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THERMAL DEFORMATION SUPPRESSION OF LARGE SMART STRUCTURE VIA ACTUATORS' FORCE OPTIMIZATION

A. Elsawaf[*], T. Vampola[a]

[*] Czech Technical University in Prague, Prague, Czech Republic
Helwan University, Cairo, Egypt
Email: elsawafahmed@gmail.com

[a] Czech Technical University in Prague, Prague, Czech Republic
Email: Tomas.Vampola@fs.cvut.cz

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Summary: *Nowadays, the improvement of smart structures offers great prospective for use in advanced aerospace and vehicle applications which are exposed to unavoidable thermal environment. This article deals with the optimization of the actuators' force in a smart structure in order to control the deformation caused by a thermal load. It is assumed that prescribed temperature distributions applied to the structure while sixteen actuators are placed on the upper surface of a large structure while elastic boundary conditions are imposed. The finite element analysis is used to model the structure and the problem is simulated with Matlab. The forces for all actuators are optimized using the particle swarm optimization technique (PSO) in order to control the maximum deformation induced. In addition, the PSO algorithm is improved to solve such optimization problem with unknown bounds for the design variables. The obtained results showed that the maximum deformation can be sufficiently reduced by the optimum design of the actuators force.*

1 INTRODUCTION

One of the predominant loads that space structures receive during space operation is thermal load. When a structure is subjected to a uniform or non-uniform temperature field, it normally reacts by producing deformations. These deformations are usually undesirable since they distort the structure and cause stresses when its component parts expand unequally. Moreover, the space structures deformation due to the thermal load can affect the spacecraft function [1-5]. A typical example is the thermoelastic distortion of the parabolic antenna, which is the main component of Microwave Radiometer Spacecraft and Synthetic Aperture Radar [3]. Another famous event occurred is the failure of the Hubble space telescope which experienced an unstable vibration and buckling induced by the rapid thermal flux change on the solar array.

Nowadays, smart structures are widely used in advanced aerospace applications, e.g., platforms, antennas, and telescopes which unavoidably exposed to a severe thermal environment. Important papers on smart structures mainly operating under isothermal conditions were surveyed [6-8]. Tauchert, et al. [9-11] reviewed key papers concerning smart structures which have been focused on control problems of a thermal displacement.

Optimization is an important issue designers faced every day to meet special requirements and ensure the best performance of a structure. Several works have been done for the optimum design of structure to suppress the thermal displacements/vibrations for example [12]. Others studied the optimization of a large structure. Fan and Xiang studied the structure optimum design of a large space structure for suppressing the thermal induced vibration [13]. However, Further studied on the optimization of a large structure is still needed.

The population-based optimization algorithms are becoming increasingly popular than traditional ones for solving complex optimization problems. The major difference between them that the traditional search techniques is start with an initial population, while the population-based optimization algorithms start with a single initial guess value. Therefore, the population-based optimization efficiently successes in finding global or near global optimum solutions while, the final result for the traditional optimization methods depends on the initial guess. Moreover, the traditional optimization methods are time consuming in solving nonlinear and complex optimization problems. Therefore, the heuristic search techniques, such as genetic algorithm, simulated annealing, particle swarm optimization algorithm (PSO), immune algorithm, and harmony search algorithms, are more effective than the gradient techniques in finding the global optimum. The advantages of PSO over other techniques that, it is algorithmically simpler, generally converges faster and more robust [14, 15]. Thus, PSO encouraged researchers from various backgrounds to use it in solving many optimization problems. Elsawaf et al. [16, 17] combined PSO with the simplex method to for an optimum structure design of a composite disk with single and multiple piezoelectric layers and to control the maximum thermal stress induced in the structural layer. Shabana et al. [18] applied PSO to optimize a nontraditional interface profile parameters so that the induced thermal stress in the structure was minimized. It was found that the stress can be minimized greatly using the obtained optimum values. For other application Metered, et al. [19] introduced an investigation into the use of a PSO algorithm to tune the PID controller for a semi-active vehicle suspension system incorporating magnetorheological damper improving the ride comfort and vehicle stability.

In this article, the thermal deformations in a large structure are minimized sing the PSO technique and applying the finite element analysis. Sixteen actuators are distributed on the top surface of the structure while a prescribed thermal load is applied. It is required to optimize the force applied to the structure from each actuator in order to suppress the thermal deformation to the fullest extent possible. A modification in the PSO algorithm is done to get along with the natural of the unknown bounds of the applied force. All numerical simulations are carried out using implicit FEM software package ANSYS and Matlab. It is found from the numerical results that, the optimized applied forces significantly reduce the deformations and hence increase the structural safety and reliability.

2 PROBLEM STATEMENT AND FILITE ELEMENT MODEL

Based on thermo-elastic deformation theory and finite element analysis software ANSYS, numerical analysis method are applied to resolve and analyze thermal-structural coupling deformation of the structure. The structure of length a, width b, and thickness h with a Cartesian coordinate system ($OXYZ$) having the origin O is considered in this study as shown in figure 1. For the finite element mesh, the element used is 20-node quadratic element and the number of elements is 270 and hence the total number of nodes is 1911 for the model.

