Structural Engineering and Mechanics, *Vol. 63, No. 5 (2017) 607-615*
DOI: https://doi.org/10.12989/sem.2017.63.5.607

Optimum design of steel bridges including corrosion effect using TLBO

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(Received March 16, 2017, Revised May 7, 2017, Accepted May 17, 2017)

Abstract. This study presents optimum design of plane steel bridges considering corrosion effect by using teaching-learning based optimization (TLBO) method. Optimum solutions of three different bridge problems are linearly carried out including and excluding corrosion effect. The member cross sections are selected from a pre-specified list of 128 W profiles taken from American Institute of Steel Construction (AISC). A computer program is coded in MATLAB to carry out optimum design interacting with SAP2000 using OAPI (Open Application Programming Interface). The stress constraints are incorporated as indicated in AISC Allowable Stress Design (ASD) specifications and also displacement constraints are applied in optimum design. The results obtained from analysis show that the corrosion effect on steel profile surfaces causes a crucial increase on the minimum steel weight of bridges. Moreover, the results show that the method proposed is applicable and robust to reach the destination even for complex problems.

Keywords: optimum design; steel bridge; teaching-learning based optimization; MATLAB-SAP2000 OAPI

1. Introduction

There are various metaheuristic methods to be used in structural optimization. Genetic algorithm, harmony search algorithm, artificial bee colony algorithm, ant colony optimization, a bat-inspired algorithm, particle swarm optimization, teaching-learning based optimization are commonly used for optimum design in the area of structural.

Rajeev and Krishnamoorthy (1992) studied discrete optimization of structures by using genetic algorithms. Kameshki and Saka (2001) used genetic algorithm on optimum design of nonlinear steel frames with semi-rigid connections. Lee and Geem (2004) proposed a new structural optimization method based on the harmony search algorithm. Kelesoglu and Ülker (2005) studied multi-objective fuzzy optimization of space trusses by Ms-Excel. Değertekin *et al.* (2007) studied tabu search based optimum design of geometrically non-linear steel space frames. Değertekin *et al.* (2008) focused on a hybrid tabu-simulated annealing heuristic algorithm for optimum design of steel frames. Esen and Ülker (2008) focused on optimization of multi storey space steel frames. Saka (2009) used harmony search algorithm for optimum design of steel sway frames according to BS5950. Hasançebi *et al.* (2010) studied on the improvements of the performance of simulated annealing in structural optimization. Değertekin and Hayalioğlu (2010) used harmony search algorithm for minimum cost design of steel frames with semi-rigid connections and column bases. Rao *et al.* (2011) focused on a novel method, teaching-learning-based optimization, for constrained mechanical design optimization problems. Değertekin (2012) studied optimum design of geometrically non-linear steel frames using artificial bee colony algorithm. Toğan (2012) researched design of planar steel frames using teaching-learning based optimization. Aydoğdu and Saka (2012) used ant colony algorithm for optimization of irregular steel frames including elemental warping effect. Crepinsek *et al.* (2012) focused on teaching-learning-based optimization algorithm and they expressed TLBO method has good performance on optimization among a number of metaheuristic methods. Dede (2013) studied optimum design of grillage structures with teaching-learning based optimization according to LRFD-AISC. Dede and Ayvaz (2013) used teaching-learning-based optimization algorithm for structural optimization. Degertekin and Hayalioglu (2013) studied the optimum design of truss structures using TLBO. Rao and Patel (2013) focused on an improved teaching-learning-based optimization algorithm for solving unconstrained optimization problems. Rafiee *et al.* (2013) used Big Bang-Big Crunch method for optimum design of steel frames with semi-rigid connections. Hadidi and Rafiee (2014) focused on harmony search based, improved particle swarm optimizer for minimum cost design of semi-rigid steel frames. Camp and Farshchin (2014) researched design of space trusses using modified teaching-learning based optimization. Dede (2014) studied application of teaching-learning-based-optimization algorithm for the discrete optimization of truss structures. Dede and Ayvaz (2015)

