ANALYSIS OF AGRICULTURAL TRACTOR CABIN STRENGHT

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Abstract The safety of using machines and technical devices, including agricultural tractors, is the most important element during their operation. The state of safety is influenced by many factors such as: safe construction, proper use, operating conditions and the human factor. Man is the most important and at the same time the weakest element of the safety system and the cause of many dangerous events. The largest number of accidents in agriculture occur due to human causes and they occur most often in developing countries, where many machines with a long service life are used. That is why the renewal of the machinery park and the safe construction of cabins even in the simplest agricultural tractors are so important. This article focuses on the strength analysis of the agricultural tractor cabin as an element that directly affects the safety of the tractor operator during various works performed in agriculture. Using finite element analysis, two cases of the impact on the agricultural tractor cabin were analysed. The first case illustrates the occurrence of a top impact on the cabin of a beam, a roll of straw, while the second case is the often occurring classic overturning of the tractor, the so-called ROPS case of rollover. The cabin structure was modeled from square cross-section profiles made of S235JR steel, as the most commonly used for this type of structure. Numerical analysis was performed in ABAQUS for the ROPS test and static and modal durability analysis in MSC Nastran. Positive results of the analysis were obtained.

Keywords: agricultural tractor, FEM, safe structure, strength.

Introduction

The state of safety is influenced by many factors, such as: safe design, proper use, operating conditions and humans. Humans are the most important and at the same time the weakest element of the safety system [1; 2] and the cause of many road accidents [3-5]. The safety of road transport means is an extremely important issue undertaken by many researchers, including: [6-11] and is also related to the integration of transport systems [10]. Many works are devoted to research on the design of vehicles [13-16], buses [17; 18] including off-road vehicles [19-21], trailers and semi-trailers [22-24] in the field of passive safety. The issues of dynamics and stability of vehicle movement are also widely discussed in the literature [25-27]. The required level of safety can be ensured by appropriate design and modern materials [28-31]. The cabin structure should have the shape of a crash structure and should not cause serious injuries to the operator in the event of the tractor overturning. International standards have been developed: OECD Code 4, SAE J2194 [32; 33], which regulate the crashworthiness of this protective structure. The rollover protective structure (ROPS test) is characterized by a large space for a protected zone sufficient to protect the operator in the event of a collision with another vehicle, damage from an impact from any direction or the tractor overturning. No part of the cabin should encroach on the operator’s free safety space.

ROPS test standards were developed due to the need to protect the operator caused by fatal rollover accidents. Initial studies, both in construction and agriculture, were conducted with actual rollovers of machines on different tracks and terrains to determine the amount of energy that would have to be absorbed by ROPS. Problems with the repeatability of rollovers led to the development of laboratory tests. Initially, these tests were based on impacts of metal pendulums on the structure, referred to as dynamic methods, but recently static methods have also been developed, which are defined as loads applied at a speed of less than 5 $mm \cdot s^{-1}$. Currently, standardization committees allow a choice between static and dynamic tests because they obtain similar results. The static test allows for a more accurate assessment of the strength and weakness of the structure, while the dynamic test allows for a better representation of real deformation conditions, since it takes into account the brittleness of materials due to high-speed deformation. Due to the better possibility of evaluation in the static test, it is preferred by various agricultural tractor manufacturers. Most of the energy is absorbed during plastic deformation of structural elements. Therefore, lower yield strength and higher elongation are desirable properties of the cabin material. At the same time, permanent deformation must be limited so that it does not violate the free space.

The article [34] describes the numerical research process aimed at designing the agricultural tractor cabin and its mounting in accordance with the static ROPS test [35]. Numerical analysis was carried out in the ABAQUS program for the ROPS test and static and modal durability analysis in the MSC Nastran program. According to the ROPS test, the plastic deformation method during initiation and durability analysis based on the material fatigue process were used to predict the material fracture. A 79% displacement correlation was obtained. The energy-force diagram for the rear vertical crushing load indicated a correlation with the test of only 37%. The energy-force values for the lateral load indicated a very good correlation of 97%. A 69% correlation was obtained for the energy-force diagram for the front vertical crushing load.