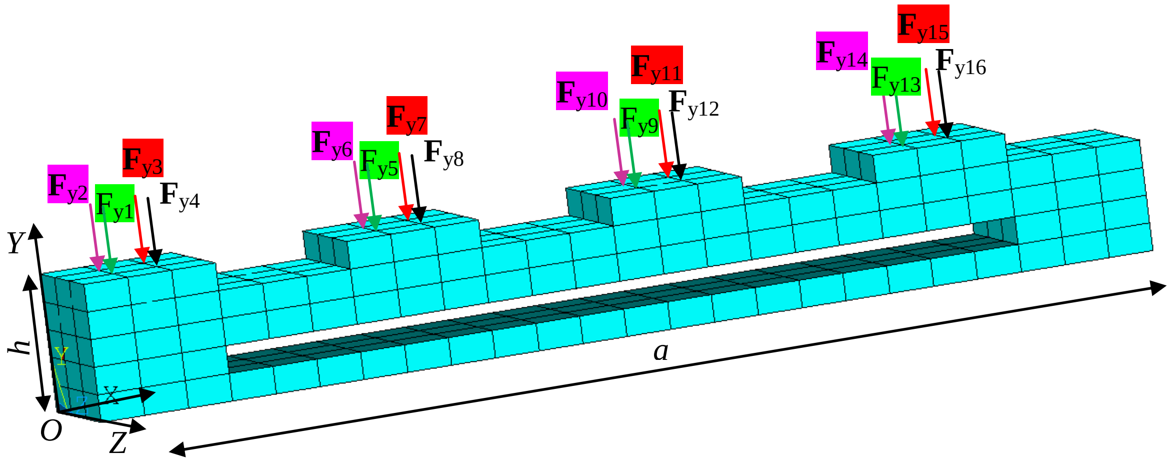


Figure 1: Finite element model with the applied forces.

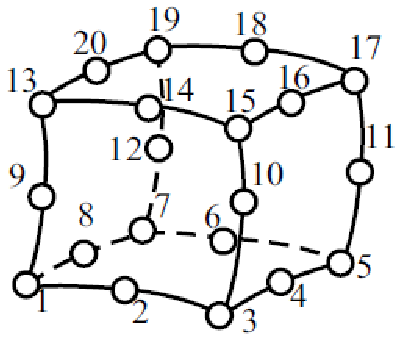


Figure 2: 20- nodes element.