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ISSN: 1225-4568 (Print), 1598-6217 (Online)

used teaching learning based optimization for combined size and shape optimization of structures. Dede and Togan (2015) studied a teaching learning based optimization for truss structures with frequency constraints. Artar and Daloğlu (2015) researched optimum design of composite steel frames with semi-rigid connections and column bases via genetic algorithm. Artar (2016a) studied optimum design of steel space frames under earthquake effect using harmony search. Artar (2016b) used teaching learning based optimization for optimum design of braced steel frames. Carbas (2016) used an enhanced firefly algorithm for design optimization of steel frames. Aydogdu (2017) studied cost optimization of reinforced concrete cantilever retaining walls under seismic loading using a biogeography-based optimization algorithm with Levy flights. Aydogdu *et al.* (2017) researched optimum design of steel space structures using social spider optimization algorithm with spider jump technique.

Although there are many studies available on various structural optimizations, it is hard to see a comparative research on steel bridges including corrosion effect in marine site. This study presents an optimum design approach for three different bridge trusses considering the corrosion effect in the performance of the structure. Teaching learning based optimization is selected to carry out optimum solutions. A program is developed in MATLAB interacting with SAP2000 by using OAPI feature for two-way data flow. The results obtained from analyses show that corrosion effect in marine site plays an important role in optimum design of steel bridges and causes the weight of the structure to increase. The results also show that the algorithm developed in the study is useful and applicable for the problems in practice.

2. Optimum design problem

The discrete optimum design problem of steel bridges for minimum weight 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.

The stress constraints as indicated in AISC-ASD specifications are expressed as below;

- For tension members, the allowable stress is calculated by

$$\sigma_{t,all} = 0.6F_y \tag{2}$$

where F_y is yield stress.

- For compression members, the allowable stresses are calculated in terms of slenderness ratio, λ_m, as

$$\lambda_m = \frac{K_m L_m}{r_m} \qquad m = 1,\ldots,ne \tag{3}$$

$$C_C = \sqrt{\frac{2\pi^2 E}{F_y}} \tag{4}$$

for inelastic buckling (λ_m<C_c)

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

for elastic buckling ($\lambda_m \geq C_c$)

$$\sigma_{c,all} = \frac{12\pi^2 E}{23\lambda_m^2} \tag{6}$$

where K_m is the effective length factor (K=1.00 for truss member), r_m is minimum radius of gyration, C_c)is the critical slenderness ratio parameter.

The stress constraints are calculated as below

$$g_m(x) = \frac{\sigma_m}{\sigma_{m,all}} - 1 \leq 0 \qquad m = 1,\ldots,ne \tag{7}$$

where σ_m and $\sigma_{m,all}$ are the computed and allowable axial stresses for m[th] truss member, respectively.

The displacement constraints are evaluated as

$$g_j(x) = \frac{\delta_{jl}}{\delta_{ju}} - 1 \leq 0 \qquad j = 1,\ldots,n \tag{8}$$

where δ_{jl} is displacement of j^{th} degree of freedom, δ_{ju} is upper bound, n is number of restricted displacements.

$$g_i(\mathrm{x}) > 0 \rightarrow c_i = g_i(\mathrm{x}) \tag{9}$$

$$g_i(\mathrm{x}) \leq 0 \rightarrow c_i = 0 \tag{10}$$

The objective function $\varphi(x)$ is then calculated as

$$\varphi(x) = W(x)\left(1 + \sum_{i=1}^{m} c_i\right) \tag{11}$$

where $\varphi(x)$ is penalized objective function, c_i represents the violation of constraints. In the optimum solution, all constraints are satisfied and penalized objective function is equal to W.

Corrosion on the surface of profile is a time depended phenomena and leads to a decrease in cross-sectional area and so the moment of inertia. Ma *et al.* (2009) have carried out significant experiments on this subject for a period of two years. As mention in the study of Ma *et al.* (2009), chloride ion is the main pollutants that play the most important role in the corrosion process of structural steel. The amount of chloride ion in atmosphere increases considerably as it approaches to sea line. Marine environments cause atmospheric corrosion on surfaces of steel sections, Fig. 1. The variation of the thickness loss of carbon steel in marine atmosphere obtained by Ma *et al.* (2009) is presented in Fig. 2.

