ANNALS OF FACULTY ENGINEERING HUNEDOARA
– International Journal of Engineering
Tome XI (Year 2013) – FASCICULE 4 (ISSN 1584 – 2673)

[1.] Vladimir MILOVANOVIĆ, [2.] Dragan RAKIĆ, [3.] Miroslav ŽIVKOVIĆ, [4.] Snežana VULOVIĆ, [5.] Miroslav MILUTINOVIĆ

THERMO-MECHANIC ANALYSIS OF CEMENT TRANSPORT WAGON - IDENTIFICATION OF THE CAUSE OF CRACKS

[1-3.] FACULTY OF ENGINEERING, KRAGUJEVAC, SERBIA
[4.] METROPOLITAN UNIVERSITY, BELGRADE, SERBIA
[5.] UNIVERSITY OF EAST SARAJEVO, EAST SARAJEVO, FACULTY OF MECHANICAL ENGINEERING, BOSNIA & HERZEGOVINA

ABSTRACT: The paper represents a solution example of a specific engineering problem using thermo-mechanical analysis. The paper provides theoretical basis of numerical solving the problem of heat conducting through continuum using the finite element method. Calculation of heat conducting using the finite element method determines the temperature field used as an input for thermo-mechanical calculation. The basic task of thermo-mechanical calculation was the identification of the cause of cracks on the powder material transport wagon. After the analysis of the wagon crack causes, repair of the cracks is suggested. Repeating of the FEM analysis on the reconstructed model confirms that the wagon satisfies the criteria of static and fatigue strength appointed by the standards.
KEYWORDS: heat conducting, FEM analysis, cracks, wagon strength

INTRODUCTION

Modern constructions of various purposes as a rule represent a combination of thin-wall elements such as shells, plates or beams being under the influence of different type of loads. Some of these loads have a completely defined character and elaborate methods of calculations. Use of software for integrating of differential equations enabled solving numerous practical examples of continuum mechanics.

Finite element method – FEM represents the most general numerical method being unavoidable in solving scientific and practical examples in almost all the fields of the science and technics. FEM is today successfully used for solving the problem of physical quantities such as heat conducting, heat and mass transfer, fluid mechanics, electrotechnics and other.

The paper presents theoretical bases of numerical solving the problem of heat conducting through continuum using the finite element method. FEM analysis identifies the main causes of cracks on powder material transport wagon. Constructive solutions of crack repair are offered as well. Thermo-mechanical calculation of the strengthened construction should confirm that such strengthened construction satisfies the criteria of static and dynamic strength.

THEORETICAL BASES

Differential equation of the energy balance is based on the fundamental conservation of energy principle. Namely, change of the inner material energy in the unit of time, in elementary volume, is equal to the quantity of heat energy accumulated in that same volume in the unit of time, or it is valid for [1].

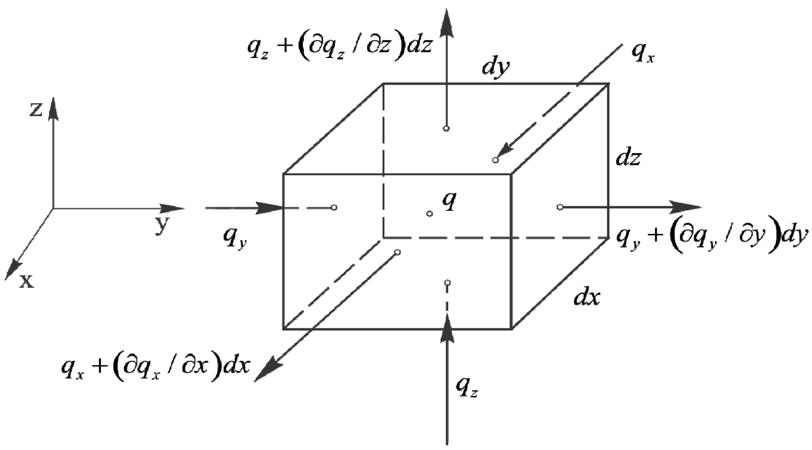

Figure 1. Elementary volume dV with heat flux components

$$\frac{dQ}{dt} = \frac{dU}{dt} \tag{1}$$

where dQ and dU are changes of the heat and inner energy in the volume dV in elementary time interval dt. Change of the inner energy can be formulated as:

$$\frac{dU}{dt} = \rho C_p \frac{dT}{dt} dV \tag{2}$$

where: ρ - material density, C_p - specific heat, a T - temperature. Using figure 1, dQ/dt can be formulated as:

