Investigation of thermal effects on analyses of truss structures via metaheuristic approaches

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Abstract: - Internal forces and displacement caused from the thermal effects can be important for structures that can be subject to large temperature changes. For that reason, determining these effects accurately during the design process is essential for security of structural systems. In this paper, a methodology called total potential optimization using metaheuristic algorithms (TPO/MA) that has been successfully applied for analyzing different types of systems such as truss, cables and tensegrity structures, is presented for investigation of analyses of truss structures considering thermal effects. Teaching learning based optimization (TLBO) algorithm is employed as metaheuristic approach. Results are compared with other methods that used well-known metaheuristic approach harmony search (HS) and finite element method (FEM). According to results, proposed approach is accurate, robust and reliable for the analyses of this kind of problem.

Key-Words: - meta-heuristics; teaching learning based optimization method; harmony search; total potential optimization method; nonlinearity; thermal effect.

1 Introduction

Methods used in the structural design are generally developed based on minimum potential energy principle that is a well-known in mechanics. This theory describes an equilibrium condition between the external and internal energies i.e. such as work done by external loads, thermal energy, strain energy, etc., for a structural system. According to this condition, if total potential energy of the system is minimum, the structure is in the equilibrium state (stable). If this condition is not satisfied, the system is in the motion or unstable.

Conventional analyses techniques use mathematical methods to find the equilibrium state for a system. This mathematical process begins by writing external (W) and internal energies means strain energy (U) and total potential of the system (Π) as seen in Eq. (1)

$$\Pi = U - W \tag{1}$$

Then, by taking the derivative of the Eq. (1), and equating it to zero, thus writing down the condition for minimization of the total potential energy of the system, one arrives at the expression

$$\mathrm{P} = K\Delta \tag{2}$$

where P is the vector with elements as external loads, K is stiffness matrix that contains material properties such as elasticity modulus, Poisson's ratio, modulus of rigidity, etc. and cross sectional properties i.e., cross sectional area, and moment of inertia *inter alia*. By using matrix operations, then the unknown displacement vector (Δ) is determined.

This expression is effective for analyses conducted based on linear theory. However, due to nonlinear effects, K cannot be determined independent of external loads and displacements,

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and thus one cannot write down Eq. (2) explicitly, as opposed to linear cases. In the traditional techniques, an iterative process is performed to overcome this problem. But, it must be noted that, exact solution cannot be obtained by using this process and the accuracy of the analyses result are depended to iteration number used in the process.

Recently proposed method called total potential optimization using meta-heuristic algorithms (TPO/MA) is can also be employed for the analyses [1]. In this approach, the displacements are randomly assigned and then work done by external loads (W) and strain energy (U) and total potential energy of the system (Π) are calculated. By the help of the metaheuristic approaches the displacement values that makes energy of the system minimum is determined. Thus, nonlinear effects can be easily calculated. This is novelty of the TPO/MA approach.

So far, the TPO/MA have been employed for analyses of various structural system including trusses, cables and tensegrity structures [2-13]. In this applications it has been shown that, TPO/MA is effective, accurate, robust and reliable for related subjects.

2 Methodology

In the 2011, TLBO approach developed by Rao et. al. [14] from the inspiration of teaching learning process in class. Optimization process of TLBO approach can be divided in five steps.

First step: In this step, data of the problem is defined. This data contains geometry and loading condition of system, design constant, number of design variables (*vn*), population number (*pn*) and maximum iteration number as stopping criterion.

Second step: In this step, initial solution matrix (class) is generated. This matrix constructed by using candidate solution vectors (learners) as much as population number and each solution vector contains randomly generated nodal coordinates for related solution. At the end of the 2^{nd} step, total potential energy values for each vector is calculated. Due to objective of the optimization process is to find nodal displacements (or deformed shape) of system that have minimum the total potential energy value. This energy values are also stored in a vector for future comparison.

Third step: In this step, the iterative process that include teacher phase, learner phase and controlling stopping criterion is begun. This stage first contains teacher phase.

