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Estimating safety of a tractor cab with the protective system ROPS

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Abstract. The safety of the cab is an important requirement in the certification of the tractor at present. Roll-over protective structures (ROPS) protects the driver when the tractor is overturned. The safety assessment of the protective system ROPS is carried out on the basis of real tests in accordance with the requirements of GOST. Computer programs allow you to conduct safety assessments using the calculation method. The article presents a mathematical model of the protective structure of the ROPS of the industrial tractor B10. The finite element method has confirmed the safety of the ROPS protection system for a tractor weighing up to 25 tons. The deformation energy of 40 867 joules is achieved with a displacement of 261 mm and a lateral force of 229 kN. The magnitude of the lateral force in a real experiment differs from the calculated value by less than 4 %.

1. Introduction

Industrial tractors can overturn in the process of work [1]. To ensure driver safety, Roll-over protective structures (ROPS) are required. The ROPS system is a safety frame designed to reduce the risk of operator damage when the machine is tilted while using seat belts [2]. The use of the ROPS protection system is an indispensable condition for the certification of all road construction machinery and earthmoving equipment [3, 4].

The safety assessment of the protective system ROPS is carried out on the basis of real tests in accordance with the requirements of GOST [5]. Many authors attempt to evaluate the safety of a protective system by the calculation method [6, 7, 8, 9, 10,11] as computer programs allow you to conduct safety assessments using the calculation method. The real problem is comparing these two methods to assess the security of a protective system.

2. GOST requirements

The load procedure that simulates the overturning of the tractor is regulated by GOST [3]. All forces acting on a ROPS system depend on the mass m of the tractor:

1. the lateral force is equal to F_y = 70 000$(m/10000)^{1,2}$. The lateral strain energy U with a lateral load is U = 13 000 $(m/10{,}000)^{1,25}$

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2. the vertical force is equal to F_z = 19,6m;
3. the longitudinal force is equal to F_x = 56 000$(m/10000)^{1,2}$.

GOST does not allow repair of the ROPS protection system during the entire loading cycle [2, 3]. Safety criterion is the inviolability of the area of the intended operator's location (deflection-limiting volume – *DLV*).

The subject of the study was adopted protective system ROPS for tractor mass B10 m=25 000 kg. Values of forces for ROPS B10 are at least F_y = 210 197 *N*, F_z = 490 000 *N* and F_x = 168 157 *N*. The absorbed energy U with a lateral force should not be less than U = 40 867 Joules.

The protective ROPS system of the B10 tractor is a two-post welded construction made separate from the cab. The ROPS system was fastened to the body of the tractor side clutches by bolting at reinforced corners. The building material is carbon steel 09G2S. Its tensile strength is $\sigma_1 \approx 245\ldots345$ *MPa*. The breaking point is $\sigma_b \approx 470$ *MPa* with plasticity δ = 21 %.

GOST requires a safety assessment of the protective systems of tractors and road building machines to be carried out on the basis of actual (real) tests.

3. Real tests

The real tests of the protective system ROPS of the industrial tractor B10 were conducted at the test site of the Ural Test Center NATI. A special stand was used for testing. The stand is a power frame, inside which the object is located. Hydraulic cylinders provide the necessary effort. The bench allows you to continuously monitor the applied force and the corresponding deformation [12].

Initially, the ROPS design was loaded with a lateral force F_y equal to the tractor weight. The load was applied horizontally at a speed of 4 mm/s and fixed every 10 mm of deformation (Figure 1). The required strain energy U = 40 867 J was obtained with a force F_y = 243 kN and lateral deformation Δ = 261 mm [12].

After the deformed design, the ROPS was statically loaded vertically for 5 minutes. The vertical load was F_z = 520 kN (Figure 2). A longitudinal force of F_x = 170 kN was applied at the end of the test (figure 3).

Figure 1. ROPS deformation under lateral loading.

Figure 2. ROPS deformation under vertical loading.

Figure 3. ROPS deformation under longitudinal loading.

