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APPLICABILITY OF POLYMER COMPOSITE MATERIALS IN THE DEVELOPMENT OF TRACTOR FALLING-OBJECT PROTECTIVE STRUCTURES (FOPS)

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Abstract. Analysis of application efficiency of polymer composite materials (PCM) in the development of tractors falling-object protective structures with the use of finite element method and modern systems of engineering analysis (CAE) is done. An elasticity and fracture model of composite materials is developed. A series of virtual crash tests of the tractor cab is carried for both cases with and without PCM. On the basis of this research, a methodology of designing PCM roofs for tractor cabs is developed.
Keywords: composite material, crash test, design, finite element model, tractor cab.

1. Introduction

Often tractors on the same platforms are used for different applications, e.g., agricultural and logging operations. However, the requirements to protective structures for tractor cabs to ensure protection from falling objects differ significantly, depending on the purpose of using a tractor. Development and production of a universal cab for both agricultural and logging operations is very expensive and inappropriate.

Trends in the global tractor industry also dictate the increased requirements to the tractor design. The tractor roof, as part of the falling-object protective structures (FOPS), is one of the design main elements. Using polymer composite materials (PCM) in the roof structure removes almost all constraints on its shape, which in its turn has a positive effect on the design. Due to mechanical properties of composite materials, besides the aesthetic function, it allows significantly decrease the impact from falling objects.

2. Goals and objectives

The goal of the project, funded by the Ministry of Education of the Russian Federation, is to develop a methodology for designing tractor cabs, taking into account regulatory and design requirements. The methodology approbation was carried out on the new generation of articulated tractors produced by Zavod SPETSTEHNIKI LTD (St. Petersburg) with improved safety, design, visibility and ergonomics, vibro-acoustic and climate comfort.

At the first stage of the project, a digital model of the tractor original design is developed to define layout constraints for the design. After that an updated exterior surface is developed; a cab frame structure being designed. Currently the work of refining the design and structural configuration of the cab is underway and shown in Figure 1 [1].

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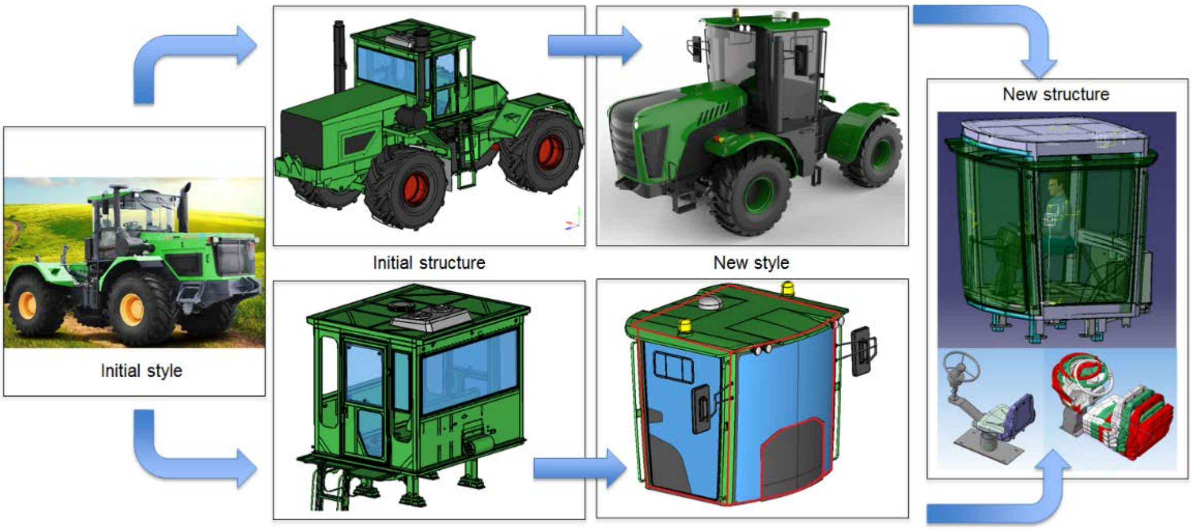


Fig. 1. New design development of a cab.

The purpose of this work is to develop a methodology for designing a unified falling objects protective structure of the tractor cab using polymer composite materials, capable to pass both level I and level II penetration protection tests [2]. To achieve this, the following problems are developed and solved within the current study for a tractor:

- finite element model (FEM) of falling-object protective structures (FOPS);
- elasticity and fracture model of composite materials;
- series of virtual FOPS crash tests;
- methodology of designing FOPS for reducing impact loads on a cab.