Teacher phase can be summarized as an updating process by using the best solution. Thus, at the beginning of the process, solution with the best objective is selected and assigned as teacher (Eq. 3).

$$X_{teacher} = X_{min\,f(X)} \tag{3}$$

Then new solutions ($X_{new,i}$) for each candidate vector ($X_{old,i}$) are calculated by using teacher vector, mean value of vectors as

$$X_{new,i} = X_{old,i} + rnd\left(0,1\right)\cdot\left(X_{teacher} - T_F \cdot X_{mean}\right) \tag{4}$$

where *rnd* is a random number between 0 to 1, and T_F is teaching factor that defined as

$$T_F = round\left[1 + rnd\left(0.1\right)\right] \rightarrow \left\{1-2\right\}. \tag{5}$$

After that, old and new vectors are compared. If the new vector is better than old one in mean of objective value, it new vector is accepted.

Fourth step: In this step, rules of learner phase is applied. According to learner phase, old vectors are updated by using values of randomly selected vectors (X_i and X_j).

$$X_{new,i} = \begin{cases} X_{old,i} + r_i \cdot \left(X_i - X_j\right); & f\left(X_i\right) > f\left(X_j\right) \\ X_{old,i} + r_i \cdot \left(X_j - X_i\right); & f\left(X_i\right) < f\left(X_j\right) \end{cases} \tag{6}$$

At the end of the learner phase, the accepting process applied in the teacher phase is conducted.

Five step: Stopping criterion is checked. If it is satisfied, the optimization process is ended. If not the iterative process is continue form third step. A detailed flowchart of the optimization process can be seen in Fig. 1

3 Numerical Examples

Analyses results for three different truss systems were presented in this section. Thermal forces is determined using Eurocode 3 (EC3) [15]. In this code, thermal forces is calculated by using reduction factor for effective yield strength and slope of elastic range. Reduction factor (k_e) value vs. temperature graph is given in Fig. 2. As seen in Fig. 2, for temperatures less than 100 °C, the effect of thermal effect is not taken into account (k_e=1).

