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Research Article

Modeling of thermal stresses on steel beam

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Abstract:

If the edges of a metal structure are subjected to a temperature difference, then because of the temperature gradient in the metal, thermal stresses will appear. To address this phenomenon, we will take the example of a steel beam, which is part of a metal construction. The geometry of the beam is regular and one end of it is subjected to a continuous emission of heat (for example, it is close to the oven) while the other end is in contact with the surrounding external environment. For simplicity, we will assume that the heat emission is constant, so the temperature of the edge of the beam is also constant. Likewise, for the temperature of the other end, we will assume that it is constant. Let the temperature of the first end be T_j, while that of the second end is T_i, then the difference $\Delta T = T_j - T_j$ causes the flow of heat, respectively the occurrence of thermal stresses. Mathematically, heat flow is described by a differential equation in the temperature field, while the functional dependence of the deformation is described by a differential equation in the field of structures - Hooke's law. So, we have two differential equations from two fields: thermal and structural. We have solved them with the finite element method in temperature-structure coupled field, while the simulation in ANSYS (ANSYS is a comprehensive engineering simulation software that is widely used for finite element analysis (FEA), computational fluid dynamics (CFD), and other simulation tasks.). The algorithm of the FE (Finite Element) method and the simulation in ANSYS prove that the treatment can be done for other integration conditions (geometry, material and different temperatures).

1. Introduction

Experience shows us that, when a metal construction is subjected to temperature changes, it is deformed (Figure 1) and in special cases even destroyed (Figure 2) [1].
To eliminate these consequences, when a metallic construction is subjected to temperature changes, then usually an empty space is left in the places where the metals are joined (Figure 3). The reason for the deformation or the destruction of the metal constructions is thermal stress. Thermal stress is the stress produced by any change in the temperature of the material in our case metal [2]. Thermal stress is induced in a metal construction when the temperature of the metal is raised or lowered, and the construction is not allowed to expand or contract freely. Thermal stress includes both heat and cold stress.

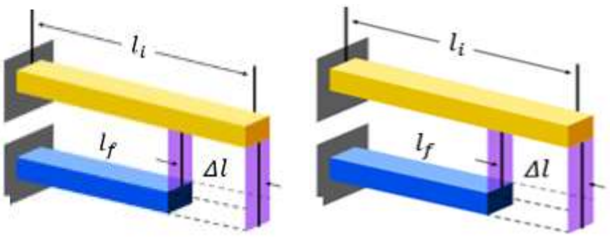
Figure 1. *Warped rails.*

Figure 2. *A broken metal beam.*

Figure 3. *Example of joining two metals plates on a bridge.*

2. Theory of thermal stress

If the metal beam is subjected to a change in temperature, then it shrinks (for the case when it cools) or extends (for the case when it heats up), figure 4. Let l_i be the length of the metallic beam at the initial temperature t_i, while at the final temperature t_f, we



a *b*

Figure 4*. Changing the length of the metal beam for the case when it cools (a) and for the case when it heats up (b).*

will mark the length of the beam with l_f.
The change in the length of the beam will be [3]:

$$\Delta l = l_f - l_i = \alpha l_i \Delta t$$

where is

$$\Delta t = t_f - t_i$$

and α is the coefficient of thermal expansion of metal in unit $1/K$.
For the case when $\Delta t = t_f - t_i > 0$ we will take $\Delta l = l_f - l_i => 0$ and for the case $\Delta t = t_f - t_i < 0$ we have $\Delta l = l_f - l_i < 0$.
In the first case, we say that during heating, the beam lengthens, while in the second, during cooling, it shrinks.
The beam strain will be [3],

$$\varepsilon_t = \frac{\Delta l}{l_i} = \alpha \Delta t$$

We have marked the strain with the index t to show that it depends on the temperature.
Based on Hooke's law, for thermal stress we will get,

$$\sigma_t = E \cdot \varepsilon_t = E \cdot \alpha \Delta t$$

E is Young's Modulus in unit $\frac{N}{m^2}$. From the last equation, it follows that the thermal stress σ_t also has the same unit of measurement $\frac{N}{m^2}$.

2.1 Investigation of thermal stresses

Of practical interest is the assessment of thermal stress. Many authors in their publications explain the ways of experimental evaluation of these stresses [4]. Well, for us in this paper the most important thing is the theoretical approach of recognizing and evaluating thermal stress. One of the most popular theoretical methods is the Finite Element Method (FE Method). There are many well-known treatments of thermal stress according to the FE Method. One of the known examples is the treatment of thermal stress in the sheet metal of the dome of the Church of Our Lady in Dresden (Figure 5) [5,6].