3. Finite element model of tractors FOPS

The cab roof was not initially taken into account, in the first version of the analysis and it was not modeled (Fig. 2a). In the second variant, the FEM included the roof with panel of the PCM (Fig. 2b). In this case, it has two functions: a full FOPS element and a design element (exterior panel). A FEM of FOPS was developed in the software package ANSA [3] for the purpose of conducting virtual testing. The FEM parameters are shown in Table 1.

a) *b)*

Fig. 2. FEM model of FOPS: *a*) traditional FOPS, *b)* FOPS from composite panels.

Table 1. FEM parameters.

№	Parameter	Value, traditional FOPS	Value, FOPS with PCM panel
1	Number of elements	154169	186388
2	Number of nodes.	172350	182245
3	Type of the elements	PSHELL	PSHELL
4	Calculation time	57 min	73 min

4. Composite material model development and verification

In the LS-DYNA software package there are several models of polymer composite materials. Comparison of the most popular of them is shown in Figure 3 [4]. To simulate the composite panel material type 22 *mat_composite_damage [5] was selected; it takes into account possible fractures of the material. The model allows define the properties of an orthotropic material with optional brittle fracture for composites [6, 7]. As a material for the tractor roof, three-layer structure is selected: glass Mat company Metyx, Metycore 600M/250PP1/600M, covered of both sides with fiberglass-type 120 and binder VSE-34. According to Ref. [8], for calculating the tensile strength and elastic modulus of fiberglass it is necessary to determine the physical and elastic-mechanical characteristics of its constituents: glass reinforcing filler and binder (matrix). The data of commercially available glass fiber reinforcement are widely presented in the literature [9-12]; on contrary, the matrices properties should be often determined experimentally. Characteristics of fiberglass and binder are given in Ref. [8].

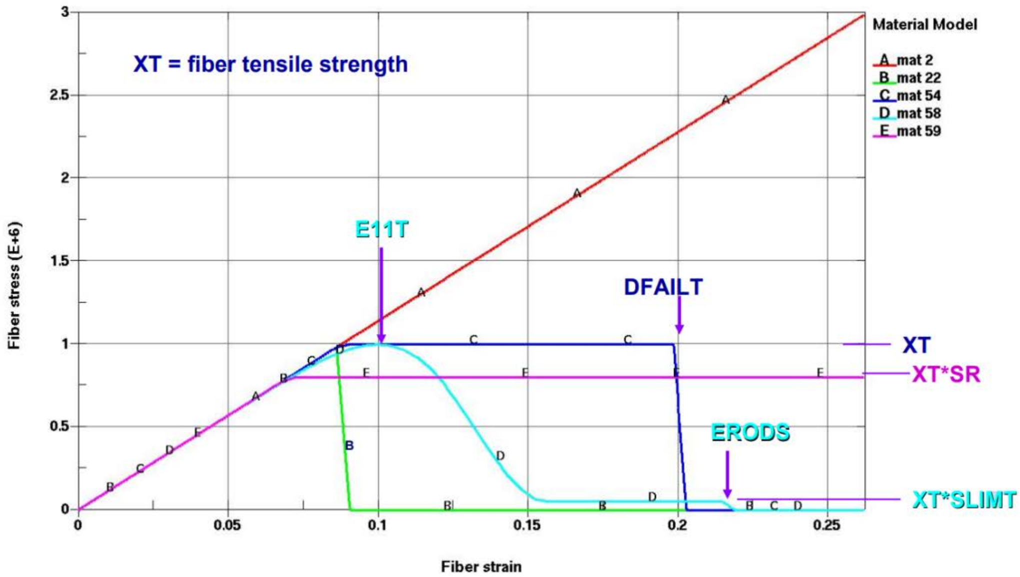


Fig. 3. Comparison of composite materials models.

MAT22 is based on a reduced Chang-Chang failure criterion, where elements are deleted when the Chang-Chang criterion is fulfilled. Chang and Chang [16] proposed a 2D failure criterion for unidirectional composite lamina which is as follows:

For tensile fiber mode: if $\sigma_{11} > 0$, then $\left(\frac{\sigma_{11}}{X_t}\right)^2 + \frac{\sigma_{12}}{S_c} = 1$;

For compressive fiber mode: if $\sigma_{11} < 0$, then $\left(\frac{\sigma_{11}}{X_c}\right)^2 = 1$;

For tensile matrix mode: if $\sigma_{22} > 0$, then $\left(\frac{\sigma_{22}}{Y_t}\right)^2 + \left(\frac{\sigma_{12}}{S_c}\right)^2 = 1$;

For compressive matrix mode: if $\sigma_{22} < 0$, then $\left(\frac{\sigma_{22}}{2S_c}\right)^2 + \left[\left(\frac{Y_c}{2S_c}\right)^2 - 1\right]\frac{\sigma_{22}}{Y_c} + \left(\frac{\sigma_{12}}{S_c}\right)^2 = 1$.