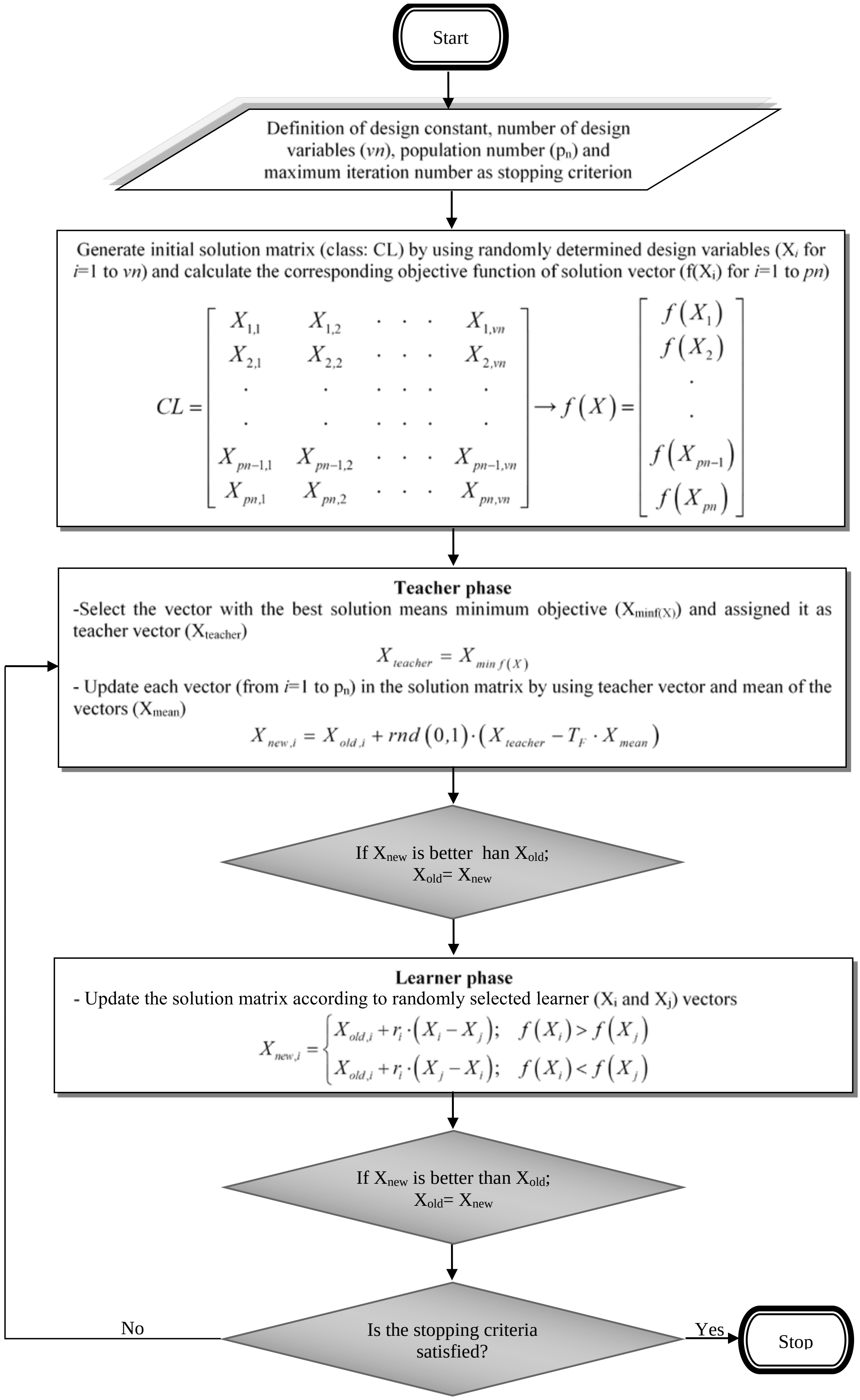

Fig. 1. Flowchart of the optimization process.

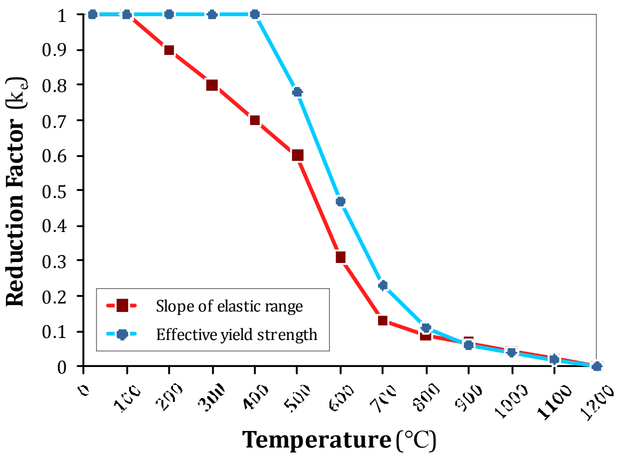

Fig. 1. Reduction factors for effective yield strength and slope of elastic range vs. elevated temperature

As seen from the stress-strain diagram given in Fig. 3, by increasing temperature from 100°C to 1100°C, material get lost nearly 98% of yield strength.

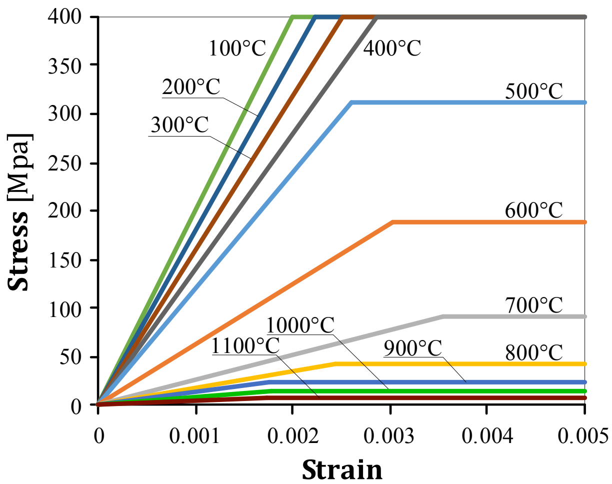

Fig. 3. Stress-strain diagram for different temperatures

In the first example is analyses a system with 2 members (Fig. 4). Cross-sectional area members, yield strength and loads are taken as 100 mm^2, 400 MPa (for 0.002 strain) and 1000 N, respectively. In order to show thermal effect the analyses were repeated for temperatures 100°C-1100°C given in Fig. 3. Total potential energy values versus analyses number graphs can be seen in Fig. 5.