According to Ma *et al.*(2009), corrosion effect is determined in marine site as below

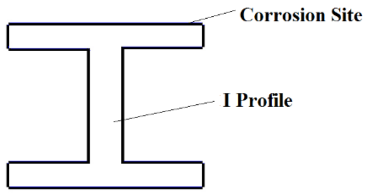

Fig. 1 Corrosion effect on surface of a steel profile

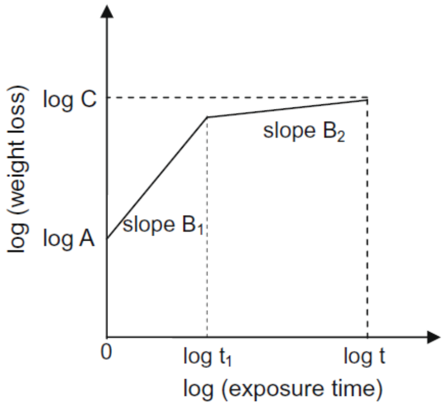

Fig. 2 The variation of the thickness loss of carbon steel in the marine atmosphere (Ma *et al.*2009)

Table 1 Regression coefficients of the natural exposure corrosion data (Ma *et al.* 2009)

Exposure site	Distances from sea line (m)	A	B_1	B_2
Marine site	95	0.527	2.19	1.06

$$C = At_1^{B_1 - B_2} t^{B_2} \qquad t \geq t1 \tag{12}$$

where C is the loss in thickness, A is that at the first month, t_1 is the length in months of the first time period (9 months) of slope B_1, and B_2 is the slope in the second time period until t experimental time (24 months). As a result of their experimental studies regression constants were determined as given in Table 1.

3. Teaching-Learning Based Optimization (TLBO)

Teaching learning based optimization method is one of the most convenient meta-heuristic search algorithms used in the optimum design of structures. While Genetic Algorithm (GA) needs mutation and cross over rate, and harmony search algorithm needs harmony memory consideration rate (HMCR) and pitch adjustment ratio (PAR), teaching learning based optimization does not need any specific control algorithm parameters as mentioned in previous studies (Rao and Patel (2012), Rao and Patel (2013)). Teaching learning based algorithm requires only the number of students in the class (population size) and number of generations. Moreover, the concept of number of teachers is to accomplish the population sorting during optimization. This situation provides to avoid the premature convergence.

Teaching-learning based optimization algorithm method was developed by Rao *et al*. (2011). This method mimics the procedures of teaching and learning between teacher and students in a class. Teacher is considered as the person who has high knowledge and he/she shares his/her knowledge with the students to increase the grade level of class. This method consists of two basic steps; teaching and learning. The basic procedures are defined below,

- Class including a group of students shows population as below

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

where each row represents a student and introduce a design solution, S is population size (the number of students), n is the number of design variables, $f(x^{1,2,\ldots S})$ is unconstrained objective function value of each student in the class. The initial class is randomly created.

- In teaching phase, the best solution in the class has minimum objective value and it is called as teacher. The other students in the class are updated as below

$$x^{new,i} = x^i + r(x_{teacher} - T_F x_{mean}) \tag{14}$$

where $x^{new,i}$ is the new student, x^i is the current student, r is a random number in the range [0,1], T_F, a teaching factor, is either 1 or 2. The mean of the class, x_{mean}, is calculated as

$$x_{mean} = (mean(x_1)....mean(x_S)) \tag{15}$$

If new student gives a better solution ($f(x^{new,i})$) than the current solution ($f(x^i)$), the new student is replaced with the current student.

$$If \quad f(x^i) < f(x^j) \quad \Rightarrow \quad x^{new,i} = x^i + r(x^i - x^j) \tag{16}$$

$$If \quad f(x^i) > f(x^j) \quad \Rightarrow \quad x^{new,i} = x^i + r(x^j - x^i) \tag{17}$$