$$\frac{dQ}{dt} = \left(q_x + \frac{\partial q_x}{\partial x}dx - q_x\right)dydz + \left(q_y + \frac{\partial q_y}{\partial y}dy - q_y\right)dxdz + \left(q_z + \frac{\partial q_z}{\partial z}dz - q_z\right)dxdy - qdV \tag{3}$$

where q_x, q_y and q_z are the components of heat flux vector. These components represent the heat quantity, which in the unit of time passes through the unit surface. Power of heat source q represents the heat quantity in the unit of time and unit of volume. In the equation (3) signs of flux components are considered. Positive sign corresponds to the positive flux projection on the direction of the outer normal unit vector on the surface whereas negative flux through the surface corresponds to the accumulation of heat energy dV . It is considered that $q > 0$ if there is a heat source in the volume dV (in the point of the material), but $q < 0$ in the case of the heat sink.

Heat conduction through continuum is defined by Fourier's law of heat conduction:

$$q_i = -\lambda_i \frac{\partial T}{\partial x_i} \qquad i = 1,2,3 \tag{4}$$

where λ_i , or λ_x , λ_y and λ_z , are coefficients of heat conduction in the case of orthotropic material. In the case of isotropic material, the following is valid:

$$\lambda_x = \lambda_y = \lambda_z = \lambda \tag{5}$$

Replacing (2) and (3) in the equation of energy balance (1) and using (4), differential equation for isotropic material obtains the following form:

$$-\rho C_p \frac{dT}{dt} + \sum_{j=1}^{3} \frac{\partial}{\partial x_j}\left(\lambda_j \frac{\partial T}{\partial x_j}\right) + q = 0 \tag{6}$$

In the practical problem solving it is the solution for the temperature field $T(x,y,z,t)$ that is searched for satisfying given initial and boundary conditions and representing a unique solution. Initial conditions are given only for unsteady problems and they mean that temperature distribution at the initial moment $t = 0$ is known:

$$T(x,y,z,0) = f_0(x,y,z) \tag{7}$$

Boundary conditions can be:

- *given fluxes on the contact surface:*

$$q_n = q_n(x,y,z,t) \tag{8}$$

- *given heat convection:*

$$q_h = h(T_0 - T_s) \tag{9}$$

Temperature T_s is surface temperature, T_0 is environment temperature, h is coefficient of convection. Using Galerkin method, differential equation (6) transforms into the equation of construction balance whose solving is presented in references [1-3].

PROBLEM DESCRIPTION

The analysis subject is the wagon used for powder material transport. Regarding the construction, manufacture and equipment, the wagon corresponds to the valid regulations defining this field: UIC, RIV and DIN.

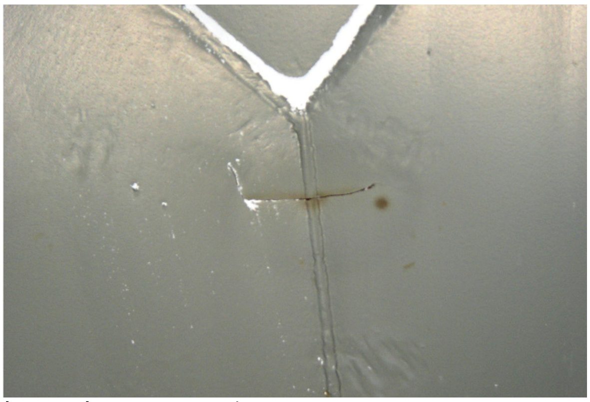

Figure 2. Observed cracks on the construction

Visual examination of the powder material transport wagon reveals the cracks on the joint of the first and fourth tank with the longitudinal girder (figure 2). Prior to the reconstruction, the strength of wagon was analyzed in order to determine the types of load present in exploitation conditions causing the cracks. Due to that reason, all the combinations present in exploitation conditions of the wagon were analyzed.

FEM MODEL DESCRIPTION

Wagon was modeled by using the software Femap [4], whereas the analysis was done in the software PAK MULTIPHYSICS [3] based on the finite element method. In accordance with the type of the construction shell elements of appropriate thickness and 3D finite elements were used to create finite element mesh.