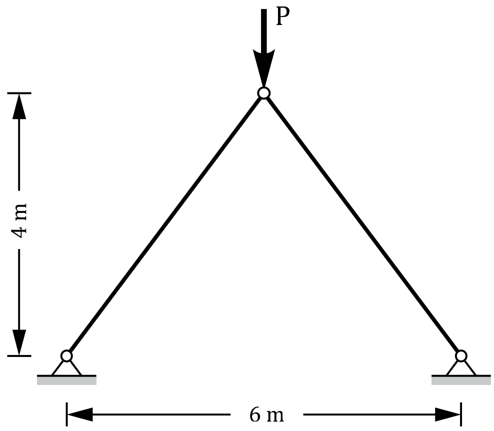

Fig. 4. Plane truss system with 2-bar

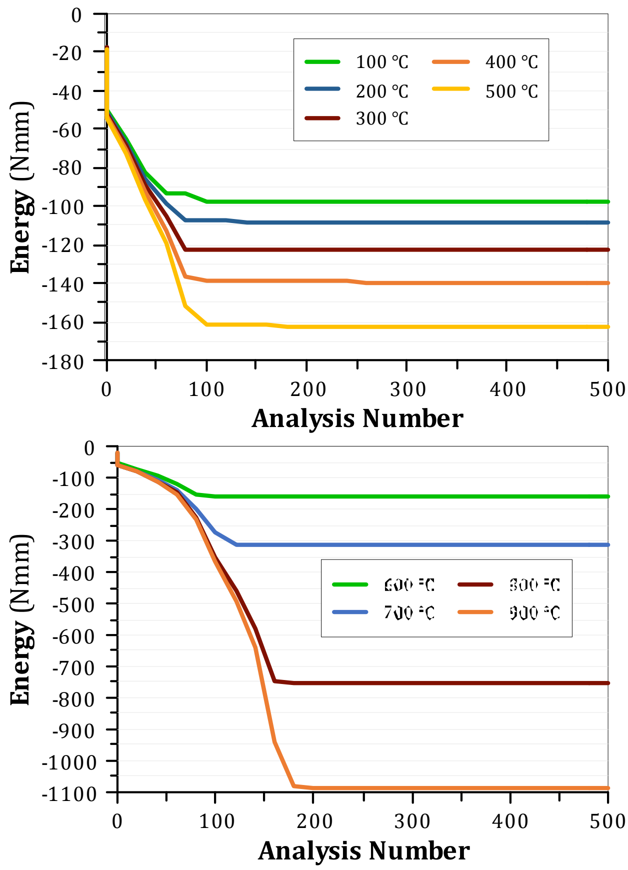

Fig. 5. Total potential energy values vs. analyses number

The second example is a plane truss system with 3 bars (Fig. 6). Cross-sectional area members, elasticity modulus and yield strength are taken as 15500 mm^2, 200000 MPa and 250 MPa, respectively. Load-displacement relationship of the system for temperatures (100°C-1100°C) can be seen in Fig. 7. In the inclination point the bar with number 2, is reached the yield strength value.

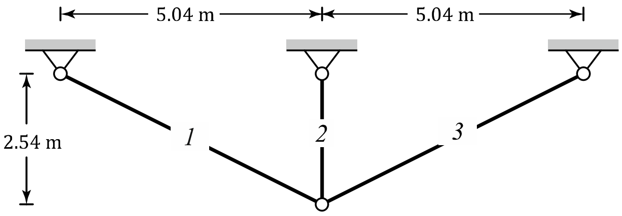

Fig. 6. Plane truss system with 3-bar [16]

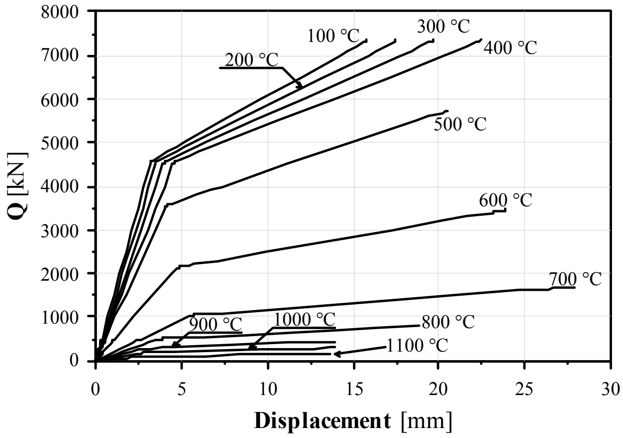

Fig. 7. Load-displacement relationship for different temperatures

In order to show accuracy effectiveness of the proposed approach, the analyses result are also compared with finite element method (FEM) and harmony search approach (HS). As seen from the results, same total potential energies is obtained for all methods (Fig. 8). However, proposed methods is suitable than HS in mean of computational cost (Fig. 9).