As mentioned in teaching phase, if the new student presents a better solution ($x^{new,i}$) than the current solution ($f(x^{new,i})$), the new student is replaced with the current student. Detailed information about TLBO method can be found from Rao *et al*. (2011), Toğan (2012), Dede (2013), Dede and Ayvaz (2013) and Artar (2016b). The steps of discrete design optimization algorithm based on TLBO are listed below,

1. Read input data and create initial classroom, randomly.
2. Decode each student in the class and Select corresponding sections from available list in SAP2000 programming. Thus, identify the model represented by each student in the class.
3. Solve each model in the class and calculate the stresses and the displacements.
4. Calculate the mean of design variables in the class.
5. In the theaching phase, determine the best solution as teacher and update the students by Eq. (14). If the new student $x^{new,i}$ gives a better solution, then replace the new student with the old student.

6. In the learning phase, select two solutions randomly (x^i, x^j) and define the new student $x^{new,i}$ by Eq. 16, according to the cases ($f(x^i)<f(x^j)$ or $f(x^i)>f(x^j)$). If the new student $x^{new,i}$ gives a better solution, then replace the new student with the old student.
7. Continue the iterations until the convergence criteria are satisfied.

4. Benchmark problem

4.1 10-bar plane truss design

In order to demonstrate the effectiveness of this method, a benchmark problem on discrete optimization is investigated. A 10-bar plane truss shown in Fig. 3 has previously carried out by many researches. There are 10 design variables shown in Table 2. The discrete variables are selected from the 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 in2). The modulus of elasticity is 10000 ksi and density of material is 0.1 lb/in3. The allowable stress for all bars is considered as ±25 ksi. Moreover, the maximum displacement for x and y directions is restricted to 2 in.

As observed from Table 2, the areas of cross sections and minimum weight obtained in this study are suitable with the ones available in literature. The weight versus iteration number is presented in Fig. 4.

5. Truss bridge design examples

A comparative study on three different plane steel bridges including and excluding corrosion effect in marine site is performed. The examples are a 61-member plane truss bridge, a 161-meber plane truss bridge and 157-member plane truss bridge. They are first designed without considering corrosion effect on the structural elements. Then, the examples are designed considering the corrosion effect in marine site for various time durations. The first example for corrosion effect is carried out for 12 and 24-month time period. The second example is resolved for 6, 12 and 24 months of time durations. The final example is performed for 24-month time period. Optimum profiles are selected from a specified list having 128 W profiles taken from AISC. The material properties used in all three examples are modulus of elasticity, E, is 29000 ksi and yield stress, F_y, is 36 ksi. The stress constraints as indicated in AISC-ASD and maximum displacement constraints are imposed on all the examples. The maximum displacements

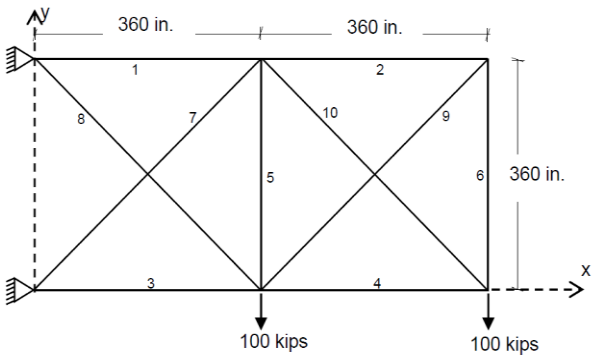

Fig. 3 10-bar plane truss design

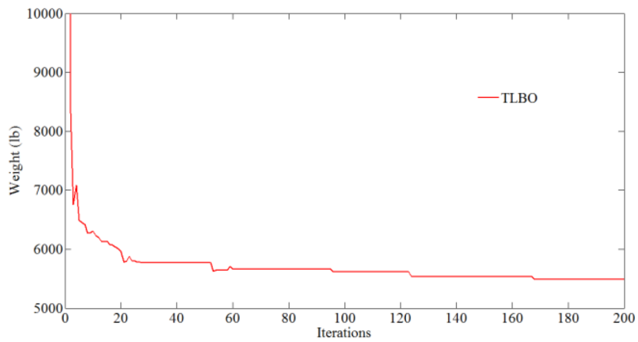

Fig. 4 Variation of the weight with the number of iteration for the benchmark problem