The operational reliability of machine-tractor units is of key importance from the point of view of stringent requirements for the duration and quality of technological processes in agriculture [36]. Currently, advanced programs using finite element methods (FEM) are used for structural research [37-41]. In the works [42; 43] the methodology of designing a structure protecting the tractor cabin against falling objects, using polymer composites, was described. The structure was to meet both level I and II penetration tests [33]. As part of the tractor cabin study, a finite element model (FEM) of falling object protective structures (FOPS) and a model of elasticity and fracture of composite materials were created. A series of virtual FOPS crash tests were conducted to reduce impact loads in the cabin.

According to [44], the FOPS tractor can be divided into two categories: Level I impact protection refers to impacts from small falling objects (e.g. bricks, small concrete blocks, hand tools, etc.). Level II impact protection from large falling objects (e.g. trees, rocks). In laboratory conditions, these tests are performed by dropping a standard object (indenter) of a specified shape and mass from a specified height. The test impact locations for both types of tests were selected according to [44] and [45]. The test results indicate that the traditional FOPS tractor failed the Level II impact protection test, while the FOPS tractor with a composite panel passed this test successfully [46]. It was concluded that the PCM roof panels absorb a significant amount of the energy of the falling object, particularly 59% in the case of Level I impact resistance tests and 30% in the case of Level II tests.

In this article, based on the authors' experience and literature reports, an attempt was made to analyze the strength of an agricultural tractor cab for two cases: impact with an object from a great height and overturning of the agricultural tractor with rollover.

Research methodology

The strength analysis of the cabin was performed for two events: fall of a hay bale with a horizontal axle from a height of two meters and a tractor overturning on its side into a ditch. These cases were selected as the most likely to occur during work on a farm. The cabin was modeled from square cross-section profiles (Fig. 1.a) made of S235JR steel.

a b c

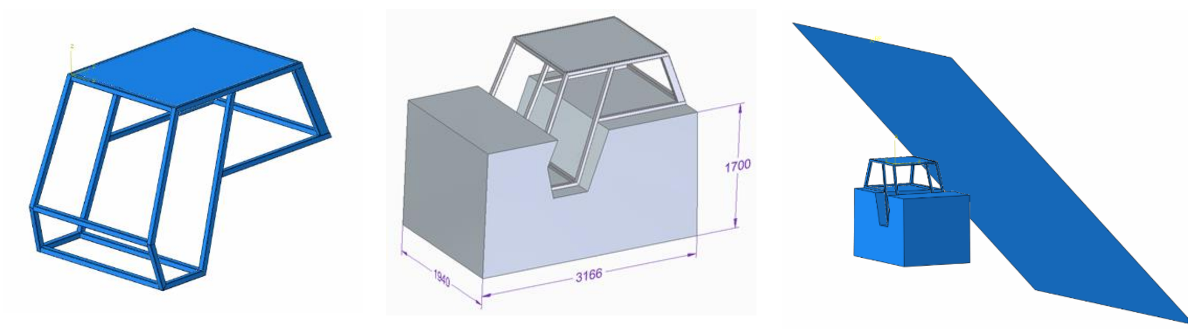

Fig. 1. **Solid models used in FEM analysis:** 1 – tractor cabin; 2 – volumetric model simulating the mass of a tractor; 3 – model of the ditch wall that the cabin hits when the tractor overturns

The cabin was modeled in the Part module of Solid Edge and then exported to Abaqus. In the next step, the solid model of the cabin was transformed into a surface model using the Assign Midsurface tool. Then, the shell sections were created and assigned a given thickness. The mass of the roll that falls on the cabin is 200 kg, the standard dimensions of a hay roll are 1.5 m x 2 m in diameter. The density of the roll is ρ = 57 kg·m^{-3}. Elastic properties – Young's modulus E = 10 MPa [47]. The mass of the entire tractor is 3500 kg, and the volume of the solid is V = 9.2 m^3. Therefore, the density is ρ = 370 kg·m^{-3}. The stiffness was assumed to be E = 70 GPa. In order to create an analysis of the tractor rollover, a simplified solid was modeled to imitate the tractor mass and approximate the center of gravity – Fig. 1.b. The ditch was modeled as a discrete rigid surface, which reflects the tractor's impact on a rigid surface. The ditch wall was added near the corner of the cabin frame at an angle of 45 degrees (Fig. 1.c). In the second case, the roll of hay was assumed to fall onto the tractor frame from a height of 2 meters. In the analysis, the roll was set a few millimeters above the roof and the initial velocity was given as $v = 6.26\ \text{m}\cdot\text{s}^{-1}$.

