without soil-structure interaction</th>
<th>TLBO with soil-structure interaction</th>
<th>This study</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>W16 x 36</td>
<td>W8 x 24</td>
<td>W8 x 28</td>
<td>W8 x 35</td>
</tr>
<tr>
<td>1-2</td>
<td>OC1</td>
<td>W12 x 65</td>
<td>W21 x 83</td>
<td>W14 x 99</td>
<td>W14 x 43</td>
</tr>
<tr>
<td></td>
<td>OC2</td>
<td>W24 x 94</td>
<td>W44 x 224</td>
<td>W44 x 224</td>
<td>W12 x 50</td>
</tr>
<tr>
<td></td>
<td>OC3</td>
<td>W12 x 120</td>
<td>W14 x 74</td>
<td>W16 x 89</td>
<td>W18 x 97</td>
</tr>
<tr>
<td>3-4</td>
<td>OC4</td>
<td>W8 x 18</td>
<td>W10 x 33</td>
<td>W14 x 48</td>
<td>W10 x 33</td>
</tr>
<tr>
<td></td>
<td>OB</td>
<td>W18 x 35</td>
<td>W12 x 72</td>
<td>W12 x 72</td>
<td>W14 x 68</td>
</tr>
<tr>
<td></td>
<td>IB</td>
<td>W5 x 19</td>
<td>W8 x 28</td>
<td>W8 x 28</td>
<td>W10 x 60</td>
</tr>
<tr>
<td></td>
<td>BR</td>
<td>W10 x 33</td>
<td>W8 x 28</td>
<td>W8 x 28</td>
<td>W14 x 48</td>
</tr>
<tr>
<td></td>
<td>CC</td>
<td>W10 x 54</td>
<td>W12 x 87</td>
<td>W10 x 49</td>
<td>W10 x 33</td>
</tr>
<tr>
<td></td>
<td>OC5</td>
<td>W12 x 72</td>
<td>W10 x 49</td>
<td>W12 x 53</td>
<td>W24 x 68</td>
</tr>
<tr>
<td>5-6</td>
<td>IC</td>
<td>W30 x 90</td>
<td>W24 x 62</td>
<td>W12 x 72</td>
<td>W14 x 68</td>
</tr>
<tr>
<td></td>
<td>OB</td>
<td>W8 x 18</td>
<td>W12 x 30</td>
<td>W8 x 24</td>
<td>W8 x 24</td>
</tr>
<tr>
<td></td>
<td>IB</td>
<td>W12 x 26</td>
<td>W14 x 34</td>
<td>W8 x 35</td>
<td>W10 x 33</td>
</tr>
<tr>
<td></td>
<td>BR</td>
<td>W6 x 15</td>
<td>W12 x 14</td>
<td>W12 x 14</td>
<td>W10 x 15</td>
</tr>
<tr>
<td></td>
<td>CC</td>
<td>W16 x 31</td>
<td>W8 x 24</td>
<td>W12 x 53</td>
<td>W10 x 45</td>
</tr>
<tr>
<td></td>
<td>OC6</td>
<td>W10 x 49</td>
<td>W8 x 31</td>
<td>W10 x 49</td>
<td>W12 x 45</td>
</tr>
<tr>
<td></td>
<td>OC7</td>
<td>W10 x 54</td>
<td>W8 x 40</td>
<td>W10 x 60</td>
<td>W14 x 38</td>
</tr>
<tr>
<td>7-8</td>
<td>IC3</td>
<td>W12 x 58</td>
<td>W24 x 55</td>
<td>W14 x 53</td>
<td>W16 x 57</td>
</tr>
<tr>
<td></td>
<td>OB</td>
<td>W8 x 21</td>
<td>W16 x 36</td>
<td>W10 x 30</td>
<td>W10 x 30</td>
</tr>
<tr>
<td></td>
<td>IB</td>
<td>W12 x 26</td>
<td>W14 x 38</td>
<td>W16 x 45</td>
<td>W18 x 50</td>
</tr>
<tr>
<td></td>
<td>BR</td>
<td>W6 x 15</td>
<td>W12 x 14</td>
<td>W12 x 22</td>
<td>W6 x 15</td>
</tr>
<tr>
<td></td>
<td>CC</td>
<td>W16 x 26</td>
<td>W8 x 24</td>
<td>W12 x 53</td>
<td>W10 x 45</td>
</tr>
<tr>
<td></td>
<td>OC8</td>
<td>W10 x 49</td>
<td>W8 x 31</td>
<td>W10 x 49</td>
<td>W12 x 45</td>
</tr>
<tr>
<td></td>
<td>OC9</td>
<td>W10 x 54</td>
<td>W10 x 54</td>
<td>W12 x 53</td>
<td>W14 x 48</td>
</tr>
<tr>
<td>9-10</td>
<td>IC</td>
<td>W14 x 38</td>
<td>W16 x 36</td>
<td>W14 x 48</td>
<td>W10 x 68</td>
</tr>
<tr>
<td></td>
<td>OB</td>
<td>W8 x 21</td>
<td>W8 x 24</td>
<td>W10 x 30</td>
<td>W8 x 35</td>
</tr>
<tr>
<td></td>
<td>IB</td>
<td>W12 x 26</td>
<td>W14 x 34</td>
<td>W18 x 40</td>
<td>W10 x 33</td>
</tr>
<tr>
<td></td>
<td>BR</td>
<td>W6 x 9</td>
<td>W12 x 14</td>
<td>W12 x 14</td>
<td>W12 x 14</td>
</tr>
<tr>
<td></td>
<td>CC</td>
<td>W12 x 26</td>
<td>W8 x 28</td>
<td>W8 x 28</td>
<td>W8 x 31</td>
</tr>
<tr>
<td></td>
<td>OC10</td>
<td>W8 x 31</td>
<td>W14 x 30</td>
<td>W14 x 30</td>
<td>W14 x 53</td>
</tr>
<tr>
<td></td>
<td>OC11</td>
<td>W8 x 40</td>
<td>W10 x 49</td>
<td>W12 x 40</td>
<td>W14 x 30</td>
</tr>
<tr>
<td></td>
<td>OC12</td>
<td>W8 x 28</td>
<td>W12 x 30</td>
<td>W16 x 36</td>
<td>W12 x 45</td>
</tr>
<tr>
<td></td>
<td>OB</td>
<td>W8 x 18</td>
<td>W8 x 24</td>
<td>W8 x 24</td>
<td>W8 x 24</td>
</tr>
<tr>
<td></td>
<td>IB</td>
<td>W12 x 30</td>
<td>W21 x 44</td>
<td>W10 x 33</td>
<td>W10 x 39</td>
</tr>
<tr>
<td></td>
<td>BR</td>
<td>W6 x 9</td>
<td>W10 x 15</td>
<td>W12 x 14</td>
<td>W12 x 14</td>
</tr>
<tr>
<td>Weight (kN)</td>
<td></td>
<td>1092.91</td>
<td>1170.03</td>
<td>1217.91</td>
<td>1201.13</td>
</tr>
<tr>
<td>Maximum lateral displacement (cm)</td>
<td>—</td>
<td>6.36</td>
<td>7.59</td>
<td>7.92</td>
<td>8.29</td>
</tr>
<tr>
<td>Interstorey drift (cm)</td>
<td>—</td>
<td>0.81</td>
<td>0.91</td>
<td>0.95</td>
<td>0.95</td>
</tr>
<tr>
<td>Maximum settlement (cm)</td>
<td>—</td>
<td>0.657</td>
<td>—</td>
<td>0.670</td>
<td>—</td>
</tr>
</tbody>
</table>