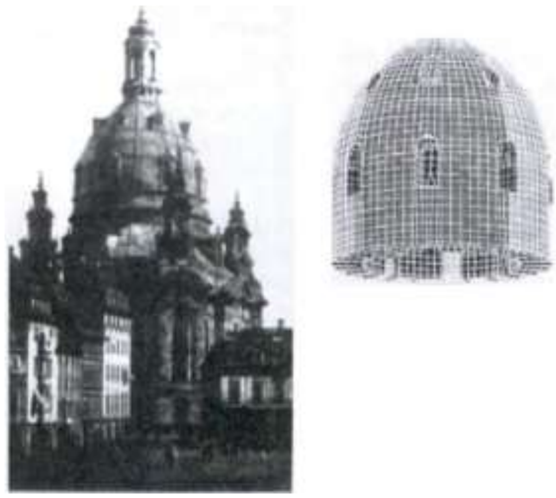


Figure 5. *Model of the dome of the church of Our Lady according to the FE Method.*

Usually, the models built according to the FE method are supported by the ANSYS application, which enables the recognition and evaluation of the thermal stress components [5, 6].

3. Modeling and results

The above example, we have treated according to the Fe method in the coupled mechanical-thermal field. According to this method, the matrix forms in the temperature respectively mechanical fields are, [6,7].

$$[\lambda] \cdot \{T\} = -\{Q\} \;\; ; \;\; [k] \cdot \{u\} = \{F\}$$

Where are:

[λ] - conductivity matrix
{T} - vector of o temperatures at the nodes
{Q} - vector of heat flow in the nodes
[k] - stiffness matrix
{u} - vector of nodes displacement and
{F}- vector of force in the nodes.

The complete equation of the couple fields' temperature structure is:

$$[k_t] \cdot \{u_t\} = \{F_t\}$$

Where

$$[k_t] = \begin{bmatrix} \lambda & 0 \\ 0 & k \end{bmatrix}, \{u_t\} = \begin{Bmatrix} u \\ T \end{Bmatrix} \text{ and } \{F_t\} = \begin{Bmatrix} F \\ Q \end{Bmatrix}$$

We have proposed a model with regular geometry with dimensions 0.5mx0.6mx10m (Figure 6) and constructed of steel. The physical characteristics of steel are thermal conductivity coefficient $\lambda = 45\ \mathrm{W/m \cdot K}$ [6] modulus of elasticity $E = 210000 \cdot 10^6\ \mathrm{N/m^2}$, [7] linear expansion coefficient $\alpha = 12 \cdot 10^{-6} \cdot {}^{1}/_{\mathrm{K}}$ [6] and Poisson's ratio $\upsilon = 0.3$ [8].
Let these be the integration conditions: for $z = 0$, the temperature is $t_i = 20$ °C, while for $z = 10$ m, let the temperature be $t_f = 100$ °C. We will assume that the temperature difference between the ends of the beam is constant $\Delta t = t_f - t_i = 80°\mathrm{C} = 80K$. While, as far as the mechanical conditions are concerned, we assume that for z=0 all the degrees of freedom are fixed, while for z=10*m*, only the degree of freedom y is fixed (the others are not because the beam can swell), (Figure 7). For these integration conditions and physical and geometric characteristics of the sample, the program was written in APDL [6]. The required solutions are the thermal stress distributions along different directions (Figure 8). As a result of the temperature difference, we have a flow of heat which causes the deformation of the crystal lattice of the metal and as a result, thermal stresses appear σ_t. To know the distribution of the thermal stress intensity along the length of the beam, according to the Fe Method, we must calculate the components of σ_t [9]

