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REVISITED APPLICABILITY OF POLYMERIC COMPOSITE MATERIALS FOR DESIGNING TRACTOR HOODS

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Abstract. The paper shows the possibility of using composite materials for design and production of tractor hoods. A method for calculating thermal loads with allowance for convection and radiation in the underhood space and its application in thermoelastic calculation were developed. The results of the most thermoelastic calculation of the hood, taking into account its composite structure and using aeroelasticity approaches, are presented; the paper shows necessity to allow for thermal loads when designing a hood of a composite material. Application of the method described in this paper allowed calculating the hood deformation under constant thermal loads and showed the advantages of using a composite material.

Keywords: optimization, polymeric composite materials (PCM), aerodynamics, radiation, convection, thermoelasticity and aeroelasticity

1. Introduction

Mathematical modeling and calculations using aeroelasticity approaches (aeroelasticity or FSI Fluid-Structure Interaction – interaction of a fluid or a gas with a mechanical structure) [1], for designing structures and mechanisms in combination with the opportunity of using modern materials for their production allow significantly reducing the time of design and manufacturing of the final product. Besides, such an approach is used to solve the problem of product optimization in terms of reducing material consumption and minimization of consequences of possible critical situations, particularly connected with using polymeric composite materials, the thermal and mechanical characteristics of which can be selected by changing the number of layers, the laying angle, and the monolayer material.

Composite materials became widespread due to their lightness, wear resistance, durability, low heat conduction, and the possibility to give them any shape. A tractor hood made of polymeric composite materials (PCM) is 40% lighter than made of steel. Besides, composite materials provide the necessary rigidity, which helps to avoid a great change in the shape of the product and the effect of this change on other parameters, for example, on the aerodynamics of the underhood space [2].The possible use of PCM in the structure of the tractor roof is considered in paper [3], in which its high durability efficiency is shown. PCM attract many researchers and developers to studying their characteristics when using in various areas [4], however, most works in this area neglect the influence of temperature due to the considerable complexity of the necessary coherent calculation, and determining the thermal and thermodynamic properties of a composite material is not always possible. There emerges a need to create a method for calculating thermal loads and transferring these loads to thermoelastic calculation to determine the hood deformation.

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This paper considers the situation of emergency operation of a tractor engine turbocharger with composite panels. During emergency operation, the turbocharger becomes very hot, which significantly increases the temperature of the underhood space and due to heat exchange and radiation, the hood heats up strongly, which can cause its significant deformations. In its turn, such heating can affect the temperature inside the cab and the work of the tractor in general. Aerodynamics of the underhood space without heat exchange is considered in many papers, for example paper [5]. The finite element calculation of the underhood space with elements of the cooling system not taking radiation into account is considered in paper [6]. Thus, in many works, the strain-stress state calculation of a hood of a composite material is made but without allowance for conjugate heat transfer, for example in works [7, 8]. In contrast to the above-mentioned works, calculations in this paper are made taking into account the role of heat-mass exchange (heat conduction and radiant heat transfer).

Analyzing the air flow nature in the underhood space with allowance for heat exchange and radiation and applying the thermal and aeroelasticity approach for transferring thermal loads make it possible to calculate the hood deformation and, further, develop approaches for minimizing thermal loads in the case of an emergency.

2. Formulation of the problem

For aerothemodynamic and thermoelastic calculation, a simplified model of a tractor, is considered as an object of study. To calculate the strain-stress state, the shell model of the hood was used, which is shown in Fig. 1.

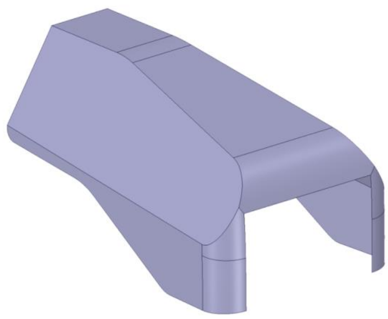

Fig. 1. Shell model of the hood

The calculation of aerodynamic characteristics was made at the tractor speed of 300 m/s. The temperature of ambient air was 300 K, the temperature of the engine turbocharger was taken equal to 1200 K, the temperature of the cylinder heads was 420 K.