29000 ksi (203,893.6 MPa) and 36 ksi (253.1 MPa), respectively. Figure 4 shows the typical plane view of a 10-storey steel frame. Also, Figure 5 represents the three-dimensional view of a V-braced frame. Each storey has a height of 3.66 m (12 ft). Modulus of elasticity for the concrete is taken as 32,000,000 kN/m², Poisson’s ratio is 0.2, and weight per unit volume is 25 kN/m³.

All floors excluding the roof are exposed to a dead load of 2.88 kN/m² and a live load of 2.93 kN/m². The roof floor is exposed to a dead load of 2.88 kN/m² and a snow load of 0.75 kN/m². The total gravity loading on the beams of roof and floors is tabulated in Table 1 [36]. Wind loads are applied to the frame according to ASCE7-05 [31]. Wind loads calculated for the 10-storey braced frame are presented in Table 2 [36]. Modulus of elasticity of the soil, Eₖ, is taken to be equal to 80,000 kN/m². The depth of the soil stratum to the rigid base is taken as Hₛ = 20 m, and Poisson’s ratio of the soil is equal to 0.25.

5.1. X-Braced Steel Space Frame. Figure 6 shows the typical 2D view of an X-braced steel space frame without and with soil-structure interaction. Optimum results of the X-braced space frame are given in Table 3. Soil parameters for the
Figure 7: Settlements of soil surface for the X-braced steel space frame with two different algorithm methods (cm). (a) TLBO. (b) HS.