The following assumptions were used for the tractor rollover analysis [33-35]:

- the tractor moves forward at a speed of $10\ \text{m}\cdot\text{s}^{-1}$,
- the tractor starts to tilt while still moving forward at a speed of $10\ \text{m}\cdot\text{s}^{-1}$,
- at some point during the rollover it reaches an angular velocity of $2\ \text{rad}\cdot\text{s}^{-1}$, just before hitting the wall in the ditch; the axis of rotation of this angular velocity is at the edge of the tire.

The analysis used the Explicit Dynamics solver, the time of each event was 0.2 s. A Shell mesh with S4 elements without reduced integration was laid out on the frame model in order to reduce the artificial energy (ALLAE). The discrete model of the frame consists of 22770 S4 elements, the mesh size was set to 0.02. The discrete model of the hay roll consists of 570 C3D8 spatial elements. The tractor mass simulation consists of 312 C3D8 elements.

Results of FEM analysis

The case of a horizontally positioned hay roll hitting the cabin is shown in Fig. 2.

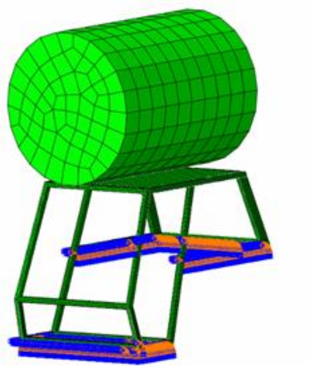

Fig. 2. **Initial phase of a hay roll hitting the tractor cabin**

The maximum values of reduced stresses with the value of σ = 293 MPa occur at the upper corners of the frame and at the central areas of the angles to which the roof sheet is attached – Fig. 3a. Plastic deformations occurred on the frame profiles in the area of contact with the hay roll. The greatest deformations occur in the corner of the frame, but they are far from the breaking point – Fig. 3b.

a b

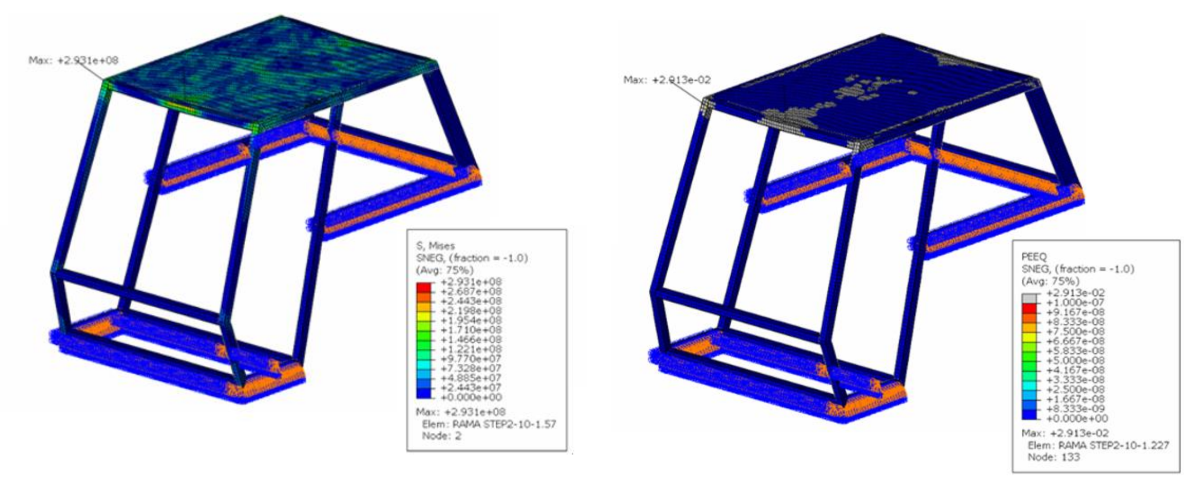

Fig. 3. **Results of FEM analysis:** a – reduced stress distribution, b – plastic strain distribution

After importing the cabin frame model into Abaqus, constraints were added that imitate welded connections between the profiles and the roof sheet. For this purpose, the tie constraint was used, which causes the nodes from the master surface to have exactly the same displacements as the nodes from the slave surface. Four constraints were created:

- constraining the cross beams to the vertical frames,
- constraining the sheet surfaces to the upper profile surfaces,
- constraining the profiles to each other in a butt joint,
- constraining all the profiles that are connected in a butt joint.