Due to a large difference in the temperatures between ambient air and the turbocharger, radiant heat transfer should be taken into account. To calculate the heat exchange by radiation, the Stefan-Boltzmann law for gray body radiation is used:

$$q = \varepsilon\sigma(T_1 - T_2)^4, \quad (1)$$

- q is heat radiation from the border,
- $T_{1,2}$ is temperatures of the bodies,
- ε is a emissivity of the body, describes the deviation of body radiation from an absolute black body,
- σ is Stefan-Boltzmann constant.

The Lambert law, which describes the amount of energy radiated by area element dS_1 in the direction of element dS_2, is also applied (Fig. 2).

$$d^2q_\varphi = Q_n dS_1 d\omega \cos\varphi\,, \qquad Q_n = \frac{\sigma}{\pi}(T_1 - T_2)^4, \quad (2)$$

where: $\varphi -$ angle between normal $\omega -$ solid angle.

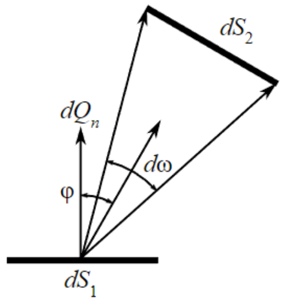

Fig. 2. Illustration of the Lambert law

With regard to the finite elements method or volumes, the general balance for the i-th element of the surface has the form [9]:

$$q_i = \varepsilon_i \sigma T_i^4 - \alpha_i I_i,\ I_i = \sum_{k=1}^{N} f_{ki} R_k\ ,\ R_k = \varepsilon_k \sigma T_k^4 + \rho_k I_k, \tag{3}$$

- α_i is the absorption coefficient of the i-th area element,
- I_i is radiation flux upon the i-th element area from the rest,
- R_k is effective radiation (emitted and reflected) of the k-th element area,
- ρ_k is the reflection coefficient of the k-th element area,
- f_{ki} is angle coefficients from the Lambert law.

The numerical calculation of the strain-stress state problems and aerodynamics was made using the ANSYS software package. In both calculations, stationary calculations were made to calculate the values sought. The strain-stress state problem was solved in a geometrically nonlinear formulation [10]. To demonstrate the difference between the linear and nonlinear formulations, let us consider the case of uniaxial stretching of a sample with initial area A with constant force P (Fig. 3).

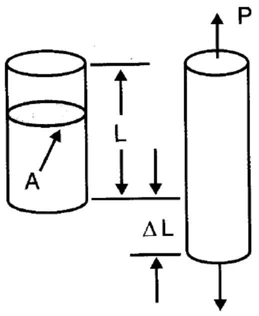

Fig. 3. Uniaxial stretching

True deformation is the result of the summation of infinitesimal deformations along the strain path of the sample:

$$\varepsilon_{true} = \int_L^{L+\Delta L} \frac{dL}{L} = \ln\left(1 + \frac{\Delta L}{L}\right). \tag{4}$$

In the case of $\frac{\Delta L}{L} \ll 1$, the expression for small deformations is obtained as it follows:

$$\varepsilon_{small} = \frac{\Delta L}{L}. \tag{5}$$

True stresses are the ratio of applied force P to the cross-sectional area at the given moment of deformation A', i.e. $\sigma_{true} = \frac{P}{A'}$. In the case of small deformations, when $A \approx A'$, $\sigma_{small} = \frac{P}{A}$. Since $A' < A \rightarrow \sigma_{true} > \sigma_{small}$. Which is very important when fracture criteria based on stresses are used [11].