Here σ_{11} is the lamina stress in the fibers direction, σ_{22} is the lamina stress in the transverse direction to the fibers, σ_{12} is the lamina in-plane-shear stress, X_t is the fiber tensile strength and X_c is the fiber compressive strength, Y_t is the fiber tensile strength in the transverse direction and Y_c is the fiber compressive strength in the transverse direction; S_c is the in-plane-shear strength.

The material model *mat_composite_damage allows simulate the behavior of a layered structure that was also done in the present work.

5. Design of a PCM panel

The main function of the PCM roof panel at crash tests is to maximize the energy absorption from falling objects. Consider the panel as a simply supported plate. The strain energy resulted from plate bending in terms of deflections w(x, y) is:

$$U = \frac{1}{2}\iiint_V (\sigma_x\varepsilon_x + \sigma_y\varepsilon_y + \sigma_z\varepsilon_z + \tau_{xy}\gamma_{xy} + \tau_{xz}\gamma_{xz} + \tau_{yz}\gamma_{yz})\, dxdydz, \tag{1}$$

where V is the plate volume.

Using the hypotheses of the plate bending theory and integrating equation (1) along the thickness, we obtain the following expression:

$$U = \frac{D}{2}\iint_A \left[\left(\frac{\partial^2 w}{\partial x^2}\right)^2 + \left(\frac{\partial^2 w}{\partial y^2}\right)^2 + 2\nu\frac{\partial^2 w}{\partial x^2}\frac{\partial^2 w}{\partial y^2} + 2(1-\nu)\frac{\partial^2 w}{\partial x \partial y}\right] dxdy =$$
$$= \frac{D}{2}\iint_A \left\{\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2}\right)^2 - 2(1-\nu)\left[\frac{\partial^2 w}{\partial x^2}\frac{\partial^2 w}{\partial y^2} - \frac{\partial^2 w}{\partial x \partial y}\right]^2\right\} dxdy, \tag{2}$$

where A is the area of plate middle surface, D is the plate cylindrical stiffness.

Assuming that the deflection of plate faces is zero, we have the following expression for the plate potential energy:

$$U = \frac{D}{2}\iint_A \left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2}\right)^2 dxdy \tag{3}$$

From equation (3) it follows that the energy absorption of a composite roof plate can be increased both by enlarging the stiffness and by increasing the deflection. On the other hand, the maximum deflection is limited to metal beams of the FOPS structure (Fig. 4).

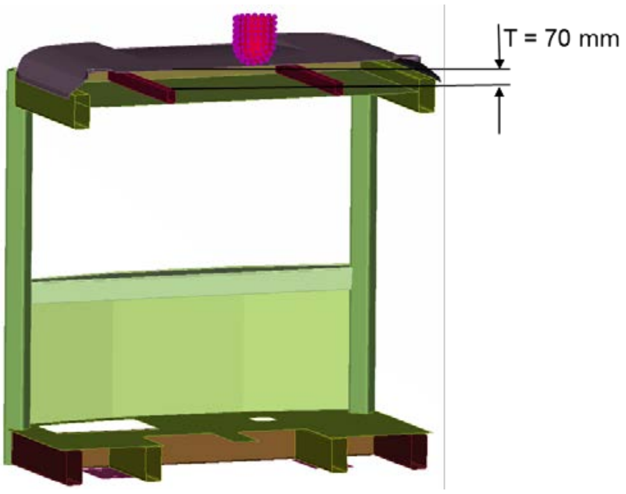


Fig. 4. Tractor FOPS in section.

Thus, it is important to choose the thickness and the material composition for the roof in such a way that its critical deflection, before fracture begins, does not exceed the distance from the roof plane to the FOPS beams. This parameter can be modified during the development of cab; in the current work it is equal to 70 mm.

A series of static tests was performed for a composite roof of different stiffness with various number of fiberglass layers (Fig. 5). Figure 6 shows the dependence of the roof panel maximum deflection on the PCM thickness. From the figure one can see that deflection 70 mm is achieved if the roof-material thickness is slightly less than 6 mm. This configuration will be used in subsequent calculations.