Table 2 Optimal design comparison for the 10-Bar plane truss

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	Sönmez (2011) Artificial bee colony algorithm	Camp and Farshchin (2014) Teaching-learning based optimization	Dede (2014) Teaching-learning based optimization	This study Teaching-learning based optimization
1	A_1	33.50	30.00	33.50	33.50	33.50	33.50	33.50
2	A_2	1.62	1.62	1.62	1.62	1.62	1.62	1.62
3	A_3	22.00	22.90	22.90	22.90	22.90	22.90	22.90
4	A_4	15.50	13.50	14.20	14.20	14.20	14.20	14.20
5	A_5	1.62	1.62	1.62	1.62	1.62	1.62	1.62
6	A_6	1.62	1.62	1.62	1.62	1.62	1.62	1.62
7	A_7	19.90	26.50	22.90	22.90	22.90	22.90	22.90
8	A_8	14.20	7.97	7.97	7.97	7.97	7.97	7.97
9	A_9	2.62	1.80	1.62	1.62	1.62	1.62	1.62
10	A_{10}	19.90	22.00	22.00	22.00	22.00	22.00	22.00
Weight(lb)		5613.84	5531.98	5490.74	5490.74	5490.74	5490.74	5490.74

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

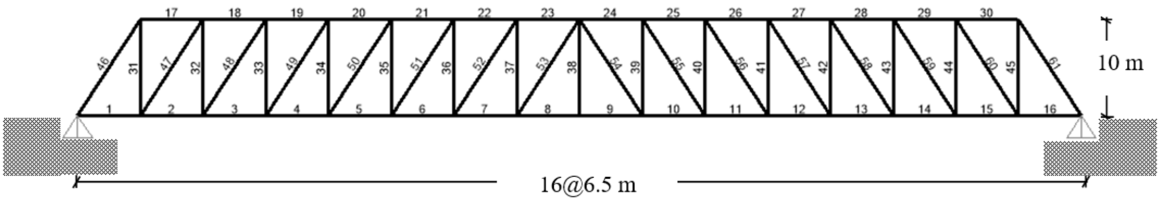

Fig. 5 61-Member plane truss bridge

Table 3 Minimum weights of best and worst runs

Minimum weights (kN)		Case 1 without corrosion effect	Case 2 with corrosion effect for 12 months	Case 3 with corrosion effect for 24 months
Best run	1516.74	1535.87	1554.69	Best run
Worst run	1518.83	1592.92	1562.38	Worst run

Table 4 Optimum solutions of the best solutions

Group no	Member no	Case 1 without corrosion effect	Case 2 with corrosion effect for 12 months	Case 3 with corrosion effect for 24 months
1	1-4	W40×298	W36×280	W44×285
2	5-8	W18×97	W27×94	W12×87
3	17-20	W44×285	W44×285	W36×280
4	21-23	W40×503	W40×503	W40×503
5	31-34	W30×191	W14×145	W44×224
6	35-38	W12×87	W16×89	W10×100
7	46-49	W36×194	W40×244	W14×193
8	50-53	W24×94	W18×106	W16×100
Weight (kN)		1516.74	1535.87	1554.69
Maximum displacement (cm)		10.396	10.397	10.40

are restricted to L/1000. Several independent runs are performed to obtain optimum solutions in the examples. Best and worst values for minimum weights are presented for each solution in the examples. Optimum solutions are carried out by a class with 20 students. In optimal solutions, execution time is between 300 and 350 minutes.

5.1 61-Member plane truss bridge

The geometry of a 61-member plane truss bridge is presented in Fig. 5 containing number of members. The minimum weights of best and worst runs are presented in Table 3. The members are collected into 8 groups as seen in Table 4. A point load of 320.00 kN is applied to each joint of the lower chord. Maximum displacement is restricted to 10.40 cm (L/1000). Table 4 also shows the best optimum solutions for the cases with and without corrosions effect. The weight of the truss versus number of iteration is presented in Fig. 6.