3. Aerodynamic calculation

Due to the complexity of the geometry of the considered flow area, a Hexa-Core type finite element model with a boundary layer of 3 elements was created. The total number of elements in the computational domain amounted to 3.5 million. Aerodynamic calculation was performed by the control volume method with the ANSYS Fluent software package. The equations of continuity, conservation of momentum and energy were solved, and the air was considered an ideal gas, i.e. the constitutive equation has the form:

$$\rho = \frac{pM}{RT}, \tag{6}$$

where M is molar mass of air, R is universal gas constant.

Since the average Reynolds number for the given geometry is quite large, $Re \approx 9 \cdot 10^5$, the flow inside the hood is turbulent, i.e. it is not stationary [11]. To describe such flows in a stationary formulation, the Navier-Stokes equations, Reynolds-averaged, are used. The disadvantage of this approach is the necessity of closure of the set of Reynolds equations, which is commonly called the establishing of additional relations – the models of turbulence. In our case, the Spalart-Allmaras turbulence model serves as such a model [12]. The choice of this model is determined by its good numerical stability and the presence of only one equation, which significantly speeds up the calculation in comparison with models with two equations [11, 12]. Approximation in the initial equations was carried out by the method of second-order accuracy in space. The connection between the velocity vector and pressure components was made using the semi-implicit method for the equations with the connection by pressure – SIMPLE. To simulate the radiant heat transfer, the Discrete Ordinates model was used [13]. Based on work [14] and the Kirchhoff radiation law, the PCM absorption coefficient was taken to be constant and equal to 0.6.

As a result of the aerodynamic calculation for the hood, a temperature field was obtained, which is subsequently used to calculate the strain-stress state (Fig. 4).

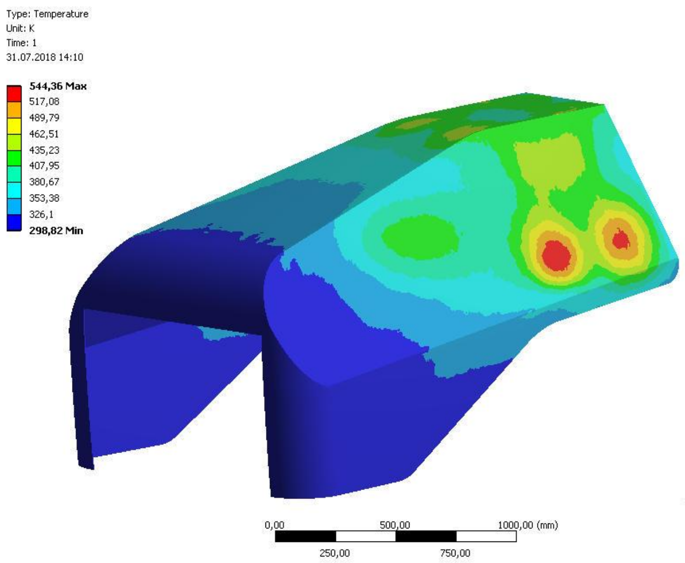

Fig. 4. Temperature field obtained for the hood

4. Mechanical testing of the composite material

For manufacturing the tractor hood, a foreign polymeric composite material (PCM) has been selected: Metyx glass mat, Metycore 600M/250PP1/600M with a binding substance based on polyester resin Dugalak Depol CP-700. To determine the physicomechanical properties of the composite material, its actual tests were carried out.

Tests of the samples given in Fig. 6 were carried out using the Zwick//Roell Z050 testing machine according to the method described in GOST 11262-80 "Plastics. Stretching test method". The actual conditions of the tests are given in Table 1. Photographs of the test are given in Fig. 5. Three samples of the material were tested.

