Wiesław JASIŃSKI *
Marcin SZCZEPANIAK *
Andrzej WOJCIECHOWSKI *
Wiesław BARNAT **

DIGITAL SIMULATION AND TESTING OF EXPLOSION INSIDE THE CONTAINER FOR THE TRANSPORT OF EXPLOSIVE REMNANTS OF WAR AND UNDER THE MINE ROLLER CARRIED OUT ON A PROVING GROUND – TIRAMISU PROJECT

Results of a digital simulation of a detonation of explosive charges inside the platform designed for the TIRAMISU project used for the transport of mines and ERW (explosive remnants of war) and under the mine roller constructed for the same project are presented. The stresses in structures of the two devices and the total effect of the impact forces generated during explosion are included herein. In the second part of the paper the proving ground tests of a detonation of explosive charges under real objects and the results of the recorded mechanical stresses forming in the structures, propagation of the blast wave and fragments are described presented. Conclusions drawn from the comparison of the results of computer simulations and obtained as the result of real tests in relation to the changes in the design of the proposed device are also found in the paper. The final version of the trailer for the transport and temporary storage of ERW, as well as the final version of the mine roller together with the remote-controlled tractor of the Pierre Trattori company is presented.

1. INTRODUCTION

While conducting the mine clearing operations one should be aware of the possibility of the occurrence of the controlled or uncontrolled explosions. These can occur mostly during the mine clearing and transport of explosives collected. For that reason, the Military Institute of Engineer Technology conducts studies of devices which maximize the safety of the operations. The innovative mine clearing device and a simple and low-cost container for the transport of various types of explosives according to the state-of-the-art in that field have been designed and manufactured at the Military Institute of Engineer Technology within the TIRAMISU project.

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* Military Institute of Engineer Technology, Department for Mine Warfare and Engineer Technology, Wrocław
** Military University of Technology, Chair of Mechanics and Applied Informatics, Warsaw

1.1. Description of the container for the transport of explosives

The vessel developed is a blast-containment container made according the project presented in Fig. 1 and it is designed for transport and storage of products containing explosives containing up to 1 kg. of TNT or TNT equivalent.