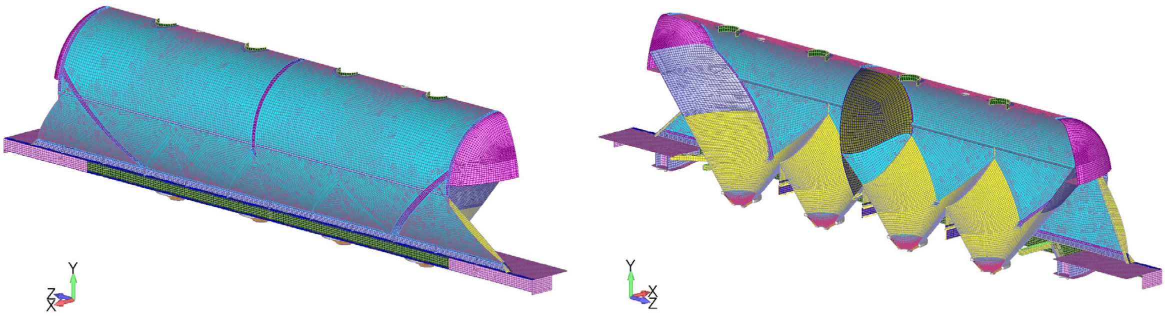

Figure 3. FEM model of wagon half

3D elements were used for modeling the support plate, relief ring and flange. Apart from the loads present in exploitation conditions, dead load of the wagon was considered as well. The construction was modeled in details with 60408 elements and 61176 nodes. For result presentation and better clarity, we used the half a model mesh without bogies (figure 3). Colors on figure 3 correspond to different thicknesses of shell elements.

CALCULATION VARIATIONS AND CRITERIA

In order to determine the cause of the wagon cracks in exploitation conditions, analyses of the wagon in all load combinations appearing in exploitation conditions were done. Performed calculations are:

- *thermo-mechanical calculation of the wagon during filling with heated cement*
- *thermo-mechanical calculation of the wagon loaded with cement of 50°C temperature, in motion*
- *calculation of dynamic strength due to the vertical load*
- *calculation of the wagon during motion in a curve*
- *calculation of the wagon during braking*

☐ THERMO-MECHANICAL CALCULATION OF THE WAGON DURING FILLING

Wagon is filled with cement up to the height of filling corresponding to the maximum allowed loading capacity of the wagon, 64.5t. Cement density is 1400kg/m^3. On the inner model side, which is in contact with cement, temperature increase is given corresponding to the temperature difference between the cement and surrounding. Three calculations were done with given temperature increases of 50°C, 80°C and 100°C. These temperature increases were used considering that the cement temperature ranges from 50°C to 80°C, and the temperature operating mode of the wagon is from -20°C to 50°C. The calculation of the heat conducting was done first to determine the temperature field on the whole wagon and then, the temperature field was used in thermo-mechanical calculation to determine thermal strains. It was given for the heat on the wagon top to be dissipated by convection whereas the heat transfer coefficient h=10 W/m^{2}K and heat conducting coefficient k=45 W/mK were used. The coefficient of linear expansion is given as a=12,6 10^{-6}1/K.

☐ THERMO-MECHANICAL CALCULATION OF WAGON LOADED WITH 50°C TEMPERATURE CEMENT DURING TRANSPORT

Thermo-mechanical calculation during filling determined a significant influence of temperature increase on stresses. For that reason, the calculation of dynamic strength due to the vertical load of heated cement was done. It was adopted that the heated cement causes the temperature increase of 50°C, as it was stated on the wagon. Also, in this case, vertical loads are increased for 1.3 times (30%), in order to include both thermal loads and dynamic loads during transport [6,7].

☐ CALCULATION OF DYNAMIC STRENGTH DUE TO THE VERTICAL LOAD

According to the standards TSI [5] and BS EN 12663:2000 [6], calculation of dynamic strength of freight car wagons due to the vertical load is done in the case of maximum allowed vertical load increased for 1.3 times (30%), in order to include dynamic loads during transport [6].

Based on the technical characteristics of the wagon, maximum vertical wagon load is obtained as the sum of maximum capacity of 64.5t and dead wagon load. Cement load of density 1400kg/m3 is given by using the pressure effective up to the height of filling.

☐ *CALCULATION OF THE WAGON DURING MOTION IN A CURVE*

According to the technical wagon characteristics, maximum velocity of the wagon with maximum vertical load is 100km/h, whereas the minimum radius of curve is 250m. Load of cement of density 1400kg/m^3 is given through hydrostatic pressure up to the height of filling, whereas the effect if inertial forces is considered by giving the adequate horizontal acceleration in the radial direction [6].