Fig. 5. Appearance of the produced samples of the selected material

Table 1 – Test conditions

Parameter	**Value**
Testing machine	Zwick//Roell Z050
Date of tests	29.11.2017
Test location	OOO «Thermotechnology» laboratory
Environmental temperature	23°C
Relative humidity	55 %
Loading speed	10000 N/min

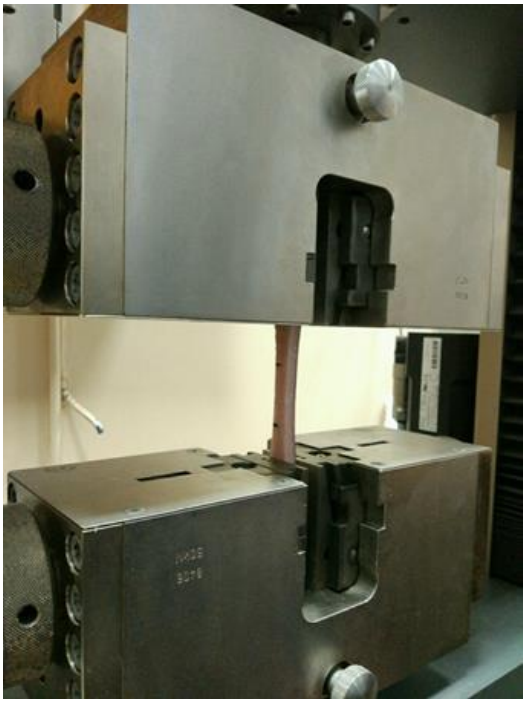

Fig. 5. Material sample in the clips of the testing machine

Figure 6 shows a photograph of the material samples after the tests.

Fig. 6. Destroyed samples after testing

As a result of the performed tests, "strain-stress" curves were obtained for the tested samples, one of them for sample A2 is presented in Fig. 7.

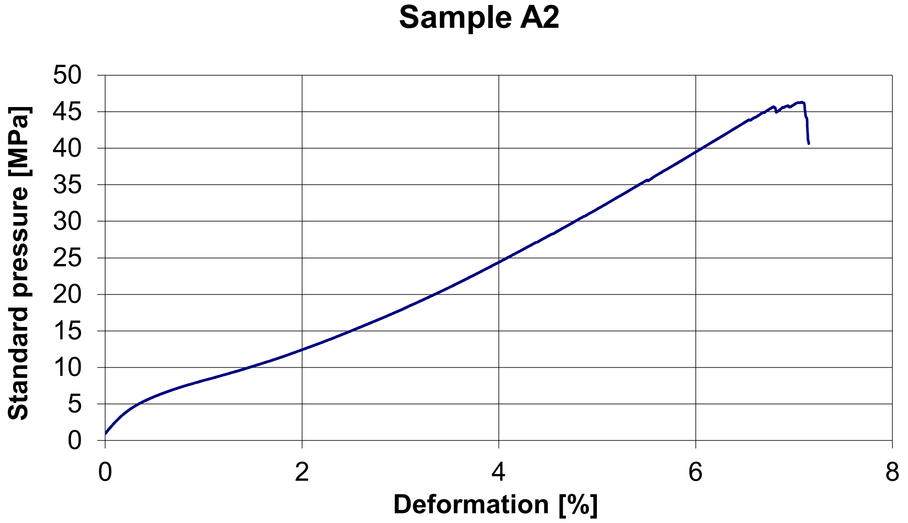

Fig. 7. "Strain-stress" curve of sample A2

5. Calculation of the strain-stress state of the hood made of PCM

According to the results of the tests, a mathematical model of the material was created. The physicomechanical properties of the presented material are given in Table 2. The thermodynamic properties are taken from [14].

Table 2. Physicomechanical properties of the material

Protocol parameter	Value
The elasticity modulus of the monolayer under uniaxial tension	6.7 GPa
The elasticity modulus of the monolayer under uniaxial compression	5.5 GPa
Poisson's ratio	0.35
The stress limit of the monolayer under uniaxial tension	46 MPa
The stress limit of the monolayer under uniaxial compression	40 MPa

This composite is an isotropic material, which means it has equal elasticity moduli and thermal expansion coefficients in each direction. To calculate the strain-stress state, a finite element model of the hood was created; sampling was done with the Shell elements 5 mm thick with the total number of elements equal to 250 thousand. The calculation was performed in the ANSYS software package in the Mechanical module. The previously obtained temperature field was transferred from the ANSYS Fluent module. The SHELL181 element type, which allows for final deformations, was used for the calculation.