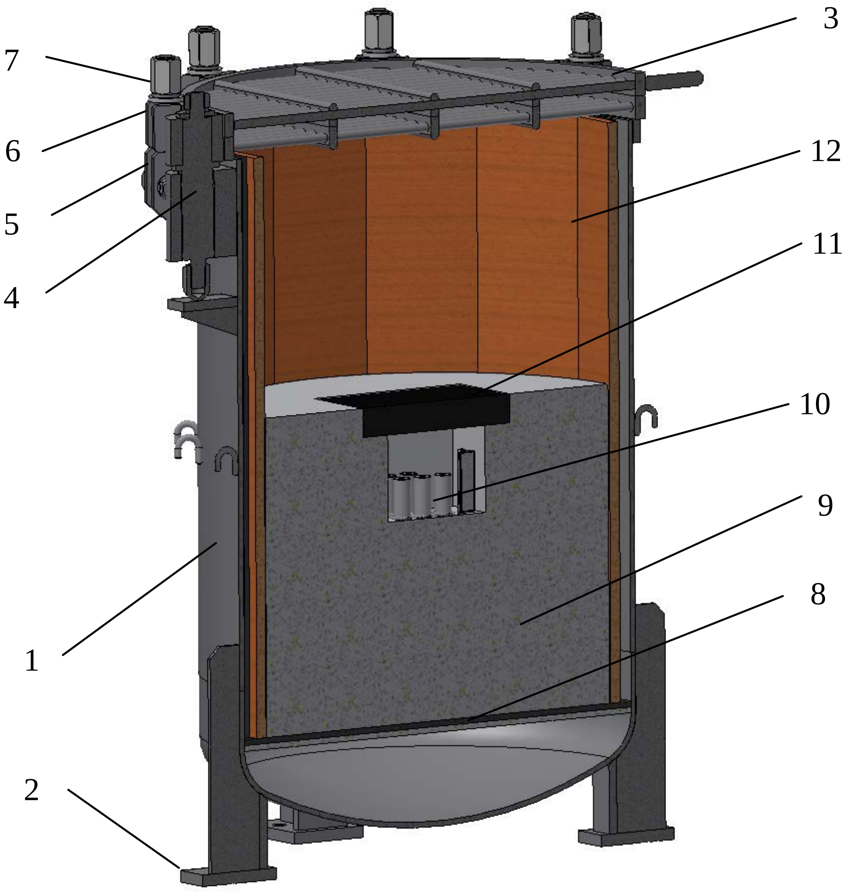

Fig. 1. Explosion-proof container

1 – body; 2 – foot; 3 – cover with grate; 4 – axis of rotation; 5 – eye bolt; 6 – bolt lock; 7 – nut; 8 – inner floor; 9 – foamed polystyrene filling; 10 – explosive; 11 – lid; 12 – surrounding boards

The container has a body (1), inside which on the circumference and at the bottom the elements are mounted for explosion energy dissipation. These elements are wooden boards (12) spaced circumferentially and connected together by rubber bands. The floor with a rubber covering (8) is located in the lower part of the container. The foamed polystyrene filling (9) is placed in the mid part of the container. The explosive (10) is placed in the chamber of the foam polystyrene filling.

Design basis.

- Inside the container, there is a filling material, whose task is to absorb some of the energy of the explosion.
- The top cover should have a shutter/grate construction allowing the release of overpressure in the upward direction but the cover prevents the solids being ejected from the container.

1.2. Description of a mine roller for anti-personnel mines

The equipment development is a mine roller manufactured according the project shown in Fig. 2 and it is designed to clear anti-personnel mines containing explosive charge up to 1 kg of TNT.

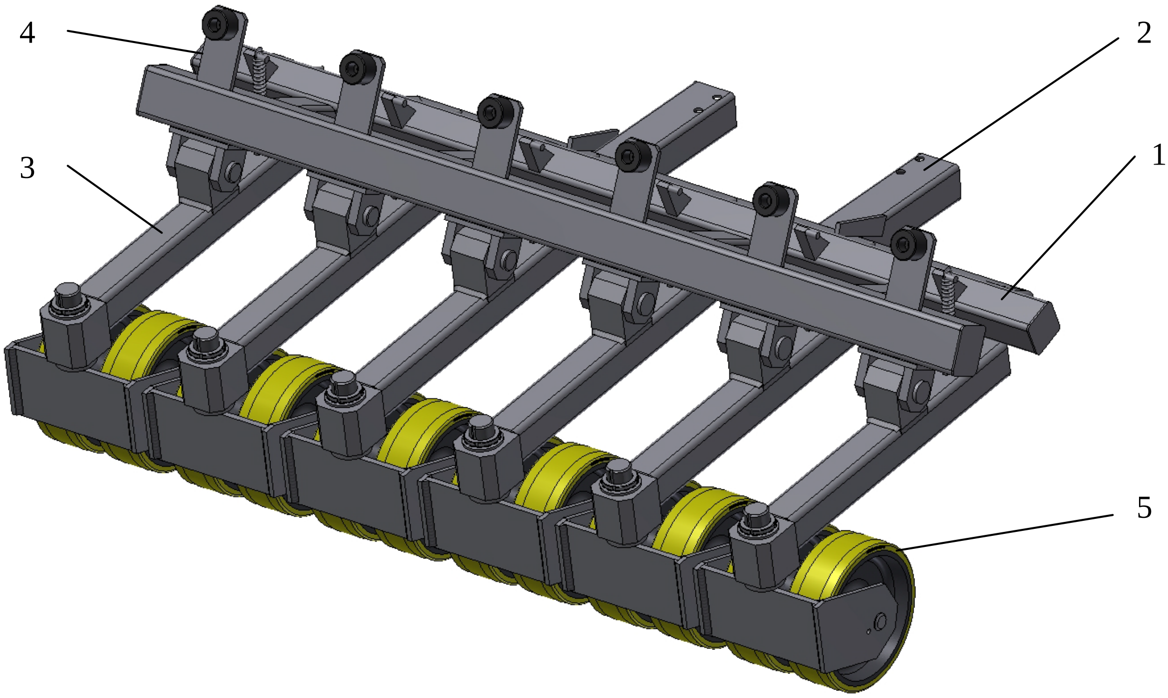

Fig. 2. Geometric model of the mine roller

1 – carrier frame; 2 – mounting bar; 3 – rocker arm; 4 – end stop; 5 – wheel set

The mine roller consists of a carrying frame (1) connected with mounting bars (2) on which the rocker arms are mounted rotationally (3). The wheel sets (5) after the detonation are able to tilt from the end stop (4).