Figure 8: Design histories of the 10-storey X-braced steel space frame. I: HS with soil-structure interaction; II: TLBO with soil-structure interaction; III: HS without soil-structure interaction; IV: TLBO without soil-structure interaction.

Figure 9: 2D view of the V-braced steel space frame without and with soil-structure interaction. (a) The case without soil-structure interaction. (b) The case with soil-structure interaction.
Historically, optimum solutions have been presented. The surface for two different algorithm methods and design space frame on elastic foundation are presented in Table 4.

Table 5: Optimum results of the V-braced space frame.

<table>
<thead>
<tr>
<th>Storeys</th>
<th>Member groups</th>
<th>Literature research, Hasancib [36]</th>
<th>This study</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>TLBO without soil-structure interaction</td>
<td>TLBO with soil-structure interaction</td>
</tr>
<tr>
<td>CC</td>
<td>W8 × 28</td>
<td>W8 × 28</td>
<td>W8 × 28</td>
</tr>
<tr>
<td>OC1</td>
<td>W14 × 43</td>
<td>W16 × 67</td>
<td>W16 × 50</td>
</tr>
<tr>
<td>OC2</td>
<td>W44 × 224</td>
<td>W27 × 161</td>
<td>W16 × 67</td>
</tr>
<tr>
<td>1-2</td>
<td>IC</td>
<td>W10 × 88</td>
<td>W18 × 106</td>
</tr>
<tr>
<td>OB</td>
<td>W8 × 28</td>
<td>W14 × 34</td>
<td>W8 × 24</td>
</tr>
<tr>
<td>IB</td>
<td>W10 × 33</td>
<td>W10 × 33</td>
<td>W8 × 35</td>
</tr>
<tr>
<td>BR</td>
<td>W12 × 14</td>
<td>W6 × 15</td>
<td>W8 × 21</td>
</tr>
<tr>
<td>CC</td>
<td>W8 × 24</td>
<td>W8 × 24</td>
<td>W8 × 31</td>
</tr>
<tr>
<td>OC1</td>
<td>W12 × 45</td>
<td>W10 × 49</td>
<td>W12 × 35</td>
</tr>
<tr>
<td>OC2</td>
<td>W10 × 45</td>
<td>W18 × 86</td>
<td>W10 × 45</td>
</tr>
<tr>
<td>3-4</td>
<td>IC</td>
<td>W21 × 62</td>
<td>W14 × 68</td>
</tr>
<tr>
<td>OB</td>
<td>W8 × 24</td>
<td>W10 × 30</td>
<td>W8 × 24</td>
</tr>
<tr>
<td>IB</td>
<td>W12 × 35</td>
<td>W8 × 35</td>
<td>W12 × 35</td>
</tr>
<tr>
<td>BR</td>
<td>W5 × 16</td>
<td>W8 × 21</td>
<td>W14 × 22</td>
</tr>
<tr>
<td>CC</td>
<td>W12 × 30</td>
<td>W8 × 24</td>
<td>W10 × 39</td>
</tr>
<tr>
<td>OC1</td>
<td>W14 × 34</td>
<td>W8 × 31</td>
<td>W16 × 36</td>
</tr>
<tr>
<td>OC2</td>
<td>W18 × 46</td>
<td>W14 × 48</td>
<td>W18 × 55</td>
</tr>
<tr>
<td>5-6</td>
<td>IC</td>
<td>W12 × 50</td>
<td>W18 × 55</td>
</tr>
<tr>
<td>OB</td>
<td>W10 × 30</td>
<td>W8 × 24</td>
<td>W14 × 38</td>
</tr>
<tr>
<td>IB</td>
<td>W8 × 35</td>
<td>W16 × 36</td>
<td>W14 × 38</td>
</tr>
<tr>
<td>BR</td>
<td>W10 × 15</td>
<td>W12 × 19</td>
<td>W12 × 22</td>
</tr>
<tr>
<td>CC</td>
<td>W8 × 28</td>
<td>W8 × 24</td>
<td>W14 × 35</td>
</tr>
<tr>
<td>OC1</td>
<td>W8 × 28</td>
<td>W8 × 35</td>
<td>W12 × 45</td>
</tr>
<tr>
<td>OC2</td>
<td>W8 × 24</td>
<td>W12 × 30</td>
<td>W10 × 45</td>
</tr>
<tr>
<td>7-8</td>
<td>IC</td>
<td>W16 × 40</td>
<td>W16 × 45</td>
</tr>
<tr>
<td>OB</td>
<td>W10 × 30</td>
<td>W8 × 24</td>
<td>W8 × 31</td>
</tr>
<tr>
<td>IB</td>
<td>W16 × 36</td>
<td>W14 × 34</td>
<td>W10 × 33</td>
</tr>
<tr>
<td>BR</td>
<td>W12 × 14</td>
<td>W12 × 16</td>
<td>W8 × 21</td>
</tr>
<tr>
<td>CC</td>
<td>W12 × 30</td>
<td>W8 × 28</td>
<td>W14 × 48</td>
</tr>
<tr>
<td>OC1</td>
<td>W10 × 33</td>
<td>W8 × 24</td>
<td>W8 × 35</td>
</tr>
<tr>
<td>OC2</td>
<td>W8 × 31</td>
<td>W8 × 24</td>
<td>W8 × 35</td>
</tr>
<tr>
<td>9-10</td>
<td>IC</td>
<td>W24 × 55</td>
<td>W12 × 26</td>
</tr>
<tr>
<td>OB</td>
<td>W8 × 24</td>
<td>W8 × 24</td>
<td>W8 × 31</td>
</tr>
<tr>
<td>IB</td>
<td>W16 × 36</td>
<td>W18 × 40</td>
<td>W14 × 34</td>
</tr>
<tr>
<td>BR</td>
<td>W10 × 15</td>
<td>W10 × 15</td>
<td>W12 × 14</td>
</tr>
<tr>
<td>Weight (kN)</td>
<td>1082.80</td>
<td>1083.80</td>
<td>1101.27</td>
</tr>
<tr>
<td>Maximum lateral displacement (cm)</td>
<td>—</td>
<td>6.93</td>
<td>7.91</td>
</tr>
<tr>
<td>Interstorey drift (cm)</td>
<td>—</td>
<td>0.91</td>
<td>0.91</td>
</tr>
<tr>
<td>Maximum settlement (cm)</td>
<td>—</td>
<td>—</td>
<td>−0.650</td>
</tr>
</tbody>
</table>

