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3D Computer Simulation and Research of the Geometric Parameters' Influence of Reinforcing Elements on the Stress State of Rectangular-Sectioned Fire Trucks Tanks

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Abstract
The stress state of tank structures of fire trucks that occurs during the movement to the place of emergency response is investigated. Rectangular-sectioned tank designs with a 1.2–1.6 times increased safety margin and an increased inter–repair period of at least 1.5–2 times have been developed and implemented in the emergency rescue units of the Ministry for Emergency Situations of the Republic of Belarus. Some results of design calculations of optimal geometric parameters of reinforcing elements of tank structures are given.

Keywords: fire truck, tank, design, motion mode, stress state, acceleration, computer simulation, stiffener, margin of safety.

1. Introduction

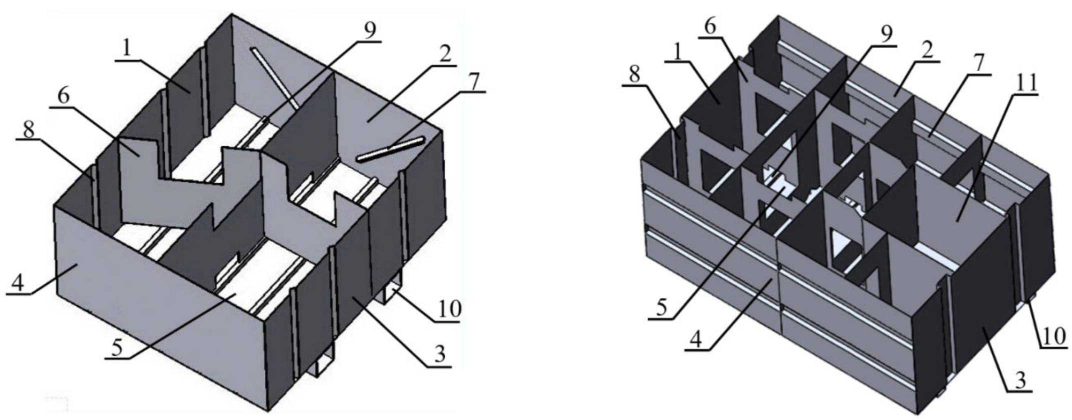
The analysis of the work of the emergency rescue units of the Ministry for Emergency Situations of the Republic of Belarus aimed at eliminating the consequences of different emergencies indicates that the time factor has a decisive influence on the fire growth and the extent of damage caused. According to the statistics, 98 % of the total number of deaths falls on the initial period of the fire growth [1]. One of the key factors in fire-frightening is timely arrival of emergency rescue units, which largely depends on the availability of modern and reliable equipment. The main utility vehicles include a fire truck, the number of which in the units of the Ministry for Emergency Situations in 2021 amounted to 2027 units. Among them 61.8 % were mounted on the chassis of the Minsk Automobile Plant (MAZ). The daily fire trucks route to the place of emergency situations occurs in the «acceleration», «braking», «turn» modes [2]. A large number of fires occur in rural areas, as well as in natural ecosystems. This makes it necessary to carry out the movement of fire trucks on country roads and also in off-road conditions [3]. Under such conditions, tank structures experience significant inertial loads transmitted through the chassis frame and from the transported liquid [4]. The analysis showed that a common cause of fire trucks repairs is in the violation of welded joints between the walls and the bottom of the tank. One of the ways to solve this problem is the scientifically based design of tanks, as well as the study of the stress level that occurs in the most critical nodes under various operating conditions of fire trucks, which is a complex technical task.

2. Research methodology

The object of the research is the most common models of tanks with a volume of 5 m^3 of fire trucks on the chassis of MAZ-5337 and 8 m^3 on the chassis of MAZ-6317. To assess the stress state of tank structures arising under various modes and conditions of fire trucks movement, a new calculation technique based on a two-stage approach is proposed, including experimental establishment of maximum values of accelerations arising under the action of inertial loads in tank structures and the development of 3D finite element models adapted to the modes of fire trucks movement [5–7].