Design basis.

- The mine roller has a modular construction consisting of easily replaceable elements which can be damaged by the explosion and which should be replaced quickly.
- The mine roller (wheel sets) is placed on movable bars (the so-called rocker arms) which move back during the explosion thus minimizing the destructive effects exerted on the device.

2. DIGITAL SIMULATION OF THE EXPLOSION

In this paper, the Finite Element Method (FEM) is a fundamental method of analyzing the impact of the explosion. The study adopted the following system of the numerical options available in the LS-DYNA [1] system:

- explicit algorithm used to solve equations pertaining to structure dynamics in the nonlinear range,
- elastic-plastic material model,
- rigid material model,
- deformable coating elements of the SHELL type (type 2) [1],
- deformable solid elements of the SOLID type (type 1) [1]
- initial and boundary conditions considering the gravitation effect, large deformations and

displacements.

The phenomena discussed in the paper are characterized by the following features:

- quickly changing in time (shot duration),
- great geometric nonlinearities (large deformations, displacements, contact) and signifficant physical nonlinearities (material nonlinearities),
- they require the small time increment Δt.

The following parameters of TNT were accepted:

- density: 1640 kg/m^3;
- detonation rate: 6930 m/s;
- Chapman-Jouget pressure (PCJ): 27 GPa.

The numerical calculations using the FEM method were conducted using the LS-Dyna program by Livermore Software Technology Corporation (LSTC) company, version 6.0, explicite option. The calculations were carried out by means of the KMiIS WAT calculation cluster named „Dobrawa", using 16 CPUs.

2.1. Digital simulation of explosion inside the container

As a result of numerical calculations, maps of displacements, strains, stresses and graphs of selected physical parameters in respect to the time were obtained.

This is presented in the figure below (Fig. 3):

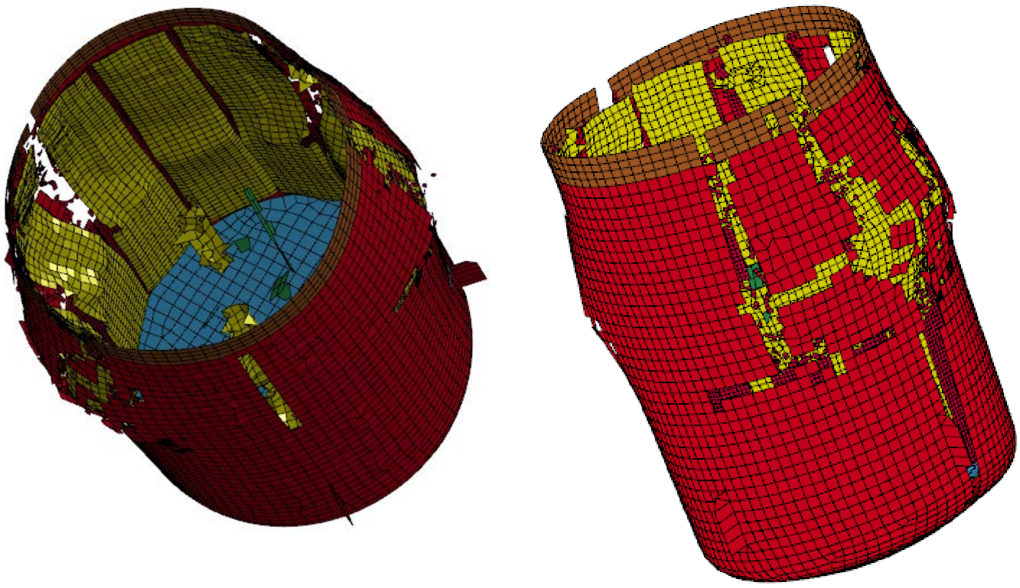

Fig. 3. Damage to the container after the explosion of 1 kg TNT

Maps of total deformations of the container body for *t*=2ms presented in Fig. 4.