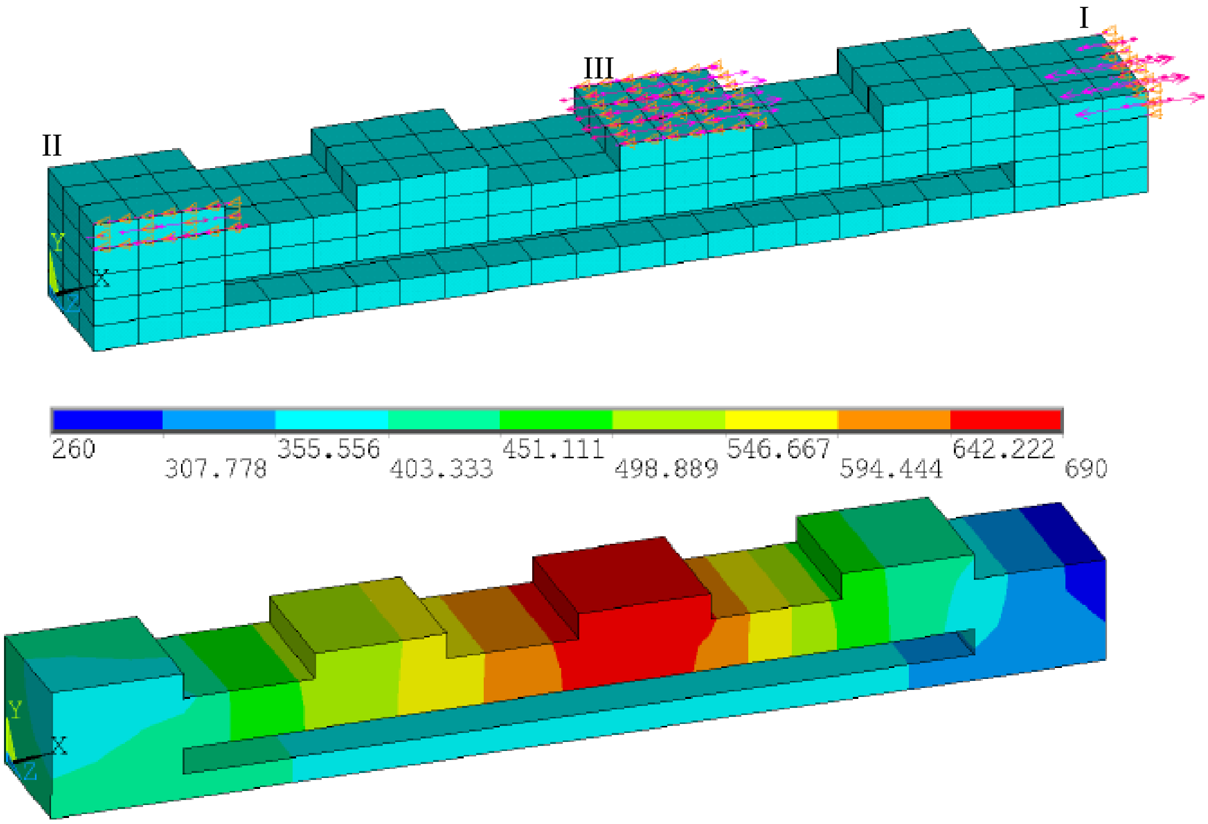


Figure 3: Temperature distribution applied acts on the finite element model (^oC).

The 20-node element is shown in figure 2 and each node have three degrees of freedom; translations in *X*, *Y* and *Z* directions. Some of the elements' nodes are fixed along the *X*, *Y* and *Z* directions as for the elastic boundary conditions. The 16 applied forces ($\mathbf{F}_{y1}$~ $\mathbf{F}_{y16}$) are distributed on the upper surface nodes as illustrated in figure 1. A detailed explanation about the formulation of the three dimensional finite element with Ansys software package can be found in [20].

For the loading conditions, the temperature boundary conditions (260,380,690 ^{o}C) acts at the position (I, II, III) respectively, and the corresponding temperature distributions are shown in figure 3. Due to the applied thermal load, thermal deformations will arise in each node and it is required to minimize these deformations for the safety of the structure.

3 OPTIMIZATION PROBLEM

Let us determine the forces ($\mathbf{F}_{y1}$~ $\mathbf{F}_{y16}$) applied to all the sixteen nodes illustrated in Figure 1, so that the maximum thermal deformation found form the 1911 nodes in the structure layer is minimized. This optimization problem is defined by

$$\left.\begin{array}{ll}\text{find} & \boldsymbol{W}=(F_{y1},F_{y2},\bullet\bullet\bullet,F_{y16}) \\ \text{to minimize} & f_{obj}(\boldsymbol{W})=\max|u_i| \ \text{ for } i=1\text{~}1911\end{array}\right\} \tag{1}$$

where $f_{obj}(\boldsymbol{W})$ is the objective function, $\boldsymbol{W}$ is the design variables required to be optimized and u_i is the thermal deformation at the node *i* in the *Y* direction. Since there are many local optima in the solution space, the particle swarm optimization (PSO) is employed to solve this problem.

3.1 PSO algorithm

PSO is one of the evolutionary optimization algorithms that took its inspiration from the biological examples and other social organisms' behavior originally contributed by Kennedy et. al, [21]. PSO algorithm optimizes a problem using a population (swarm) of candidate solutions (particles). The particles have their own positions and velocities, and fly around the problem space in swarms looking for best fitness value. Upper and lower bounds (UB and LB) of the design variables are predefined so that the particle will not fly beyond those bounds in the solution space. The particles are initially scattered in the solution space with initial positions within the predefined bounds and velocities. The position $\alpha_\beta^{(\tau)}$ and velocity $v_\beta^{(\tau)}$ of a particle β at the generation τ are iteratively enhanced in the solution space towards the optimum solution. Each movement of a particle is influenced by its local position $b_\beta^{(\tau)}$ and the overall best position $g^{(\tau)}$ obtained from the candidates in the solution space. When the process repeated for sufficient number, the best solutions eventually will be found. Eq. (2), shown the mathematical formula used for updating the positions and the velocities of the particles [22];

$$\begin{aligned}\alpha_\beta^{(\tau+1)} &= \alpha_\beta^{(\tau)} + v_\beta^{(\tau+1)} \\ v_\beta^{(\tau+1)} &= \chi \times \begin{pmatrix} v_\beta^{(\tau)} + acc_1 \times rand_1 \times \left[b_\beta^{(\tau)} - \alpha_\beta^{(\tau)} \right] \\ + acc_2 \times rand_2 \times \left[g^{(\tau)} - \alpha_\beta^{(\tau)} \right] \end{pmatrix}\end{aligned} \tag{2}$$

χ is the constriction coefficient, acc_1 and acc_2 are acceleration coefficients, $rand_1$ and $rand_2$ are random numbers between 0 and 1. The above mention optimization procedures with the PSO algorithm for the problem described in Eq. (1) are shown in figure 4.

3.2 Improvement on the PSO algorithm

As mentioned above the particles initial and the iteratively updated position are limited to the predefined UB and LB. If the updated particle's position has a value more than the UB then will modified to have the UB value instead. If the updated position has a value lower than the LB then it return to the LB value. The predefined UB and LB have a great influence in finding the optimum solution hence, it should be set probably. However, for some optimization problems the UB and LB are set wrongly due to the unawareness of the problem searching space and that would affect the quality of the solution.