Energy graphs show a much greater share of plastic deformations in relation to elastic deformations. The impact energy was absorbed half by generating elastic stresses, and half by plasticizing the structure – Fig. 4a. The zero level of artificial energy ALLAE, and the lack of change in the total energy ETOTAL (Fig. 4.b) indicate the correctness of the analysis. The total energy ETOTAL allows for checking the correctness of the principle of energy conservation in the analysis. This principle implies that the energy balance in the analysis is constant. Sudden changes in this energy warn that non-physical behaviors occurred in the analysis.

a b

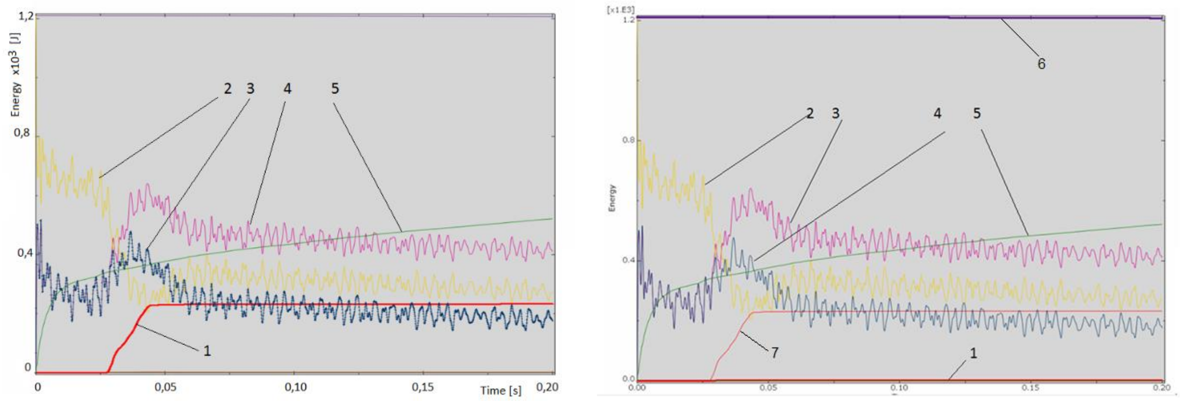

Fig. 4. **Energy diagram:** a – showing the greater share of plastic to elastic deformations; 1 – ALLAE; 2 – ALLKE; 3 – ALLSE; 4 – ALLIE; 5 – ALLVD; b – zero energy level ALLE; no visible change in total energy ETOTAL: 1 – ALLAE; 2 – ALLPD; 3 – ALLIE; 4 – ALLCD; 5 – ALLVD; 6 – ALLDMD; 7 – ALLPD

The total energy balance in Abaqus is the sum of several energies: ETOTAL = ALLIE + ALLFD + ALLCCE-ALLWK-ALLCCDW. Maps of plastic deformations created after the tractor overturned show significant effects of the collision. The tractor frame was very strongly deformed – Fig. 5.

a b

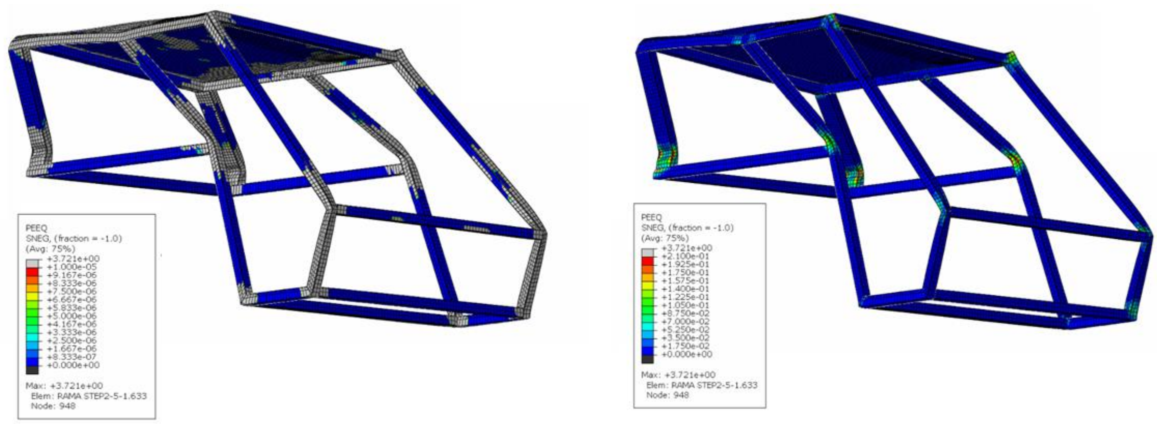

Fig. 5. **Map of plastic deformations after tractor overturning:** a – grey colour indicates places where plastic changes of the frame occurred, b – deformation of the cabin frame – visible deformations