Table 6: Soil parameters for the 10-storey V-braced steel space frame on elastic foundation.

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>γ</th>
<th>k (kN/m²)</th>
<th>2( kN/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Teaching-learning-based optimization</td>
<td>4.70318</td>
<td>11306.947</td>
<td>67945.018</td>
</tr>
<tr>
<td>Harmony search algorithm</td>
<td>4.70957</td>
<td>11322.086</td>
<td>67853.886</td>
</tr>
</tbody>
</table>

Optimum results of the V-braced space frame on elastic foundation are presented in Table 4. Moreover, Figures 7 and 8 display settlements of the soil surface for two different algorithm methods and design histories of optimum solutions, respectively.

5.2. V-Braced Steel Space Frame. Figure 9 shows the typical 2D view of a V-braced steel space frame without and with soil-structure interaction. Optimum results of the V-braced space frame are shown in Table 5. Soil parameters for the space frame on elastic foundation are given in Table 6. Also, Figures 10 and 11 show the soil surface settlements obtained using two different algorithms and design histories of optimum solutions, respectively.

5.3. Z-Braced Steel Space Frame. Figure 12 represents the 2D side view of a Z-braced steel space frame without and with...
5.4. Eccentric V-Braced Steel Space Frame. Figure 15 shows the 2D side view of an eccentric V-braced steel space frame without and with soil-structure interaction. The braces are connected to the beam from one-third of the beam length. Optimum results of the eccentric V-braced space frame are presented in Table 9. Soil parameters for the space frame on elastic foundation are presented in Table 10. Moreover,
Table 7: Optimum results of the Z-braced space frame.