In the studied problem the upper and lower bounds of the design variables (applied forces) of the optimization problem are difficult to define. Therefore, the UB and LB are modified to be flexible with no limitation on the updated particle's position as follows;

UB and LB are initially predefined then during the iteration process those bounds are updated according to the information transferred form the particles. If any of the particles find a best fitness value during the iteration process beyond the UB and LB, the particle is allowed to fly beyond those initial bounds and the UB and LB are modified.

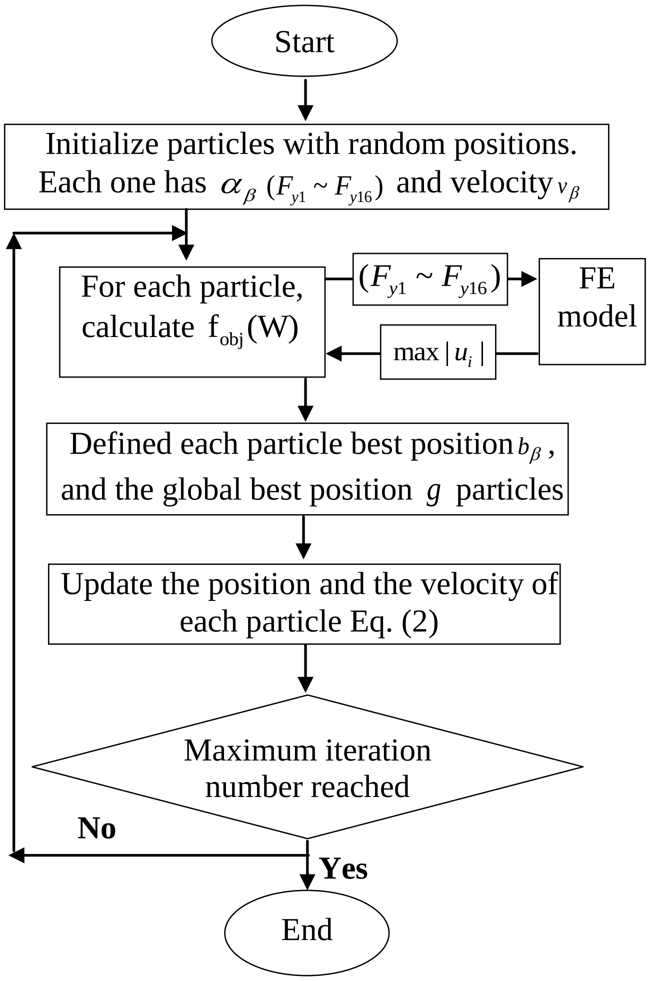


Figure 4: Optimization procedure flow chart.

4 NUMERICAL RESULTS AND DISCUSSIONS

The aim of this study is to minimize the deformation occurred in the structure due to the prescribed thermal load for the safety of the structure. This can be done by optimizing the applied forces on the upper surface of to the structure which was described in Eq. (1). The Ansys software package and the Matlab software are used for modeling and simulating the structure behavior of the structure. As mentioned previously the structure is meshed up to 270 elements with the 20-node quadratic element and the total number of nodes for the structure is 1191 nodes. It will be unreadable to show the deformation of the structure refereeing to those nodes. Therefore the deformations of the structure are shown with respect to the Cartesian coordinates. The length × width × height for the structure are 4(m) × 0.5(m) × 0.5(m). The deformations in the *Y* direction are only considered in this study.

Two materials have been studied for the structural which are steel and aluminum with the following properties:

	Young's modulus (Pa)	Possion's ratio (-)	Thermal expansion (1/K)	Thermal conductivity (W/m/K)
Steel	2.1e11	0.3	18.1e-6	33
Aluminum	0.7e11	0.35	23.1e-6	237

Table 1: Material properties of the structure (unit).

The thermal conductivity is considered to be equal in all directions. For, the elastic boundary conditions, the following nodes' positions are fixed from translation movement in the *X*, *Y* and *Z* directions given as in Table 2.

X	*Y*	*Z*
0 ~ 0.5	0	0 ~ 0.5
0	0.05	0
0	0.05	0.1667
0	0.05	0.333
0	0.05	0.5
0	0.1	0 ~ 0.5

Table 2: Fixed nodes in the X, Y and Z directions.

The initial UB and LB for the applied forces for both the cases of Aluminum and Steel are -100 (KN) and 100 (KN). The applied forces optimum values obtained by solving the optimization problem for both the structure with the St. and Al. are given in Table 3.