All the necessary values of the efforts and the absorbed energy were achieved in the process of actual testing of the protective structure [2]. No penetration of ROPS design elements into the DLV zone was observed. The safety of the protective system of the ROPS tractor B10 is confirmed. However, the result based on real tests is valid for five years [11].

4. Calculation model

The finite element method (FEM) is widely used to solve various physical problems recently. This allowed us to simulate the work of the structure under consideration, taking into account its geometry, materials and workloads.

The 3D model was built using the Solid Works design package. Simplification of the geometry allowed the use of a structured ordered mesh. The geometric model was divided into finite solid-state elements in the form of tetrahedra. The choice of a rational size of the final element was carried out on the basis of a series of static calculations with different sizes of elements (10, 20 and 40 mm) and the same load. As a result of the analysis, a mesh with a mesh size of 20 mm was selected. The number of nodes was 263,807. The number of elements is 137,305. There are no distorted elements.

The finite element model ROPS was rigidly fixed to 3/4 of the height of the reinforced corners (figure 4). Rigid fastening forbade all movements and turns. The inelastic properties of the material were given by the polylinear hardening law (figure 5) [13]. Nonlinear static calculation allowed us to take into account plastic deformations and the effect of large displacements. The load was set in the model in steps. This made it possible to take into account residual deformations that occurred after lateral loading.

Figure 4. Model of boundary elements with mesh and snapping.

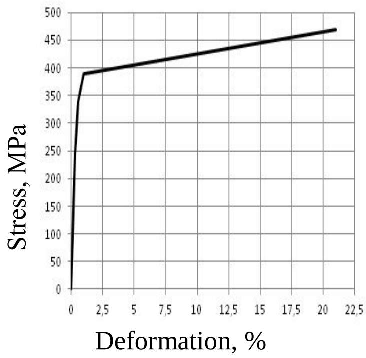

Figure 5. Hardening Diagram for Steel 09G2S.

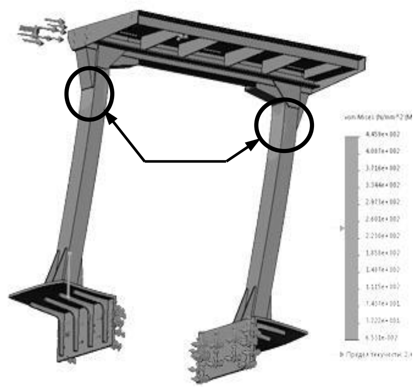

Figure 6. Voltages in the protective system ROPS with lateral force.

The problem was solved when the formulation of a nonlinear analysis in the calculation of the von Mises plasticity taking into account the effect of large displacements [14]. This made it possible to take into account the nonlinearity of the material (plasticity diagram) and the nonlinearity of the geometry (updating the direction of the load, taking into account the strains obtained). The nonlinear problem was solved step by step. The number of loading steps was chosen automatically according to the condition of convergence of the solution, small load increments and permissible errors of the linear behavior of the structure.

The lateral load was applied to the top of the protective structure and was evenly distributed over half its length. The immersion of the structure was carried out step by step with an increase in the force of 10 kN. The strain values were recorded at each loading stage.

The transverse force reaches the required value $F_y = 210$ kN with deformation $\Delta = 201$ mm, but the amount of absorbed energy is not enough $U = 26\,976$ J according to the calculation. Energy $U = 40\,867$ J is achieved with a lateral load of $F_y = 229$ kN, which corresponds to a displacement of $\Delta = 261$ mm. Maximum stresses $\sigma_{max} = 446$ MPa were observed in the upper part of the vertical posts (figure 6).

The integrity of the DLV zone was checked when the required values of force and energy were achieved (figure 7). The residual strain was 240 mm after removing the lateral load.

The vertical force was applied after removing the lateral force to the deformed structure. The force was distributed throughout the roof 250 mm wide. The ROPS system received an additional offset of 40 mm under the action of the vertical force F_z = 500 kN and remained operational (figure 8).

Longitudinal load F_x = 170 kN was applied to the upper part of the structure from the rear in the zone of greatest proximity to the DLV. Under the action of this load, the design has shifted forward by 72 mm (figure 9).