<table>
<thead>
<tr>
<th>Storeys</th>
<th>Member groups</th>
<th>Literature research, Hasancebi [36]</th>
<th>TLBO without soil-structure interaction</th>
<th>TLBO with soil-structure interaction</th>
<th>HS without soil-structure interaction</th>
<th>HS with soil-structure interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2</td>
<td>CC</td>
<td>W8 x 31</td>
<td>W8 x 31</td>
<td>W8 x 31</td>
<td>W8 x 31</td>
<td>W8 x 31</td>
</tr>
<tr>
<td></td>
<td>OC2</td>
<td>W21 x 83</td>
<td>W16 x 67</td>
<td>W12 x 65</td>
<td>W10 x 68</td>
<td>W10 x 68</td>
</tr>
<tr>
<td></td>
<td>OC3</td>
<td>W24 x 103</td>
<td>W30 x 108</td>
<td>W14 x 132</td>
<td>W30 x 108</td>
<td></td>
</tr>
<tr>
<td>IC</td>
<td>W12 x 106</td>
<td>W14 x 99</td>
<td>W18 x 106</td>
<td>W14 x 109</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OB</td>
<td>W8 x 24</td>
<td>W8 x 24</td>
<td>W8 x 24</td>
<td>W8 x 24</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IB</td>
<td>W10 x 33</td>
<td>W12 x 35</td>
<td>W12 x 35</td>
<td>W14 x 43</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BR</td>
<td>W6 x 15</td>
<td>W8 x 24</td>
<td>W12 x 30</td>
<td>W8 x 15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CC</td>
<td>W10 x 54</td>
<td>W8 x 35</td>
<td>W16 x 36</td>
<td>W14 x 30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OC2</td>
<td>W10 x 49</td>
<td>W14 x 90</td>
<td>W12 x 35</td>
<td>W12 x 65</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OC3</td>
<td>W14 x 74</td>
<td>W30 x 108</td>
<td>W12 x 72</td>
<td>W18 x 55</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3-4</td>
<td>IC</td>
<td>W14 x 74</td>
<td>W21 x 68</td>
<td>W16 x 77</td>
<td>W21 x 73</td>
<td></td>
</tr>
<tr>
<td>OB</td>
<td>W16 x 36</td>
<td>W8 x 24</td>
<td>W8 x 24</td>
<td>W8 x 24</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IB</td>
<td>W16 x 40</td>
<td>W12 x 35</td>
<td>W12 x 35</td>
<td>W14 x 38</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BR</td>
<td>W5 x 16</td>
<td>W12 x 16</td>
<td>W12 x 19</td>
<td>W8 x 24</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CC</td>
<td>W8 x 24</td>
<td>W8 x 31</td>
<td>W8 x 35</td>
<td>W8 x 31</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OC2</td>
<td>W8 x 31</td>
<td>W10 x 49</td>
<td>W14 x 48</td>
<td>W12 x 35</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OC3</td>
<td>W24 x 55</td>
<td>W16 x 45</td>
<td>W16 x 50</td>
<td>W21 x 68</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5-6</td>
<td>IC</td>
<td>W18 x 65</td>
<td>W24 x 55</td>
<td>W18 x 60</td>
<td>W24 x 62</td>
<td></td>
</tr>
<tr>
<td>OB</td>
<td>W8 x 24</td>
<td>W16 x 36</td>
<td>W12 x 30</td>
<td>W16 x 36</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IB</td>
<td>W14 x 38</td>
<td>W14 x 34</td>
<td>W12 x 35</td>
<td>W14 x 34</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BR</td>
<td>W8 x 15</td>
<td>W12 x 22</td>
<td>W6 x 15</td>
<td>W8 x 28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CC</td>
<td>W8 x 24</td>
<td>W8 x 24</td>
<td>W8 x 31</td>
<td>W8 x 40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OC2</td>
<td>W10 x 49</td>
<td>W8 x 31</td>
<td>W14 x 48</td>
<td>W12 x 35</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OC3</td>
<td>W18 x 35</td>
<td>W14 x 43</td>
<td>W16 x 36</td>
<td>W14 x 48</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7-8</td>
<td>IC</td>
<td>W18 x 50</td>
<td>W16 x 40</td>
<td>W12 x 40</td>
<td>W27 x 84</td>
<td></td>
</tr>
<tr>
<td>OB</td>
<td>W10 x 30</td>
<td>W8 x 24</td>
<td>W16 x 36</td>
<td>W12 x 35</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IB</td>
<td>W12 x 35</td>
<td>W14 x 34</td>
<td>W10 x 33</td>
<td>W10 x 33</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BR</td>
<td>W12 x 14</td>
<td>W10 x 15</td>
<td>W12 x 14</td>
<td>W10 x 15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CC</td>
<td>W8 x 31</td>
<td>W8 x 31</td>
<td>W14 x 34</td>
<td>W8 x 31</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OC2</td>
<td>W10 x 30</td>
<td>W8 x 35</td>
<td>W10 x 33</td>
<td>W10 x 33</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OC3</td>
<td>W12 x 26</td>
<td>W8 x 40</td>
<td>W10 x 33</td>
<td>W10 x 33</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9-10</td>
<td>IC</td>
<td>W14 x 43</td>
<td>W14 x 34</td>
<td>W12 x 45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OB</td>
<td>W10 x 26</td>
<td>W24 x 55</td>
<td>W14 x 34</td>
<td>W14 x 30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IB</td>
<td>W10 x 33</td>
<td>W14 x 34</td>
<td>W16 x 36</td>
<td>W16 x 36</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BR</td>
<td>W12 x 14</td>
<td>W12 x 14</td>
<td>W12 x 14</td>
<td>W12 x 14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weight (kN)</td>
<td>1058.90</td>
<td>1095.27</td>
<td>1151.40</td>
<td>1124.00</td>
<td>1166.02</td>
<td></td>
</tr>
<tr>
<td>Maximum lateral displacement (cm)</td>
<td>—</td>
<td>7.98</td>
<td>7.84</td>
<td>7.21</td>
<td>8.19</td>
<td></td>
</tr>
<tr>
<td>Interstorey drift (cm)</td>
<td>—</td>
<td>0.91</td>
<td>0.915</td>
<td>0.915</td>
<td>0.915</td>
<td></td>
</tr>
<tr>
<td>Maximum settlement (cm)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.669</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 8: Soil parameters for the 10-storey Z-braced steel space frame on elastic foundation.