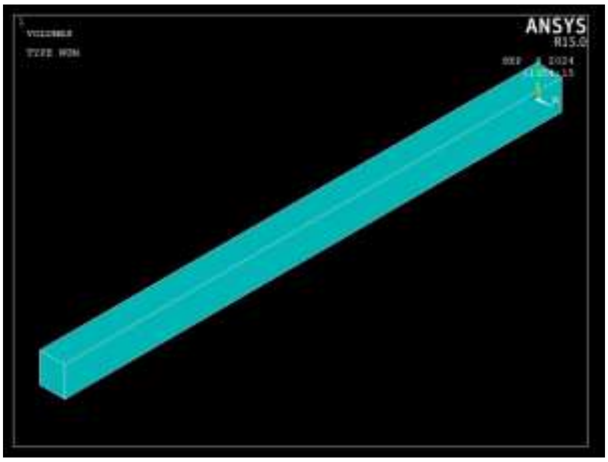


Figure 6. *The model in the workbench of ANSYS.*

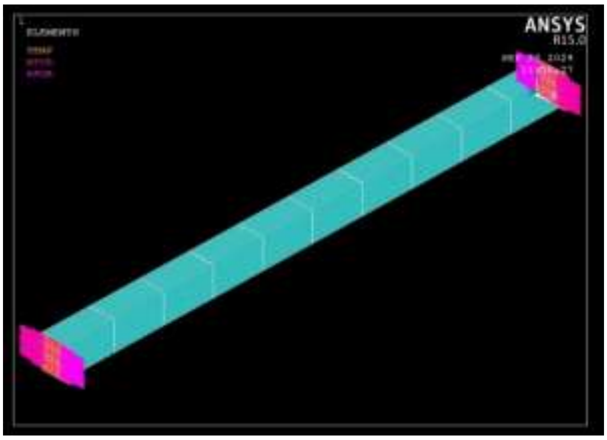


Figure 7. *Conditions of integration in the model.*

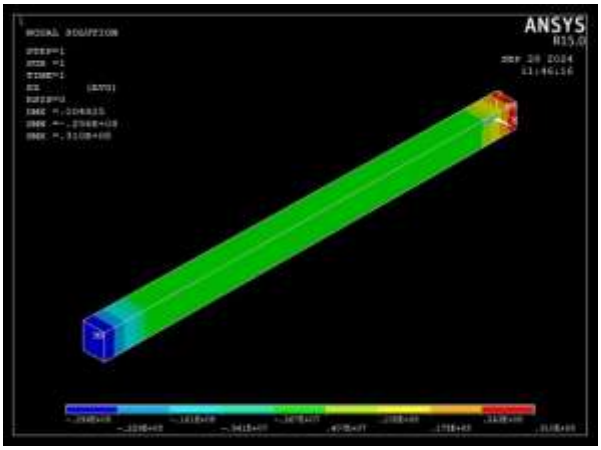


Figure 8a. *The distribution of stresses along the axis z.*

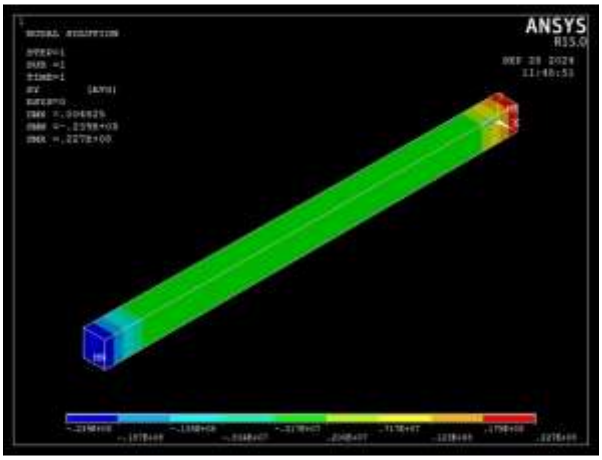


Figure 8b. *The distribution of stresses along the axis y.*

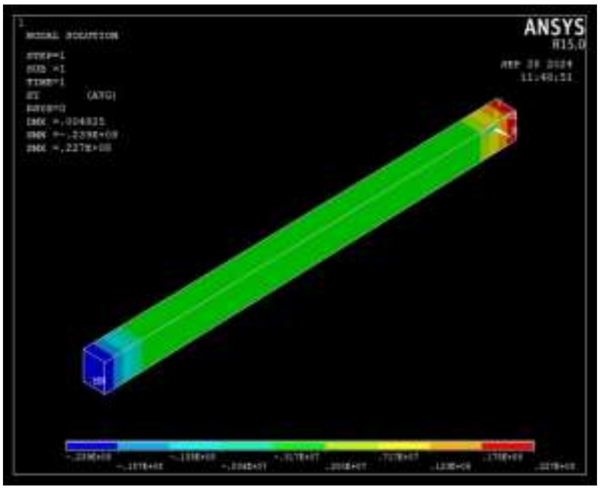


Figure 8c. *The distribution of stresses along the axis x.*

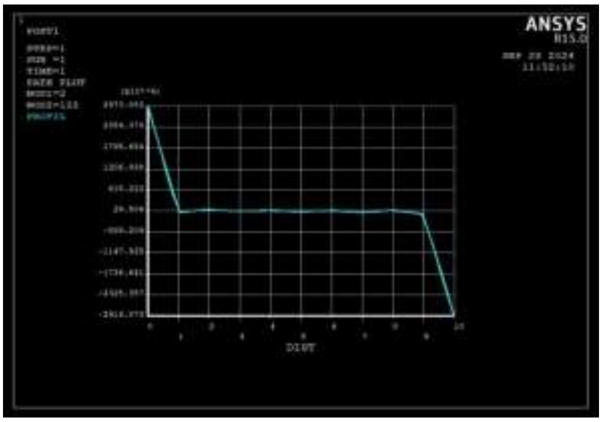


Figure 9. *Profile s(z).*

$$\sigma_t = \begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \\ \sigma_i \\ \\ \sigma_{n-1} \\ \sigma_n \end{Bmatrix}$$

Where $\sigma_1, \sigma_2, \ldots \sigma_i, \ldots\ldots \sigma_n$, are the components of the vector σ_t at nodes i.

and finally, in figure 9, we will present the distribution profile of the intensity of stress along the z axis [10]. It should also be noted that there a number of works done on steel and reported [11-16].

Based on the above text and the results (simulations), we can conclude the following:

- Thermal stress can be modeled with the FE method
- Thermal stress is modeled in the coupled fields' temperature structure
- Modeling is supported by the ANSYS software
- In the same manner, other cases can also be modeled (materials and other integration conditions)

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
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