☐ *CALCULATION OF THE WAGON DURING BRAKING*

According to the technical wagon characteristics, maximum velocity of the wagon with maximum vertical load is 100km/h, whereas the stopping distance when braking is 700m. Load of cement of density 1400kg/m^3 is given through hydrostatic pressure up to the height of filling. Also, in this case, inertial forces are considered by giving the adequate horizontal acceleration in longitudinal direction.

CALCULATION RESULTS BEFORE RECONSTRUCTION

The analyses were done for all the variations of load defined in the previous chapter. Results are presented only for the most favorable combinations of load as a base for identification of the causes of cracks on the joint of the first and fourth tank with the longitudinal girder.

a. THERMO-MECHANICAL CALCULATION OF THE WAGON DURING FILLING WITH 100°C TEMPERATURE INCREASE

Three calculations were done with the temperature increases of 50°C, 80°C and 100°C on the inner surface of the tank in contact with warm cement. Heat conduction calculation was done in order to determine the temperature field on the whole wagon and then, the temperature field was used in thermo-mechanical calculation for thermal strain determination.

Effective stress field for the case of 100°C temperature increase is presented on the figure 4. Zone of maximum stress value is presented on the figure 5.

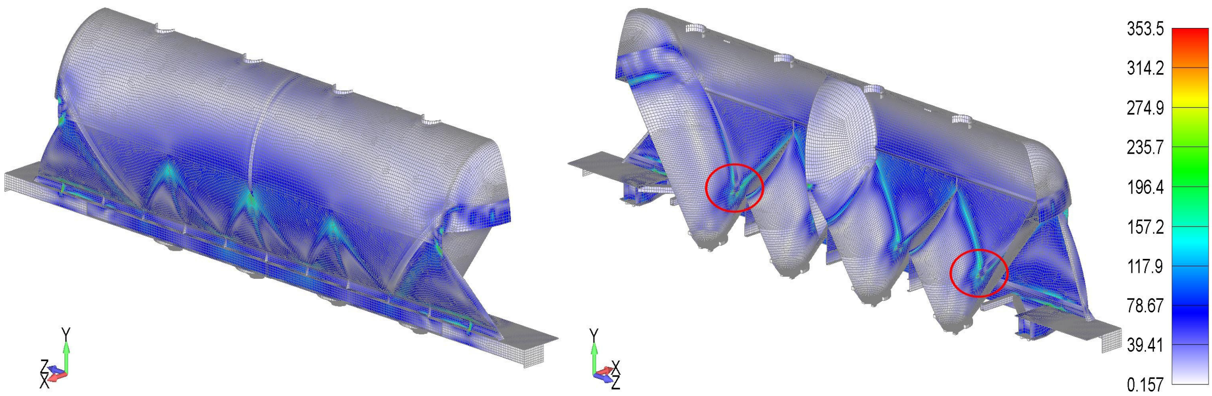

Figure 4. Effective stress field on the wagon half

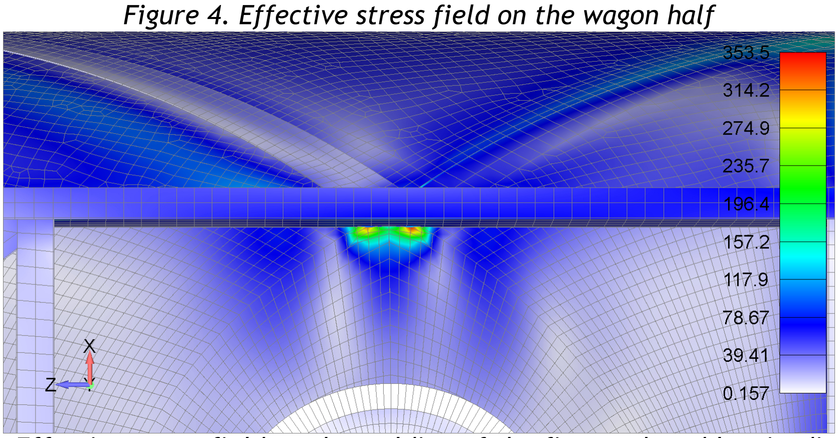

Figure 5. Effective stress field on the welding of the first tank and longitudinal girder

Maximum effective stress value is 353.5MPa being on the welding of the first tank for the longitude girder as seen on the figures 5 and 4, (marked details). Obtained stress is above allowed stress in the case of the static load [5-6]. Crack on this spot from the inner side is presented on the figure 2 to the right whereas the welding spot from the outer side is seen on the figure 2 to the left.