As seen in Table 3, maximum displacement constraints are very close to upper limit of 10.40 cm. Therefore, the displacement constraints are very active determinants in optimum design for the truss. It is observed from Table 3 that the minimum weight of optimum solution for the case without corrosion effect is 1516.74 kN and the other minimum weights of the cases with corrosion effect in marine site for 12 and 24 months are 1535.87 kN and 1554.69 kN respectively. These values are 1.26% and 2.50% heavier than the minimum weight obtained for the case without corrosion effect. It indicates that if the steel profiles are not protected against corrosion, the truss should be designed with the larger cross sections and the structure gets heavier accordingly. Therefore, it is convenient to say that the corrosion effect plays crucial role in optimum design.

5.2 161-Member plane truss bridge

Fig. 7 shows the geometry of a 161-member plane truss bridge including number of members. The minimum weights of best and worst runs are presented in Table 5. The members are collected into 15 groups, Table 6. A point load of 320.00 kN is applied at each joint of the upper chord. Maximum displacement is restricted to 6.50 cm (L/1000) for first interval and 13.00 cm for second interval. The best solutions of the cases with corrosion effect for 6, 12 and 24-month time durations in addition to optimum solution without corrosion effect are also presented in Table 5. Variations of the weight with the number of iteration for all cases are shown in Fig. 8.

It is observed from Table 6 that the maximum displacements in the second interval are very close to its upper limit being 13.00 cm. This shows that the displacement constraints are very important for optimum

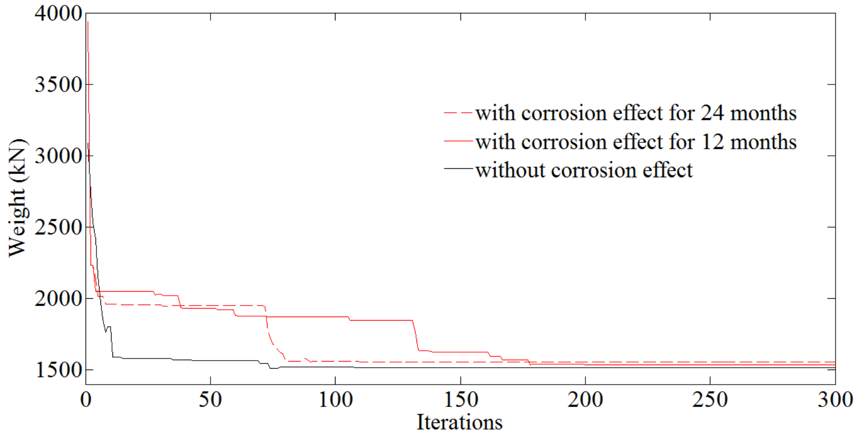

Fig. 6 Variation of the weight with the number of iteration for 61-bar plane truss bridge

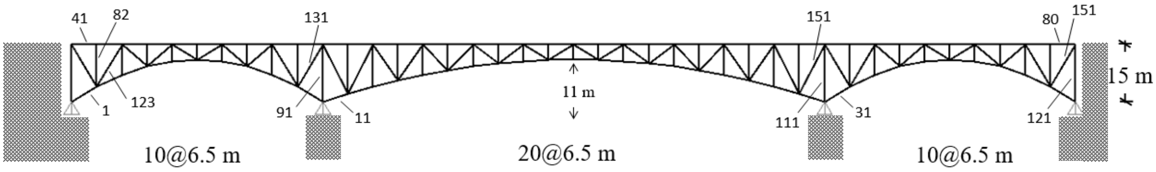

Fig. 7 161-member plane truss bridge

Table 5 Minimum weights of best and worst runs

Minimum weights (kN)	Case 1 without corrosion effect	Case 2 with corrosion effect for 6 months	Case 3 with corrosion effect for 12 months	Case 4 with corrosion effect for 24 months
Best run	1834.41	1862.68	1897.14	1906.77
Worst run	1856.60	1870.23	1917.66	1919.16