To conduct the studies of acceleration magnitude, the parameters and conditions characterizing the features of the fire trucks movement modes to the place of emergency situations were determined: mode No. 1 – driving on a straight section of paved road at a speed of 50±2 km/h; mode No. 2 – driving on a dirt road of category VI-b with a permissible speed of 20–30 km/h [8]; mode No. 3 – driving on a straight section of paved road at a speed of 50±2 km/h, followed by slowing down the engine to a speed of 10–15 km/h to enter the left turn by 90°; mode No. 4 – acceleration from a standstill on a straight section of paved road to a speed of 30±2 km/h and emergency braking to a complete stop.

The creation of 3D tanks models with a volume of 5 m^3 of fire trucks on the chassis of MAZ-5337, as well as 8 m^3 on the chassis of MAZ-6317 on a scale of 1:1 were carried out in the SolidWorks software package (Figure 1), and the development of their finite element models together with calculation in the ANSYS software package.



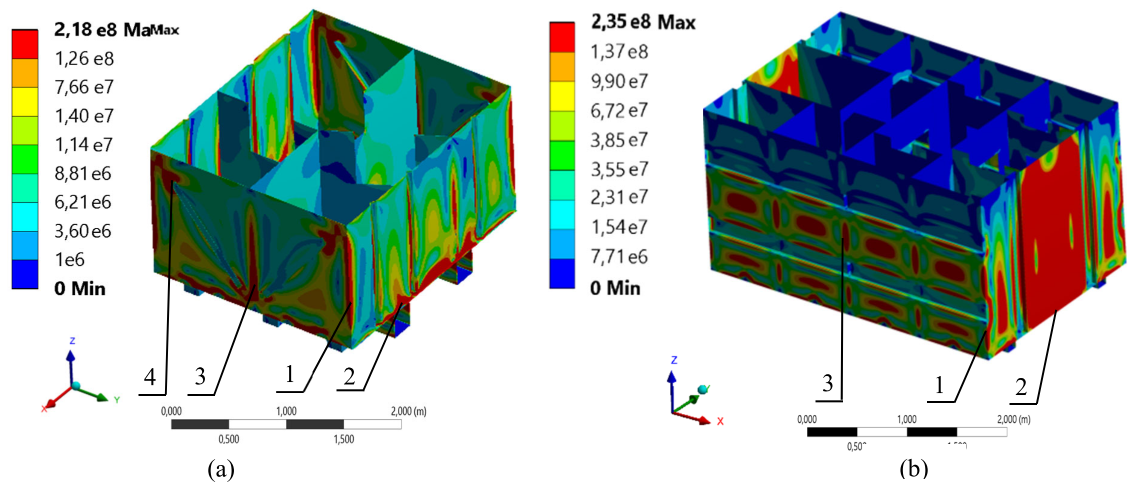
(a) (b)

1, 3 – front and back walls; 2, 4 – back walls; 5 – bottom;
6 – breakwaters (internal longitudinal and transverse); 7, 8 – stiffeners;
9 – transverse reinforcements in the form of U-shaped cross-section profiles;
10 – longitudinal spars; 11 – foam tank

Fig. 1. 3D models of mass production tanks with a volume of 5 m^3 (*a*) of fire trucks on the chassis of MAZ-5337 (view without roof) and 8 m^3 (*b*) fire truck on the MAZ-6317 chassis (view without roof)

Tank structures include internal breakwaters and elements that increase their strength (stiffeners), the bottom of the tanks rests on two spars through damping elements. The tank structures of the fire trucks are made of stainless steel AISI 430 2B [9]. Their developed finite-element models contain more than 300.000 of elements and nodes. For each mode of fire trucks movement the hydraulic pressure on the tank walls is set. The vector of the acting force (along the *XYZ* axes) and the density of the liquid, as well as the experimentally determined maximum acceleration value arising under the action of inertial loads in the structure were taken into account.