According to the obtained values, it can be concluded that the load in the case of high temperature increases has a significant influence on appearing of the cracks on the joint of the first and fourth tank with the longitudinal girder, (figure 5).

RECONSTRUCTION AND CALCULATION RESULTS OF THE RECONSTRUCTED WAGON

According to the analysis of the stress and strain cause of cracks on the joint of the tank and longitudinal girder are thermal loads.

Figure 6. Crack repair on the tanks

Crack repair is suggested on the cistern tank as well as the removal of weldings connecting the tank with the longitudinal girder (figure 6) with the clearance of at least.

b. THERMO-MECHANIC WAGON CALCULATION DURING FILLING WITH 100^{o}C TEMPERATURE INCREASE

Effective stress field in the case of 100^{o}C temperature increase, is presented on the figure 7. Figure 8 shows the effective stress field in the zone of repaired crack on the first tank. Obtained stresses in the whole construction, as well as the stresses in the zone of repaired cracks, are below allowed stress for the static loads [5-7].

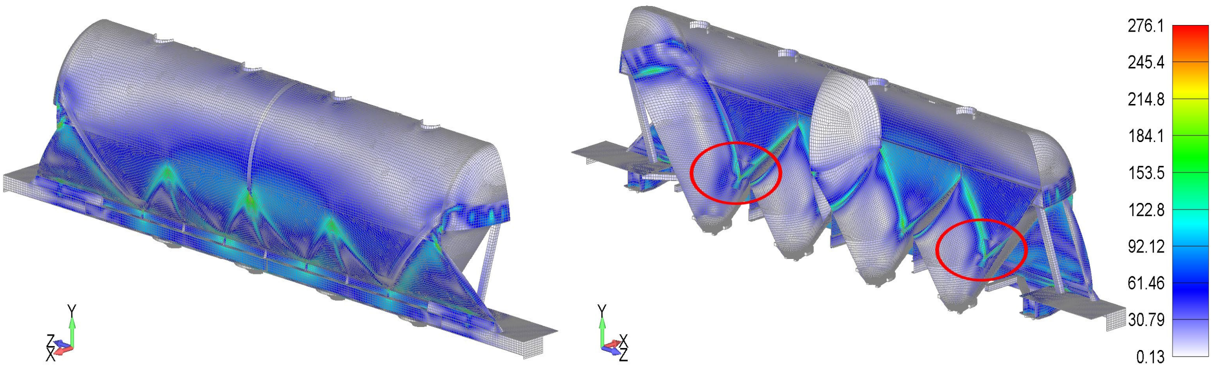

Figure 7. Effective stress field on the reconstructed model

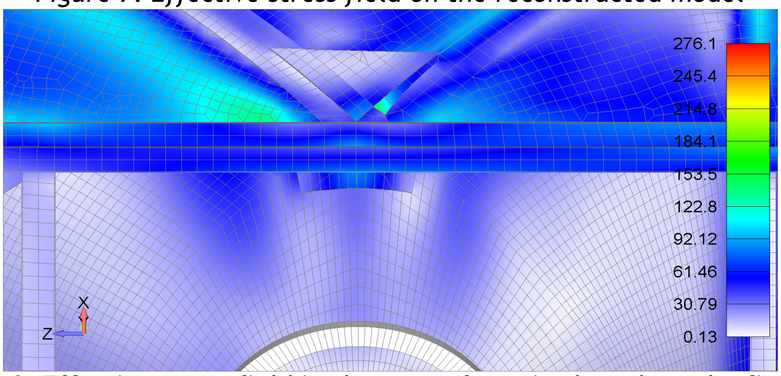

Figure 8. Effective stress field in the zone of repaired crack on the first tank

CONCLUSIONS

The aim of this paper was to discover the causes of cracks on the heated cement transport wagon from the presented basic equations for heat conducting, implemented in the program PAK MULTIPHYSICS. Thermo-mechanic analyses of the existing construction identified the combinations of load causing damages on the wagon. In order to solve the problem, repair of the tank cracks is suggested as well as the removal of weldings connecting the tank with the longitudinal girder so the clearance of at least 5mm is reached. Repeated analyses, for all the load combinations, confirmed that all the stresses in the construction, as well as on the repair spots, are below allowed values. According to the presented results, it can be concluded that the reconstructed wagon for powder material transport satisfies all the requests in terms of the static and fatigue strength appointed by the mentioned standards.

ACKNOWLEDGMENT

The part of this research is supported by Ministry of Education, Science and Technological Development, Republic of Serbia, Grant TR32036.

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