6. Calculation results

During the calculations, a temperature field was obtained, which later was used to calculate the strain-stress state of the hood made of PCM. The displacements field for the hood in real scale is presented in Fig. 8.

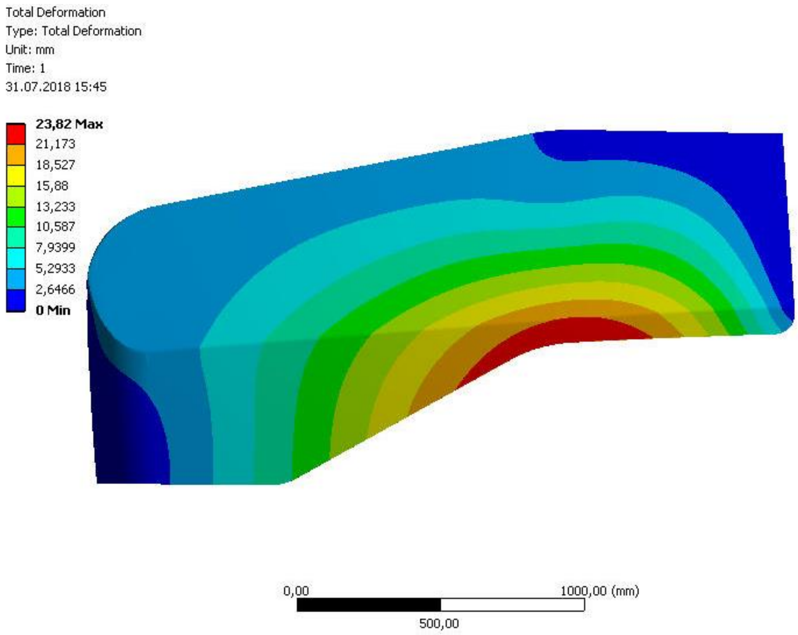

Fig. 8. Displacement field, mm

The maximum deviation is 23.82 mm which is approximately equal to 5 thicknesses of the hood. Such deformation is significant and can affect the aerodynamics of the underhood space. The maximum stresses at the fixing points exceeded, which means the destruction of the material at the attaching points. It can be seen that due to large deformations and partial destruction of the material, the necessity allow for such stresses at the design stage emerges.

In order to avoid the material destruction, it is suggested to increase thickness of PCM in the fixing points. Also, a possible solution to this problem will be a decrease in the PCM absorption coefficient, since the main contribution to the temperature field in this calculation is made by radiation, it is enough to change the color of the final product.

It is worth noting that when making the bonnet of classic materials, for example, aluminum, the material destruction will start to occur not only in fixing points but also in the points closest to the turbocharger. It is connected to the high heat conduction of classic materials, which gives higher thermal loads.

7. Conclucion

A method has been developed for the calculation of the tractor hood made of PCM with allowance for the influence of thermal loads due to the emergency operation of the engine turbocharger, and it has been shown that it should be used when designing tractor hoods. During the aero- and thermodynamic calculations, the temperature field was obtained and during the thermoelastic calculation – the displacement field.

It has been shown that the hood deformation under the action of thermal loads is significant and can affect the aerodynamics of the underhood space and the material integrity in the fixing points of the hood to the body. This result will enable creating a procedure of optimization of the underhood space to minimize the displacement field or thermal loads, and therefore, the stress field at the fixing points.

The obtained results showed the following advantages of PCM over classic materials: low weight, durability not inferior to classic materials, lower thermal loads due to low heat conduction, and ease in optimization. This gives reasons to consider high applicability of composite materials for the production of tractor hoods.

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