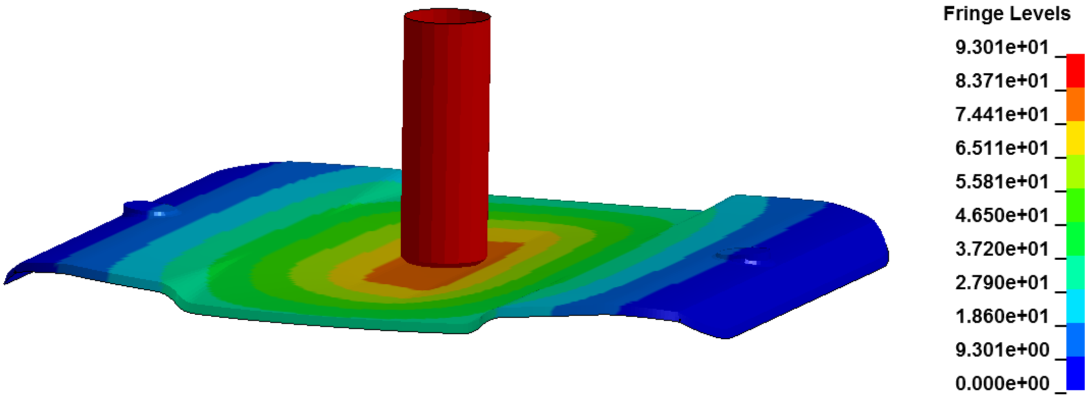


Fig. 5. Deflection of composite roof during static tests.

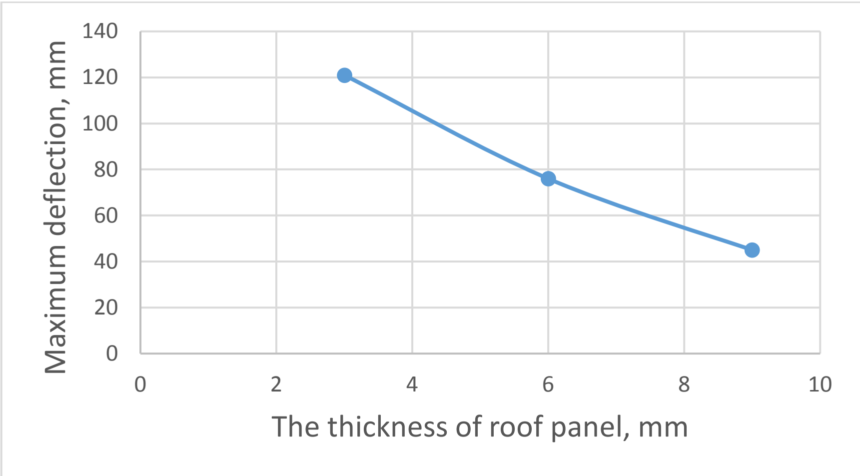


Fig. 6. Dependence of roof-panel deflection on PCM thickness.