The calculation of 3D finite-element models of fire truck tanks allowed us to investigate the nature of the formation and distribution of stress fields arising in structures, as well as to establish the most loaded nodes (Figure 2) [6, 10].



3 – T-joints of breakwaters and walls; 4 – T-joints of stiffeners and side walls

Fig. 2. Models of field distribution arising in the construction of mass production tanks with a volume of $5 m^3$ (*a*) fire trucks on the MAZ-5337 chassis and $8 m^3$ (*b*) on the MAZ-6317chassis, Pa

The analysis of the obtained calculation results allowed us to establish that the major equivalent Mises stresses in the constructions of fire trucks tanks with a volume of $5 m^3$ on the MAZ-5337 chassis, as well as $8 m^3$ on the MAZ-6317 chassis, occur when the fire truck is on modeling mode No. 2 (movement on a dirt road of VI-b category with an acceptable speed 20–30 km/h). Moreover, the coefficient of safety margin for yield strength was, respectively, 1.1−1.3 and 1.2−1.5, which is not enough for structures of this type as operating experience shows. Accordingly, this mode of fire trucks movement has been adopted for further design calculations.

3. Design calculations

To increase the safety margin of fire truck tanks, a set of studies was carried out. It allowed us to develop a number of structural changes. To reduce the stresses arising in the areas of the tanks corner joints with a volume of $5 m^3$ of fire trucks on the MAZ-5337 chassis, it is proposed to use additional elements in the vertical plane at an angle of 45° to the neighboring walls such as reinforcing gussets in the form of a strip or corner. The studies of rational geometric parameters of reinforcing gussets were carried out according to the plan of a full factorial experiment. The length z_1, width z_2 and thickness of the reinforcing gussets z_3 were chosen as factors affecting the equivalent stresses σ (MPa). A regression equation has been compiled taking into account their interaction:

$$\sigma=123.96–5.46x_1–3.54x_2–1.63x_3+1.71x_1x_2–0.04x_1x_3–0.29x_2x_3–0.38x_1x_2, \quad (1)$$

where x_1, x_2, x_3 – coded factors z_i.

The significance of the obtained equation coefficients (1) is verified using the Student's criterion. The equation was also checked for adequacy according to the Fisher criterion. After switching from coded variables to natural ones, the equation took the following form:

$$\sigma=163.0438–0.037572z_1–0.135762z_2–1.63z_3+0.00011628z_1z_2. \quad (2)$$

The calculation results showed that the use of reinforcing gussets in the form of a strip with dimensions of 900×150×3 mm provided a 27–29 MPa reduction in the level of stresses arising in the areas of corner walls joints of tanks with a fire truck's volume of 5 m^3 on the MAZ-5337 chassis.

In order to reduce the stresses arising in the areas of T-joints of breakwaters and walls, studies of the rational geometric parameters of four stiffeners in the form of an equilateral angle with dimensions of 700×60×3 mm, which are fixed on the side walls at an angle of 45°, were carried out. The results of the research showed that an increase in length by 250 mm (maximum value) in the upper and lower parts of these stiffeners provides a decrease of 11–12 MPa in the stress level arising in the areas of corner joints of the tank walls, by 18–21 MPa in the areas of T-joints of breakwaters and walls, as well as by 57–61 MPa in the areas of the T-joints of the stiffeners and side walls (Figure 3).