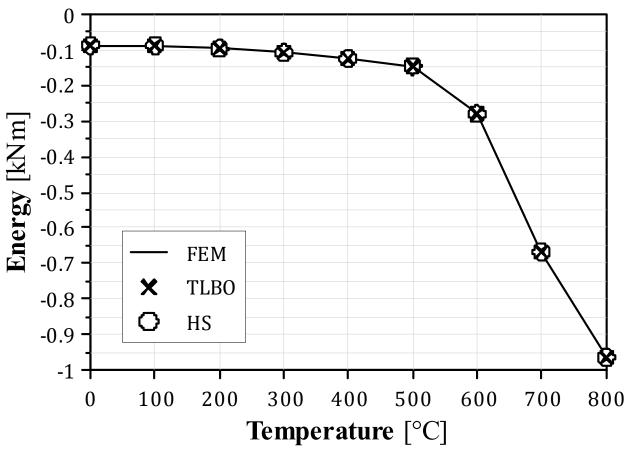

Fig. 8. Total potential energies for different temperatures

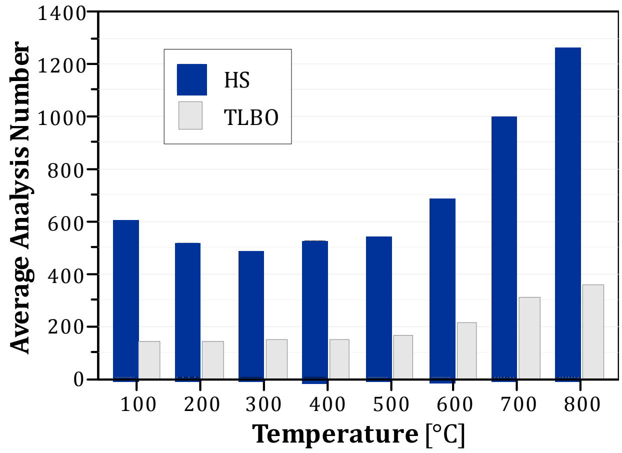

Fig. 8. Average number of analyses for different temperatures

For third example, the proposed methods is applied to a 6 bar plane truss system. Cross-sectional area for members 2-4 is 100 mm^2 and for members 1, 5 and 6 is 200 mm^2. Yield strength of the materials and load (P) are taken as 400 MPa (for 0.002 strain) and 5 kN (at node 4), respectively. Geometry and support condition of joints can be seen from the Fig. 9.

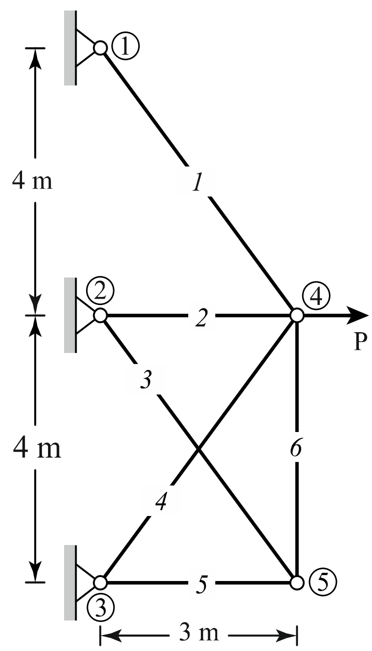

Fig. 9. Plane truss system with 6-bar

Displacements and temperature relationship for joints 4 and 5 for can be seen in Figs. 10 and 11. In the figures, u represents displacements in x direction and v represents displacements in y direction. As seen from the figures, although small displacement is obtained for low temperatures, displacements becomes much more than low ones for higher temperature conditions. The reason of this behaviour is caused from the decreasing the yield strength of the material by increasing temperatures (see Fig. 3). Thus, structural members are reached to yield strength for smaller loads due to the high temperatures.