	$\mathbf{F}_{y1}$	$\mathbf{F}_{y2}$	$\mathbf{F}_{y3}$	$\mathbf{F}_{y4}$	$\mathbf{F}_{y5}$	$\mathbf{F}_{y6}$	$\mathbf{F}_{y7}$	$\mathbf{F}_{y8}$	$\mathbf{F}_{y9}$	$\mathbf{F}_{y10}$	$\mathbf{F}_{y11}$	$\mathbf{F}_{y12}$	$\mathbf{F}_{y13}$	$\mathbf{F}_{y14}$	$\mathbf{F}_{y15}$	$\mathbf{F}_{y16}$
Al	69.9	77.7	18.9	-33.2	24.4	-88.7	77.7	-81.8	63.0	64.7	-68.6	40.5	-8.0	-59.6	27.6	19.0
St	56.2	80.3	-86.9	-80.4	-26.4	3.6	-41.6	-39.9	48.7	-80.4	153.0	-28.0	41.9	42.1	25.5	-88.5

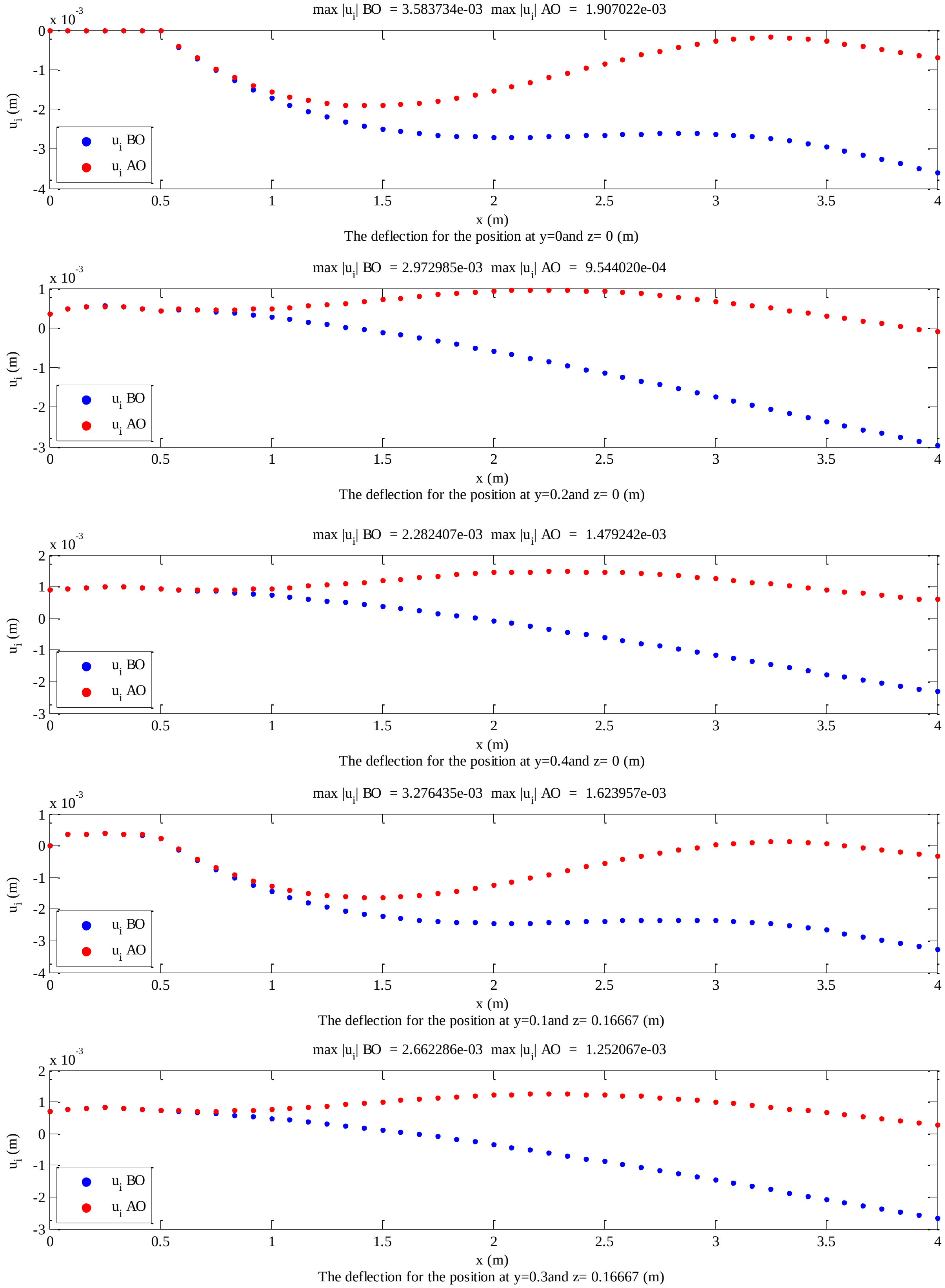
Table 3: Optimum forces obtained for St. and Al.

For convenience in presentation of numerical results, the numerical results obtained from solving the optimization problem given in Eq. (1) are shown at different positions as in the following figures.

It is seen that the optimum applied forces obtained are not restricted to the initial predefined bounds values.

4.1 Aluminum structure optimization

Figure 5 shows the structure deformations in the *Y* direction (u_i) before optimization (BO) and after applying the optimized force (AO) for different selected positions with Al structure.