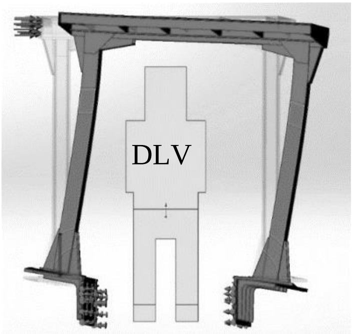

Figure 7. ROPS deformation under lateral loading.

Figure 8. ROPS deformation under vertical loading.

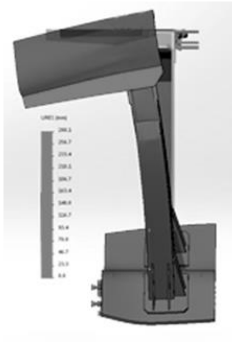

Figure 9. ROPS deformation under longitudinal loading.

The protective system ROPS withstood the entire cycle of loading. The design extinguished the required amount of energy *U*. The acquired deformations did not violate the DLV zone.

5. Comparison of calculation results and real testing

There is a good agreement between the results of the calculation and the actual tests. The required value of lateral force occurs earlier than the sum of the absorbed energy in both ways of assessing safety. The nature of the deformation of the structure is similar for all types of loading in the calculation and actual testing.

The required energy U = 40 867 J is absorbed by the protective structure during the deformation Δ = 261 mm in the calculation and the real experiment. The force values differ by no more than 4 % (the calculated force value is F_y = 229 kN, the experimental one is F_y = 243 kN).

We constructed the dependence of the force on the deformation $F_y(\Delta)$ to compare the process of energy absorption (figure 10).

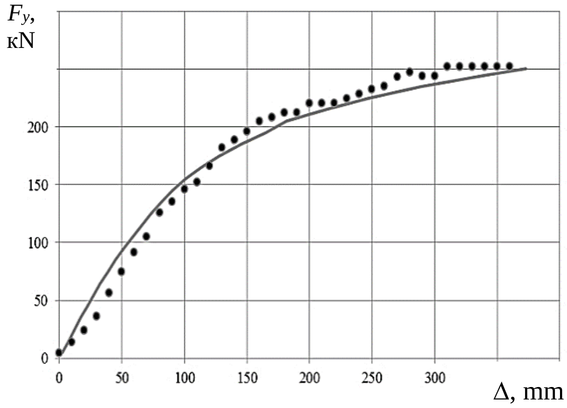

Figure 10. Dependence of lateral force on deformation.
●●● experimental points
—— calculated curve.

The calculated curve $F_y(\Delta)$ lies above the experimental points at low loads. This is due to the increased rigidity of the mathematical model due to the fixation used. Then the experimental values of strain are slightly ahead of the calculated values of strain. This is due to the heterogeneity and defects in the material, the error of welds and of joints, etc. The maximum deviations of the experimental values of the lateral force F_y from the calculated curve $F_y(\Delta)$ do not exceed 8 % throughout the entire range of displacements [15].

The magnitude of the absorbed energy was calculated as the area under the curve of lateral force and deformation $F_y(\Delta)$:

$$U = 0{,}5\left(\Delta_1 F_{y1}\right) + 0{,}5(\Delta_2 - \Delta_1)(F_1 + F_2) + \cdots + 0{,}5(\Delta_n - \Delta_{n-1})(F_{n-1} + F_n), \quad (1)$$

where F_{yi} and Δ_i are force and deformation at step i of loading ($i = 1 \ldots n$).

The calculated values of the absorbed energy differ from the experimental values of the energy by less than 7% over the entire range of deformations. This is a fairly acceptable error confirming the adequacy of the calculated model.

6. Conclusion

The protective structure withstood all types of loading without penetration of its elements into the DLV zone. Both results confirmed the safety of the ROPS protection system for the 25-tonne B10 tractor.

The calculated safety assessment method was less expensive and more informative. He allowed to get not only the strain at each stage of the load, but also the stress in the structure. The computational model allowed us to find the weaknesses of the structure for its further improvement. Using the resources supercomputer of South Ural State University will allow replacing costly real tests in the future [16].

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