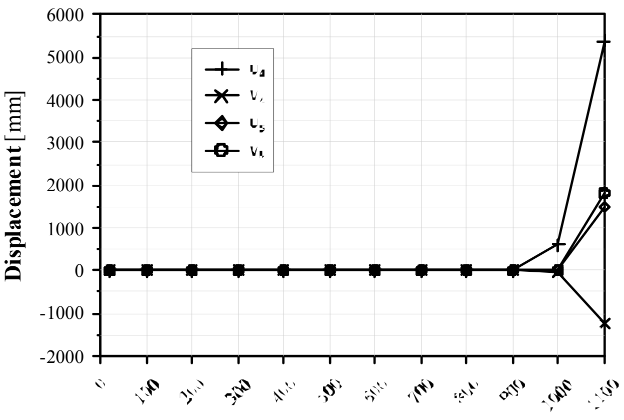

Fig. 10. Displacement values for temperatures between 20°C to 1100°C.

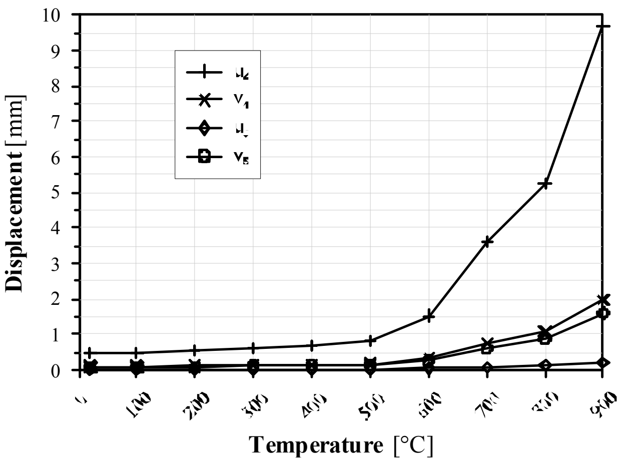

Fig. 11. Displacement values for temperatures between 20°C to 900°C.

In order to investigate, the effect of selected population number to total number of analyses that obtained optimum result, the analyses are repeated for population number 5, 10, 15 and 20, respectively. As seen from the figure, until population number 15, the required analyses numbers are decreased by increasing the population number and then it is begun to increase for population number 20. Consequently, the best population number is obtained as 15.

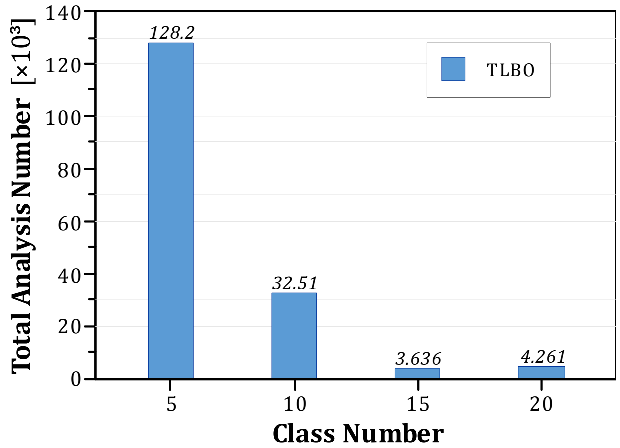

Fig. 11. Total number of analyses and population number relationship

4 Conclusion

This paper proposes a methodology called TPO/MA for truss analyses considering thermal effects. As metaheuristic approach a recently developed method called teaching-learning based optimization (TLBO) algorithm is employed. In order to prove effectiveness of the proposed method, the analyses are compared with finite element method (FEM) and with TPO/MA using harmony search (HS) algorithm as metaheuristic method.

According to analyses results, the proposed method is effective for finding accurate results. As seen from Fig. 8, compatible result are found for proposed method and FEM nonlinear analyses.

As known, computational cost is an important parameter for metaheuristic methods. Comparing to TLBO analyses number, HS approach needs approximately 10 times more analyses to find optimum results (see Fig. 8). Another important parameter for population based metaheuristic algorithm is population number used in the analyses (see Fig. 12). The effect of the population number is also investigated in the study. From the analyses results, the best population number is found as 15 for the problem.

As conclusion, the proposed method is effective, feasible, robust and accurate approach for this kind of problems.

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