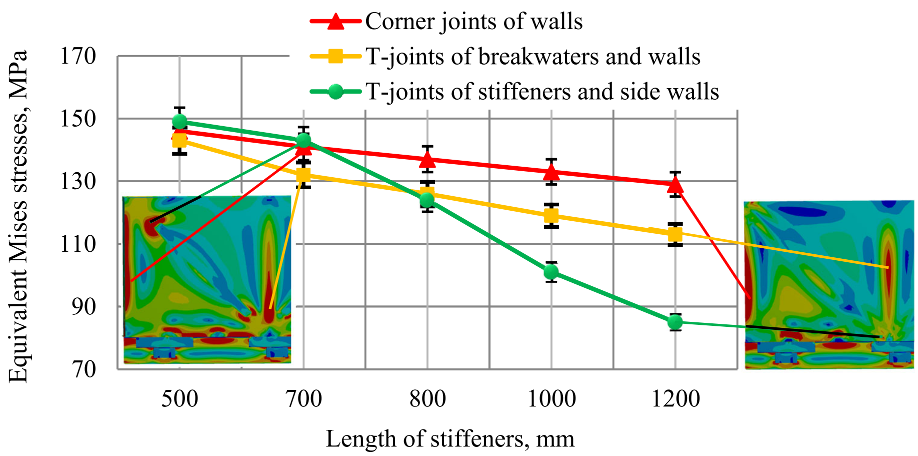


Fig. 3. The dependences of equivalent stresses arising in the most loaded nodes of a 5 m^3 tank of fire trucks on the MAZ-5337 chassis on the length of the stiffeners in the form of an equilateral angle. The type of stress fields at characteristic points on a fragment of the side wall of the construction

To reduce the stresses arising in the areas of the tank's corner joints that connect both front and back walls as well as bottom, an additional installation of U-shaped equal-flange profiles with dimensions of 50×50×3 mm (two pieces 300 mm long, four – 400 mm, two – 780 mm) fixed to the bottom at a distance of 15–20 mm from the corner joints of the walls and bottom is proposed. An alternative solution was considered to install equal-flange corners. The results of the research have shown that the use of U-shaped equal-flange profiles most effectively reduces by 29–32 MPa the level of stresses arising in the corner joints' areas of the front, back walls and bottom, as well as by 11–12 MPa in the areas of the walls' corner joints (Figure 4).

The comprehensive implementation of the developed scientifically-based design recommendations was carried out in a 3D model of an upgraded tank with a volume of 5 m^3 of fire trucks on the MAZ-5337 chassis. Its calculation is represented in Figure 5*a*. The results obtained made it possible to establish a decrease in the voltage level at 21–60 MPa, arising in the design of the upgraded tank with a volume of 5 m^3 of fire trucks on the MAZ-5337 chassis, compared with the mass-production one, while the coefficient of safety margin for yield strength was 1.4–2.