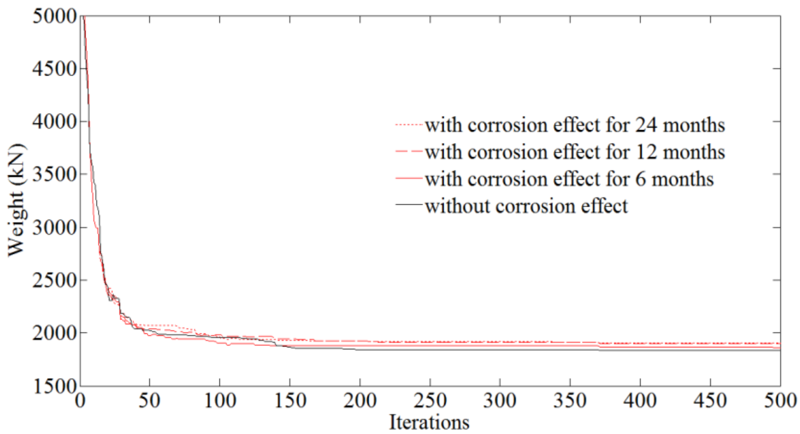

Fig. 8 Variation of the weight with number of iteration 161-bar plane truss bridge

solutions of this truss bridge. Moreover, Table 6 shows that the minimum weight of optimum solution for the case without corrosion effect is 1834.41 kN. On the other hand, the minimum weights for the cases with corrosion effect in marine site for 6, 12 and 24-month time intervals are 1862.68 kN, 1897.14 kN and 1906.77 kN, respectively. In other words, the weights of plane steel bridge are 1.54%, 3.41% and 3.94% heavier for 3 different time intervals compare to the optimum weight of the truss without corrosion effect. In this example, corrosion effects on profile surface increase the structural weight significantly and the weight increases as duration of time gets longer.

5.3 157-Member plane truss bridge

Fig. 9 shows a 157-member plane truss bridge including member numbers. The minimum weights of best and worst runs are presented in Table 7. The members are collected into 16 groups as seen in Table 8. A point load of 320.00 kN is applied to each joint of the lower chord. Maximum displacement is restricted to 13.00 cm (L/1000). Table 8 also presents the optimum solutions of the cases without and with corrosion effect for 24 months. Fig. 10 presents the design history for both the cases considered.

As shown in Table 8, maximum displacement

Table 6 Optimum solutions of the best run

Group no	Member no	Case 1 without corrosion effect	Case 2 with corrosion effect for 6 months	Case 3 with corrosion effect for 12 months	Case 4 with corrosion effect for 24 months
1	1-2	W30×108	W30×108	W30×108	W30×108
2	3-8	W16×89	W21×83	W21×83	W21×83
3	11-15	W40×362	W40×298	W40×298	W40×298
4	16-20	W44×285	W44×224	W40×298	W44×224
5	41-50	W16×26	W12×30	W12×30	W10×33
6	51-70	W44×285	W40×328	W40×328	W40×328
7	81-83	W24×55	W24×62	W24×55	W24×62
8	84-88	W10×15	W12×14	W10×15	W12×14
9	92-95	W12×22	W12×22	W12×22	W12×22
10	96-100	W8×24	W12×22	W8×24	W8×24
11	122-123	W12×26	W12×26	W12×26	W16×26
12	124-126	W16×26	W16×26	W16×26	W10×33
13	132-134	W21×44	W21×50	W18×50	W24×55
14	135-137	W27×94	W18×86	W21×68	W18×106
15	138-141	W16×45	W18×106	W12×96	W14×109
Weight (kN)		1834.41	1862.68	1897.14	1906.77
Maximum displacement for first interval (cm)		4.92	4.91	4.93	4.71
Maximum displacement for second interval (cm)		12.99	12.99	12.99	13.00