Plastic deformations have a large share in the entire structure and are at a high level. The white areas show deformations above the tensile limit, so the cab frame would most likely have cracked in this place. Such an event could pose a threat to life. The graphs (Fig. 6) show a huge share of plastic energy to elastic energy. This shows that the structure lost stability and plasticization occurred immediately.

a b

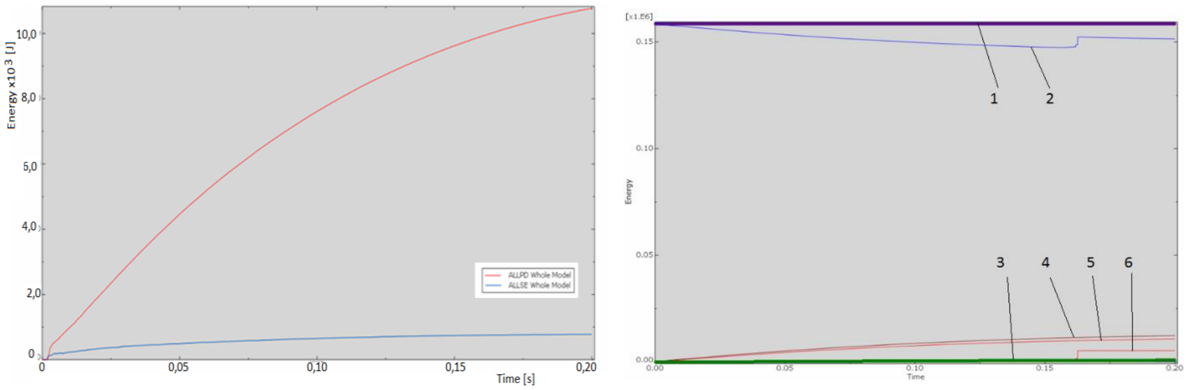

Fig. 6. **Distribution of energy generated when the cabin hits the edge of the ditch:** a – plastic to elastic energy ratio; b – Zero level of artificial energy ALLAE; no change in total energy ETOTAL: 1 – ETOTAL; 2 – ALLKE; 3 – ALLVD; 4 – ALLIE; 5 – ALLPD; 6 – ALLMW

The above graph (Fig. 6a) shows a very large share of plastic energy ALLPD to elastic energy ALLSE, which indicates that the structure was immediately plasticized and the kinetic energy from the fall was dissipated through the plasticization of the material. The zero level of artificial energy ALLAE and the lack of change in total energy ETOTAL indicate that the analysis was correct (Fig. 6b).

Conclusions

The numerical tests carried out indicate that in the event of a hay roll hitting the roof of the tractor cabin, there is no risk of deflection of the roof plane or bending of the supporting frame structure. The maximum stress values are created in the horizontal beams of the frame. In the vertical beams, stresses do not exceed 4 MPa. These elements are therefore not deformed, they retain their rigidity. In this case, there is no threat to the tractor operator. In the event of the tractor tipping over on its side and hitting a flat obstacle inclined at an angle of 45°, deformation of the vertical frame elements is observed at their connection points with the horizontal profiles. The deformation energy causes permanent deformation of the structure and as a result may lead to a threat to the safety of the tractor operator.

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Author contributions

Conceptualization, J.C.; methodology, J.C. and A.N.; software, A.N.; validation, A.N. and L.G.; formal analysis, A.N. and L.G.; investigation, J.C., A.N., L.G. and J.V.; data curation, A.N.; writing – original draft preparation, J.C., A.N., L.G. and J.V.; writing – review and editing, J.C., A.N., L.G. and J.V.; visualization, J.C., and J.V.; project administration, J.C.; funding acquisition, J.C. All authors have read and agreed to the published version of the manuscript.

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