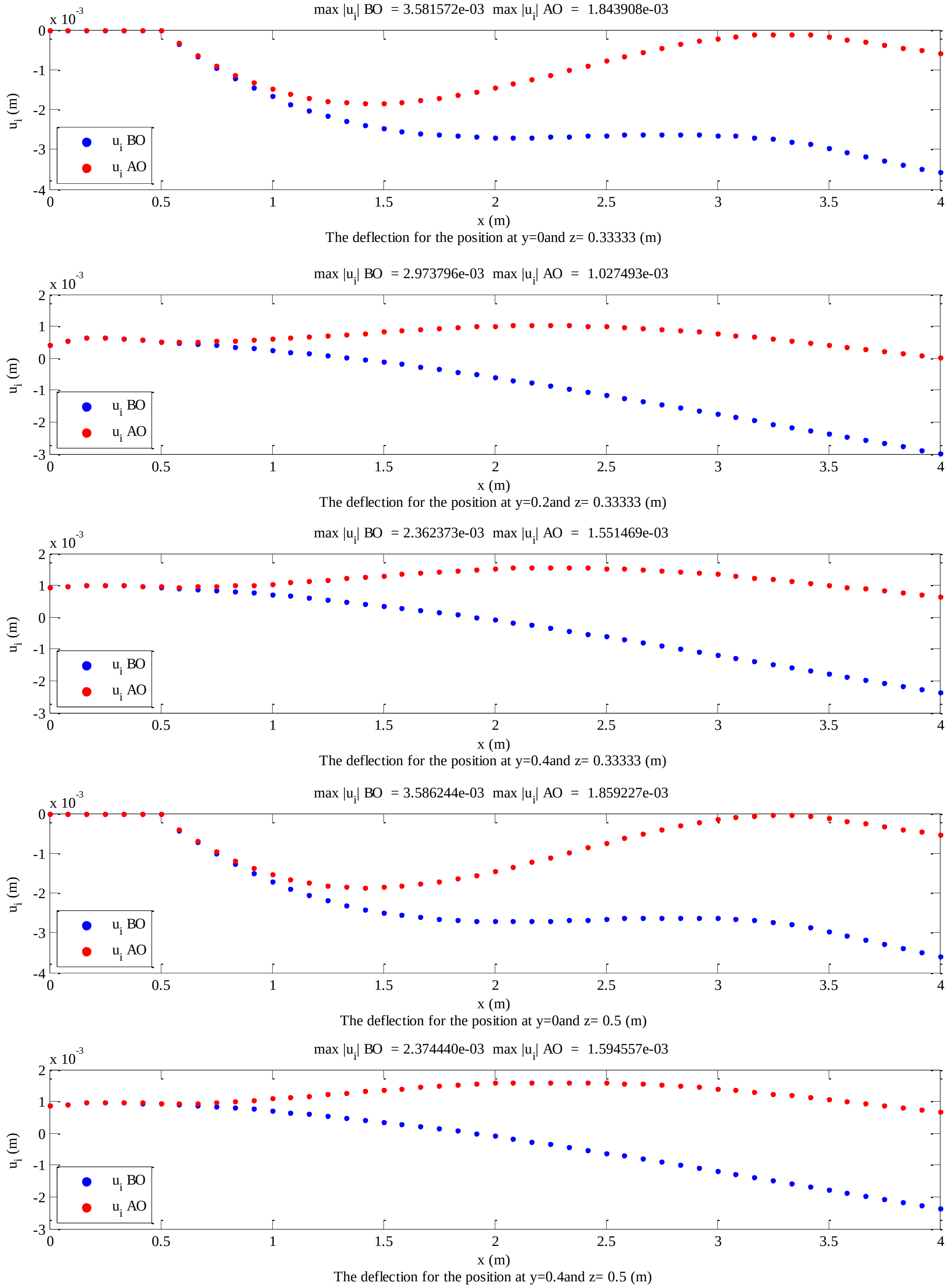
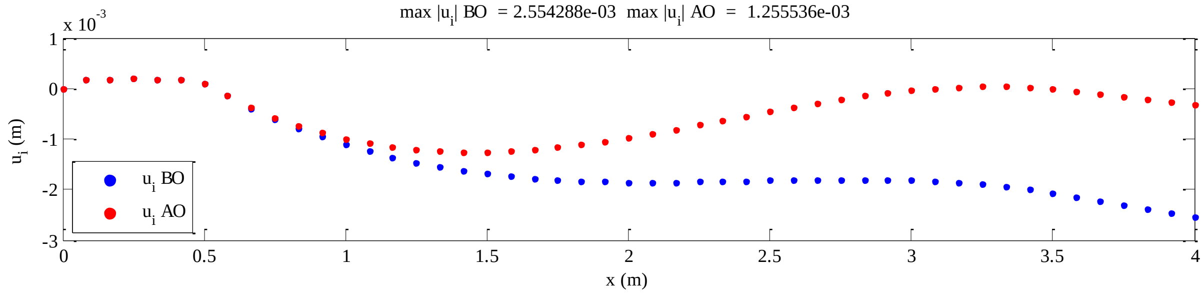