<table>
<thead>
<tr>
<th>Algorithm methods</th>
<th>γ</th>
<th>k (kN/m³)</th>
<th>2t (kN/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Teaching-learning-based</td>
<td>4.52586</td>
<td>10887.654</td>
<td>70571.370</td>
</tr>
<tr>
<td>optimization</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Harmony search algorithm</td>
<td>4.50073</td>
<td>10828.379</td>
<td>70995.363</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figures 16 and 17 show settlements of the soil surface carried out with two different algorithm methods and design histories of optimum solutions, respectively.

It is observed from Tables 3, 5, and 7 that the minimum weights of the braced frames for the case without soil-structure interaction are very similar to the ones available in literature research [36]. In this study, the V-braced type provides the lowest steel weight of 1083.80 kN by using teaching-learning-based optimization. Z-braced and X-braced types provide the second and third low weights, 1095.27 kN and 1170.03, respectively. Moreover, the minimum weight of the eccentric V-braced frame, 1275.01 kN, is nearly 15%, 14.1%, and 8.2% heavier than the minimum steel weights of the V-, Z-, and X-braced frames, respectively. On the other hand, harmony search algorithm presents 2.6–4.7% heavier minimum steel weights than the ones obtained from teaching-learning-based optimization for the case without soil-structure interaction. The tables including optimum results also show that the value of interstorey drift is very close to the limit value (h/400). Therefore, the displacement constraints play very crucial roles in the optimum design of the braced frames. Five
independent runs are performed for each braced type for the case without soil-structure interaction. In the case with soil-structure interaction, the minimum weights of all braced frames increased depending on settlements on the soil surfaces. It is observed from Tables 4, 6, 8, and 10 that the soil parameters of 10-storey braced steel frames on elastic foundation are similar for all cases. The minimum steel weights are mostly obtained by teaching-learning-based optimization. For the X-braced frame, the minimum weight obtained by TLBO for the case with soil-structure interaction is 4.01% heavier than the weight of the frame excluding soil-structure interaction. This ratio is 5.32% for the harmony search algorithm. Moreover, settlement values on the soil surfaces are nearly −0.66 cm as seen in Figure 7. For the V-braced frame including soil-structure interaction, TLBO and HS present 1.66 and 5.9% heavier weights, respectively. The settlements in this braced

Figure 13: Settlements of soil surface for the Z-braced steel space frame with two different algorithm methods (cm). (a) TLBO. (b) HS.

Figure 14: Design histories of the 10-storey Z-braced steel space frame. I: HS with soil-structure interaction; II: TLBO with soil-structure interaction; III: HS without soil-structure interaction; IV: TLBO without soil-structure interaction.

Figure 15: 2D view of the eccentric V-braced steel space frame without and with soil-structure interaction. (a) The case without soil-structure interaction. (b) The case with soil-structure interaction.
Advances in Civil Engineering

Table 9: Optimum results of the eccentric V-braced space frame.