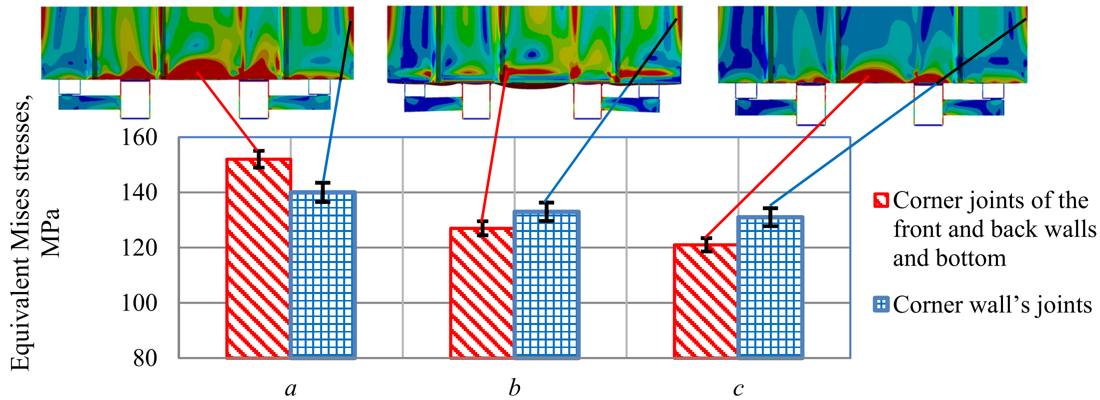
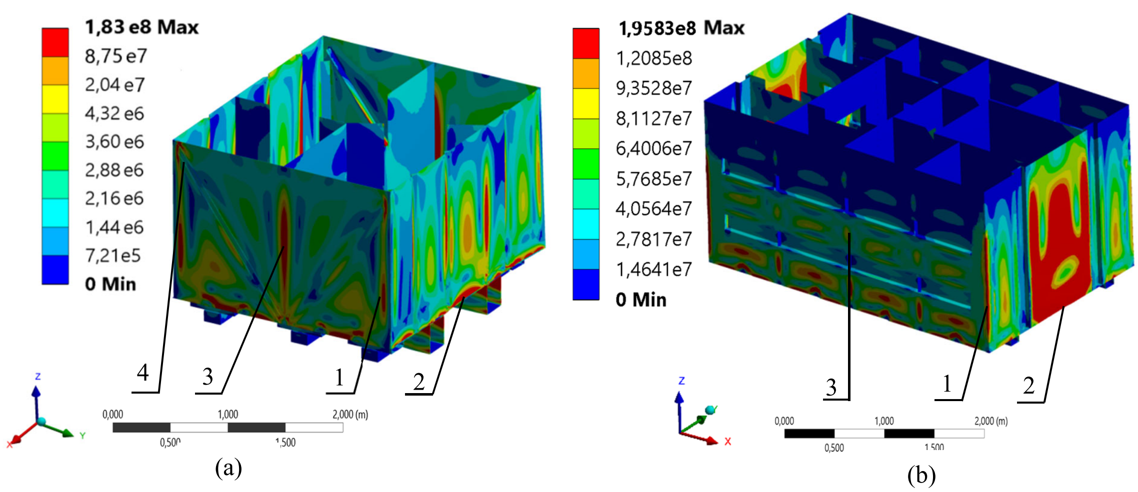


Fig. 4. Dependences of equivalent stresses arising in the areas of elements' corner joints of tanks with a volume of 5 m^3 of fire trucks on the MAZ-5337 chassis on the type of their constructions (mass-production (*a*), upgraded with the installation of corners (*b*) and profiles U-shaped section (*c*)) and the type of stress fields at characteristic points on a fragment of the front wall of the construction

The modern fire trucks tanks of rectangular cross-section are similar in shape, design and arrangement of elements. In this regard, recommendations for the design of mass-production tanks with a volume of 5 m^3 of fire trucks on the MAZ-5337 chassis are implemented in a 3D model of an upgraded tank design with a volume of 8 m^3 of fire trucks on the MAZ-6317 chassis [6, 7, 10]. Its calculation is presented in Figure 5*b*.



1 – corner joints of the walls; 2 – corner joints of the front, back walls and bottom;
3 – T-joints of breakwaters and walls; 4 – T-joints of stiffeners and side walls

Fig. 5. Models of stress fields arising in the structures of upgraded tanks with a volume of 5 m^3 (*a*) fire trucks on the chassis of MAZ-5337 and 8 m^3 (*b*) on the chassis of MAZ-6317, Pa

The results obtained made it possible to establish a decrease in the stress level by 26–56 MPa, arising in the design of the upgraded tank with a volume of 8 m^3 of fire trucks on the MAZ-6317 chassis, compared with the mass-production, while the coefficient of safety margin for yield strength was 1.6–2.1.

4. Conclusion

A new calculation technique has been developed that allows designing elements and components of fire truck tank structures. A feature of the methodology is the operational loads' accounting that characterize the features of the movement modes of fire trucks to the place of emergency response. Based on the research results, new patterns have been established linking the level of stresses arising in the most loaded nodes of tanks with a volume of both 5 and 8 m^3 with the modes of movement of fire trucks on the MAZ-5337 and MAZ-6317 chassis, as well as the type, size and location of elements that increase the strength of their constructions. Upgraded tank designs of fire trucks with a 1.2–1.6 times increased margin of safety and at least 1.5–2 times increased inter-repair period are protected by patents [11, 12].

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