6. Virtual tests

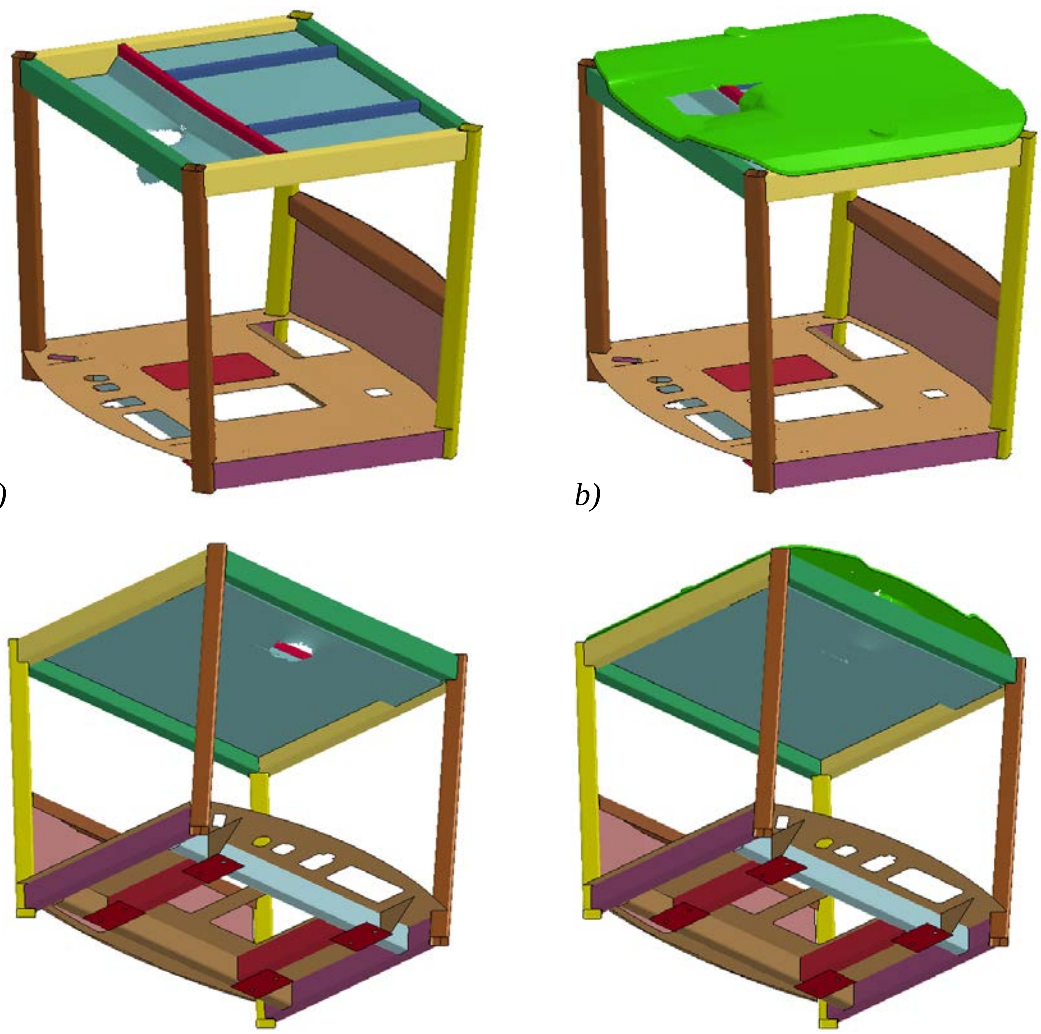
According to Ref. [13] the tractor FOPS can be divided into two categories: level I impact protection deals with the impact from small falling objects (e.g., bricks, small concrete blocks, hand tools, etc.) encountered in highway maintenance, landscaping and other construction site services; level II impact protection does from large falling objects (e.g., trees, rocks) for machines involved in site clearing, overhead demolition or forestry. In laboratory conditions, these tests are conducted by dropping a standard object (indenter) of a predetermined shape and mass from a certain height. The test parameters are given in Table 2.

Table 2. Test parameters for level I and II impact protection.

Impact protection level	Indenter parametrs		
	Form	Weight, kg	Drop height, m
Level 1	round	45	3,1
Level 2	cylindrical	227	5,22

One of the objectives of the present work is the development of a methodology for designing unified tractor cabs, according to the technical regulations of the Customs Union [14], which are able to ensure both the level I and level II impact protection. This cab will significantly reduce the cost of development and manufacture.

Both FOPS, investigated within the present work, pass the test of level I impact protection. Figure 7 shows tractor FOPS after a series of virtual tests for level II impact protection. The places for the test impact were selected according to [13] and [15].



a) *b)*

Fig. 7. Results of level II impact protection test, where *a*) traditional tractor FOPS, *b*) tractor FOPS with composite roof panels.

From Figure 7 it follows that the traditional tractor FOPS failed level II impact protection test, while the FOPS tractor with composite panel passed this test. Analyzing the data calculated for the FOPS of the tractor cab with a PCM roof, one can see that the FOPS have passed of the crash tests. The PCM roof of the cab collapsed at all the stages of testing, but the deflection of metal structures was reduced by an average of 30%, thus ensuring greater protection of a tractor driver. Applying an indenter in the crash tests of a PCM tractor cab roof panel, we have observed the decrease of its speed by 36% for level I impacts and by 16% for level II impacts at the moment of interaction. From this we can conclude that the PCM roof panels absorb a significant amount of the energy of a falling object, particularly 59% for level I impact protection tests and 30% for level II impact protection ones.

7. Conclusions

The results of the research presented in this work were used to design a universal tractor cab satisfying the requirements for level I and level II penetration protection (FOPS). The results were achieved through the use of PCM as the cab roof panel material. While remaining an important design element, the roof became a functional part of the tractor FOPS. A design methodology aimed at minimizing roof deflection on impact was also developed. In the future, PCM roof panels can replace traditional metal roofs through the use of new strengthened composite materials, by using thicker plates or implementing reinforcing metal insertions. As the result, reduction in materials consumption and overall weight of the cabs together with improved ergonomics (due to extension of the workspace) might be achieved.

Acknowledgments

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