<table>
<thead>
<tr>
<th>Storeys</th>
<th>Member groups</th>
<th>TLBO without soil-structure interaction</th>
<th>TLBO with soil-structure interaction</th>
<th>HS without soil-structure interaction</th>
<th>HS with soil-structure interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2</td>
<td>CC W24 × 68</td>
<td>W14 × 14</td>
<td>W14 × 14</td>
<td>W10 × 10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>OC1 W24 × 24</td>
<td>W12 × 12</td>
<td>W14 × 14</td>
<td>W12 × 12</td>
<td>W40 × 40</td>
</tr>
<tr>
<td></td>
<td>OC2 W36 × 36</td>
<td>W14 × 14</td>
<td>W10 × 10</td>
<td>W16 × 16</td>
<td></td>
</tr>
<tr>
<td>3-4</td>
<td>IC W14 × 14</td>
<td>W10 × 10</td>
<td>W18 × 18</td>
<td>W16 × 16</td>
<td>W14 × 14</td>
</tr>
<tr>
<td></td>
<td>OB W10 × 10</td>
<td>W18 × 18</td>
<td>W18 × 18</td>
<td>W16 × 16</td>
<td>W12 × 12</td>
</tr>
<tr>
<td></td>
<td>IB W18 × 18</td>
<td>W16 × 16</td>
<td>W8 × 8</td>
<td>W8 × 8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BR W10 × 10</td>
<td>W16 × 16</td>
<td>W10 × 10</td>
<td>W8 × 8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CC W10 × 10</td>
<td>W12 × 12</td>
<td>W18 × 18</td>
<td>W14 × 14</td>
<td></td>
</tr>
<tr>
<td></td>
<td>OC3 W12 × 12</td>
<td>W12 × 12</td>
<td>W14 × 14</td>
<td>W12 × 12</td>
<td></td>
</tr>
<tr>
<td></td>
<td>OC4 W10 × 10</td>
<td>W12 × 12</td>
<td>W12 × 12</td>
<td>W21 × 21</td>
<td></td>
</tr>
<tr>
<td>5-6</td>
<td>IC W14 × 14</td>
<td>W16 × 16</td>
<td>W24 × 24</td>
<td>W16 × 16</td>
<td></td>
</tr>
<tr>
<td></td>
<td>OB W18 × 18</td>
<td>W12 × 12</td>
<td>W14 × 14</td>
<td>W16 × 16</td>
<td></td>
</tr>
<tr>
<td></td>
<td>IB W14 × 14</td>
<td>W24 × 24</td>
<td>W16 × 16</td>
<td>W14 × 14</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BR W10 × 10</td>
<td>W6 × 6</td>
<td>W12 × 12</td>
<td>W6 × 6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CC W10 × 10</td>
<td>W12 × 12</td>
<td>W8 × 8</td>
<td>W14 × 14</td>
<td></td>
</tr>
<tr>
<td></td>
<td>OC5 W16 × 16</td>
<td>W8 × 8</td>
<td>W12 × 12</td>
<td>W12 × 12</td>
<td></td>
</tr>
<tr>
<td></td>
<td>OC6 W10 × 10</td>
<td>W8 × 8</td>
<td>W16 × 16</td>
<td>W14 × 14</td>
<td></td>
</tr>
<tr>
<td>7-8</td>
<td>IC W10 × 10</td>
<td>W18 × 18</td>
<td>W10 × 10</td>
<td>W10 × 10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>OB W12 × 12</td>
<td>W8 × 8</td>
<td>W16 × 16</td>
<td>W8 × 8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>IB W14 × 14</td>
<td>W14 × 14</td>
<td>W10 × 10</td>
<td>W10 × 10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BR W12 × 12</td>
<td>W12 × 12</td>
<td>W12 × 12</td>
<td>W12 × 12</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CC W12 × 12</td>
<td>W8 × 8</td>
<td>W14 × 14</td>
<td>W14 × 14</td>
<td></td>
</tr>
<tr>
<td></td>
<td>OC7 W8 × 8</td>
<td>W8 × 8</td>
<td>W10 × 10</td>
<td>W8 × 8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>OC8 W10 × 10</td>
<td>W12 × 12</td>
<td>W16 × 16</td>
<td>W16 × 16</td>
<td></td>
</tr>
<tr>
<td>9-10</td>
<td>IC W14 × 14</td>
<td>W10 × 10</td>
<td>W14 × 14</td>
<td>W14 × 14</td>
<td></td>
</tr>
<tr>
<td></td>
<td>OB W8 × 8</td>
<td>W8 × 8</td>
<td>W10 × 10</td>
<td>W8 × 8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>IB W12 × 12</td>
<td>W10 × 10</td>
<td>W14 × 14</td>
<td>W10 × 10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BR W10 × 10</td>
<td>W12 × 12</td>
<td>W12 × 12</td>
<td>W6 × 6</td>
<td></td>
</tr>
<tr>
<td>Weight (kN)</td>
<td>1275.01</td>
<td>1355.05</td>
<td>1335.23</td>
<td>1441.58</td>
<td></td>
</tr>
<tr>
<td>Maximum lateral displacement (cm)</td>
<td>7.76</td>
<td>8.09</td>
<td>7.51</td>
<td>7.66</td>
<td></td>
</tr>
<tr>
<td>Interstorey drift (cm)</td>
<td>0.91</td>
<td>0.91</td>
<td>0.91</td>
<td>0.91</td>
<td></td>
</tr>
<tr>
<td>Maximum settlement (cm)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