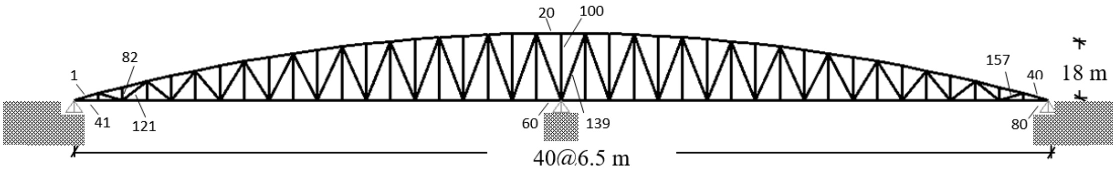

Fig. 8 Variation of the weight with number of iteration 161-bar plane truss bridge

constraints are very close to upper limit, 13.00 cm. Therefore, they are very active determinants in optimum design. Also, it is observed from Table 8 that although the minimum weight of optimum solution for the case without corrosion effect is 4536.91 kN, it increases to 4671.66 kN when the corrosion effect is incorporated for 24-month time duration. The minimum weight is 2.97% heavier for Case 2. It again emphasizes the importance of protection of steel profile surface against corrosion effect.

6. Conclusions

In this study, optimum designs of three different plane steel truss bridges are obtained using TLBO. Corrosion effect on the steel material is also considered in the design and results are presented comparatively. One of the latest stochastic algorithm methods, teaching learning based optimization, is preferred to reach optimum solutions. All structural analysis part of the study is performed by SAP2000 using the Open Application Programming Interface (OAPI) features of the software. A fast and robust coupling with SAP2000 provides two-way data flow during execution of the analysis and design of the system as well as to facilitate pre and post processors. A program is developed in MATLAB for the purpose to interact with SAP2000-OAPI. Stress constraints as indicated in AISC-ASD specifications and maximum displacement constraints are imposed on the examples. The results obtained from analyses are shown in tables and figures. The important conclusions drawn from the present study are briefly summarized below;

- The first example is a 61-member plane bridge with 8 groups of structural members. In Case 1, it is designed for the condition without corrosion effect. In Case 2 and Case 3, the truss is designed including the corrosion effect in marine site for 12 and 24 months. The minimum weight of plane steel bridge is 1.26% and 2.50% heavier when corrosion effect is included.
- The second example is 161-member plane truss bridge and its members are collected in 15 groups. The optimum solutions are carried out four several cases. In Case1, optimum design is performed without considering the corrosion effect. The other cases, Case

Table 7 Minimum weights of best and worst runs

Minimum weights (kN)	Case 1 without corrosion effect	Case 2 with corrosion effect for 24 months
Best run	4536.91	4671.66
Worst run	4550.09	4752.50

Table 8 Optimum solutions of the best run

Group no	Member no	Case 1 without corrosion effect	Case 2 with corrosion effect for 24 months
1	1-5	W40×397	W40×397
2	6-10	W40×431	W40×431
3	11-15	W12×120	W18×130
4	16-20	W40×431	W40×431
5	41-45	W40×503	W40×503
6	46-50	W40×397	W44×224
7	51-55	W44×224	W44×224
8	56-60	W40×503	W40×503
9	81-85	W14×34	W12×35
10	86-90	W18×50	W8×28
11	91-95	W6×15	W6×15
12	96-100	W12×14	W12×14
13	120-124	W14×48	W10×45
14	125-130	W14×193	W44×224
15	131-134	W44×224	W36×280
16	135-138	W44×224	W44×285
Weight (kN)		4536.91	4671.66
Maximum displacement (cm)		13.00	12.99

2, Case3 and Case 4, optimum designs are obtained including corrosion effect in marine site for 6, 12 and 24-month time durations. The optimum weights of plane steel bridges are 1.54%, 3.41% and 3.94% heavier when the corrosion effects are included in Case 2, 3 and 4 respectively compare to the weight obtained in Case 1.

- The last example is 157-member plane truss bridge and its members are collected into 16 groups. This example is designed for two different cases. The minimum weight of optimum solution in the case with corrosion effect for 24-month time duration is 2.97% heavier.
- As mentioned above, the steel profile surfaces must be protected against corrosion effect. Otherwise, the minimum weights of plane steel bridges significantly increase.
- Moreover, it is observed that maximum displacement constraints play very active role in optimizations.
- Finally, the results show the usefulness of the algorithm preferred in this study.

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