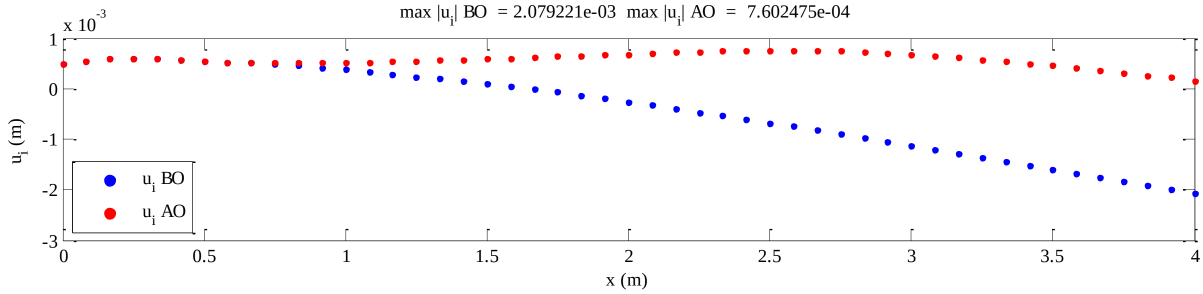
Figure 5: Structure deformations before optimization (BO) and after optimization (AO) for Al.

4.2 Steel structure optimization

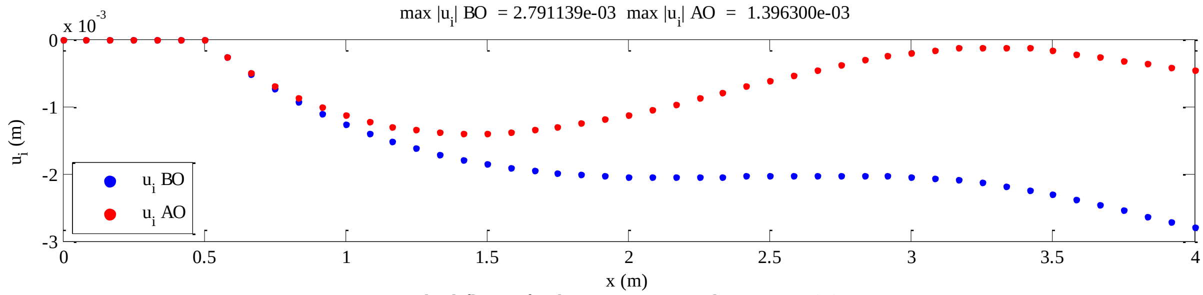
The optimization problem given in Eq. (1) have been also solved when the structure material is St. The numerical result for the structure deformations in the *Y* direction (u_i) BO and AO optimization in other different positions than chosen for Al are shown in figure 6.



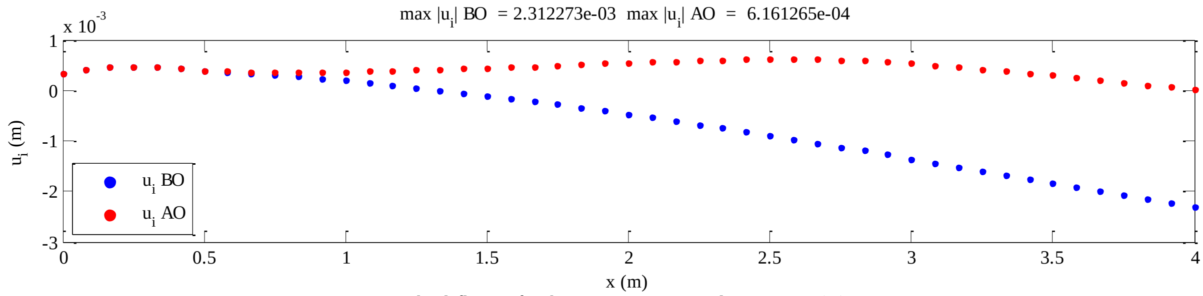
The deflection for the position at y=0.1and z= 0 (m)



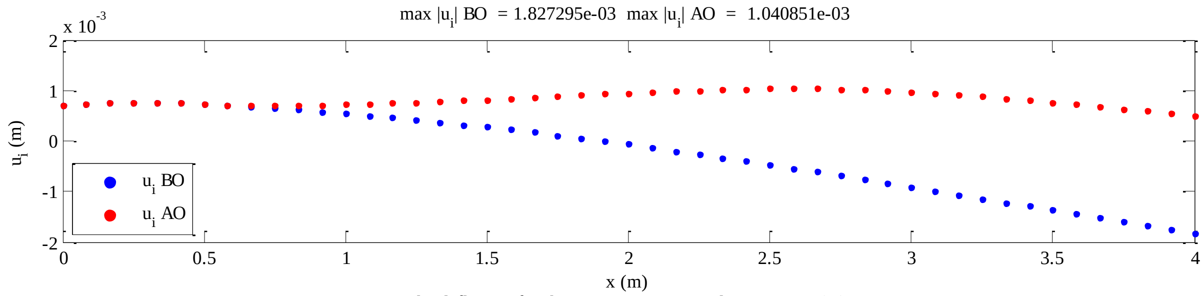
The deflection for the position at y=0.3and z= 0 (m)



The deflection for the position at y=0and z= 0.16667 (m)



The deflection for the position at y=0.2and z= 0.16667 (m)