Table 10: Soil parameters for the 10-storey eccentric V-braced steel space frame on elastic foundation.

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>γ</th>
<th>k (kN/m²)</th>
<th>2r (kN/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Teaching-learning-based optimization</td>
<td>5.04545</td>
<td>12120.214</td>
<td>63375.683</td>
</tr>
<tr>
<td>Harmony search algorithm</td>
<td>5.01478</td>
<td>12047.186</td>
<td>63760.516</td>
</tr>
</tbody>
</table>

The frame are nearly −0.65 cm as given in Figure 10. For the Z-braced frame with soil-structure interaction, the minimum weights obtained are 5.11% and 3.73% heavier by using TLBO and HS, respectively. The settlements in this braced frame are similar to the ones of the other braced frames. For the eccentric V-braced frame with soil-structure interaction, the minimum steel weights obtained are 6.27 and 7.94% heavier by using TLBO and HS, respectively. Moreover, the convergences of optimum solutions with iteration steps are seen in Figures 8, II, 13, and 17 in detail.

6. Summary and Conclusions

In this study, the optimum design of a 10-storey steel space frame braced with X, V, Z, and eccentric V-shaped bracings including soil-structure interaction is investigated. Optimum solutions are obtained using two different metaheuristic algorithm methods: teaching-learning-based optimization (TLBO) and harmony search (HS). For this purpose, a code is developed in MATLAB computer program incorporated with SAP2000-OAPI (open application programming interface). Required cross sections are automatically selected from a list of 128 W profiles taken from AISC (American Institute of Steel Construction). The
frame model is exposed to wind loads according to ASCE 7-05 in addition to dead, live, and snow loads. The stress constraints in accordance with AISC-ASD (American Institute of Steel Construction-Allowable Stress Design), maximum lateral displacement constraints, interstorey drift constraints, and beam-to-column connection constraints are applied in analyses. A three-parameter Vlasov elastic foundation model is used to consider the soil-structure interaction effect. The summary of the results obtained in this study are briefly listed below:

(i) It is observed from analyses that the minimum weight of the space frame varies by the types of bracing. The lowest steel weight, 1083.80 kN, is obtained for the V-braced steel frame by using TLBO. Z-braced and X-braced types provide the second and third low weights, 1095.27 kN and 1170.03, respectively. These results are similar to the ones available in literature [36]. The heaviest among them is the minimum weight of the eccentric V-braced frame, 1275.01 kN.

(ii) Harmony search algorithm presents 2.6–4.7% heavier steel weights than the ones obtained from teaching-learning-based optimization for the frames without soil-structure interaction. Although the lighter analysis results are obtained in TLBO, a representative structure model in TLBO is analyzed twice in an iteration step by SAP2000 programming. On the other hand, it is enough to analyze the system once in HS. This situation requires longer time for the analysis in TLBO.

(iii) Interstorey drift values are very close to its limit value of 0.915 cm (h/400). Therefore, the constraints are important determinants of the optimum design of the braced frames.

(iv) Consideration of soil-structure interaction results in heavier steel weight. For the X-braced frame including soil-structure interaction, the minimum weights are obtained to be 4.01 and 5.32% heavier by using TLBO and HS, respectively. For the V-braced frame, these values are calculated to be 1.66 and 5.9% heavier, respectively. For the Z-braced frame, these values are obtained to be 5.11% and 3.73% heavier, respectively. Moreover, for the eccentric V-braced frame, the minimum weights are obtained to be 6.27 and 7.94% heavier by these algorithm methods.

(v) Settlement values on the soil surfaces are nearly 0.61–0.67 cm for all braced frames.

(vi) Finally, the techniques used in optimizations seem to be quite suitable for practical applications. An adaptive setting for the parameters will be very useful and user-friendly especially for the structures with a large number of members as in the case here. This will be considered in future studies.
Conflicts of Interest
The authors declare that they have no conflicts of interest.

References