The deflection for the position at y=0.4and z= 0.16667 (m)

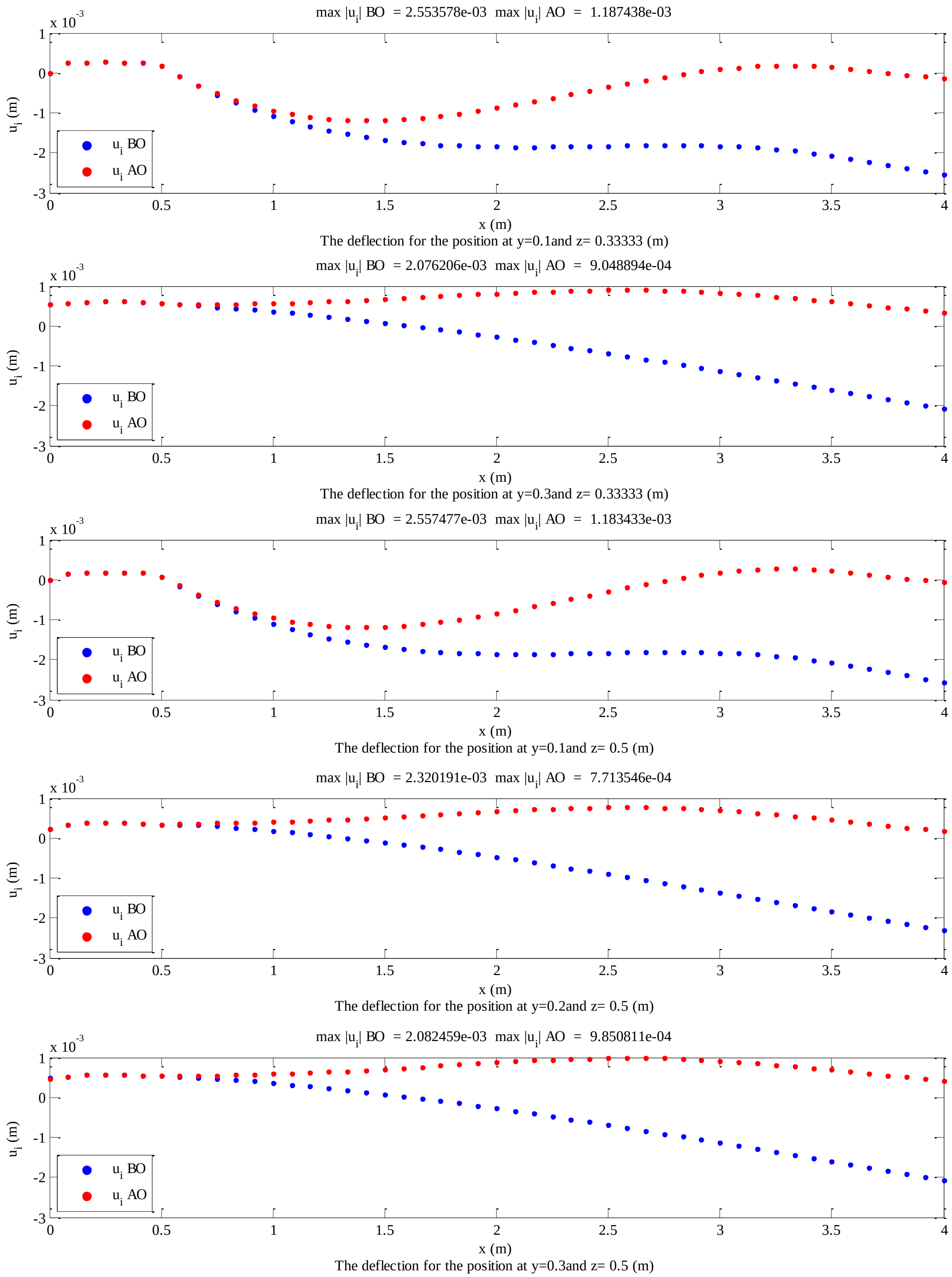


Figure 6: Structure deformations before optimization (BO) and after optimization (AO) for St.

Figures 5 and 6 show the structure deformations for all nodes in different positions for Al and

St respectively. The values of maximum thermal deformations before optimization (max $|u_i|$ BO) and after optimization (max $|u_i|$ AO) are written for each position. It is clearly seen from all the positions that those values have been effectively decreased.

9 CONCLUSIONS

In this paper, the optimization of sixteen actuators' force applied to a large smart structure in order to suppress the maximum thermal deformation induced from a prescribed load has been addressed. The finite element analysis is used to model the structure using the Ansys software package with 1911 nodes. The particle swarm optimization technique is employed for solving the optimization problem to search about the optimum values of the sixteen actuators force distributed on the upper surface of the structure. The particle swarm optimization algorithm was improved to overcome the unknown searching bounds for the actuators' force. The optimum values for the actuators' force were obtained for two different structure materials, used in this study, which is Aluminum and Steel. The numerical results showed that the maximum thermal deformations for different locations on the structure have been sufficiently reduced for all the positions and the two materials.

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