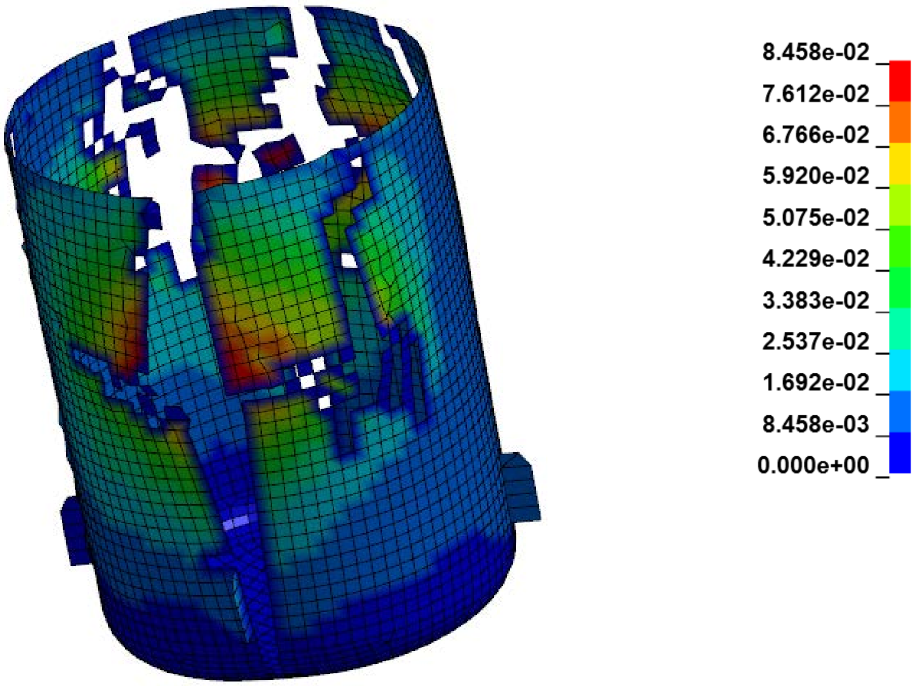

Fig. 4. Map of total deformations [m]

Maps of reduced stresses are presented in Fig. 5:

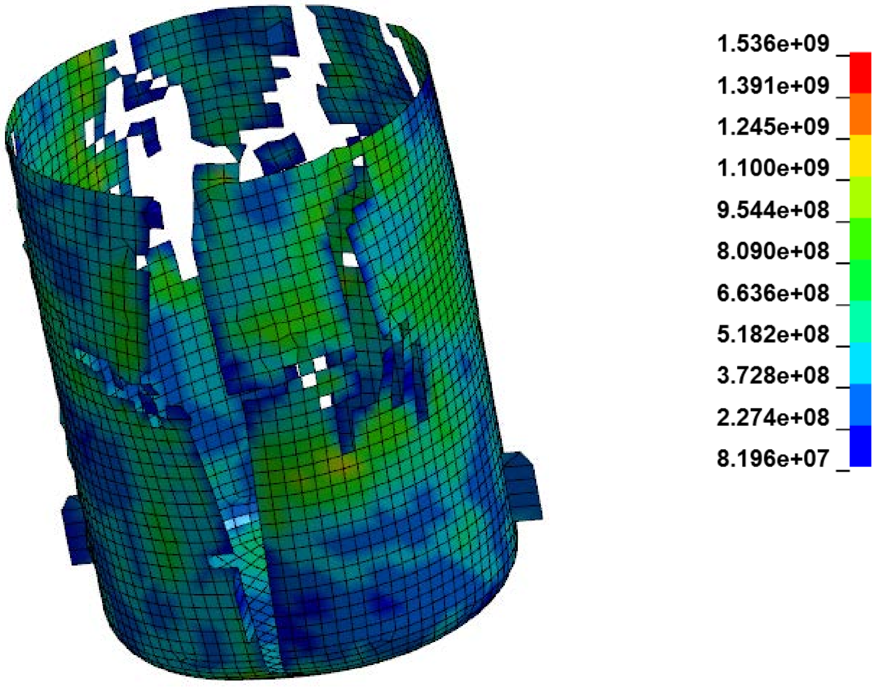

Fig. 5. Map of reduced stresses (acc. to Huber criterion) [Pa]

Structural elements absorbing the energy of explosion (wooden boards, rubber) are completely destroyed (Fig. 3). The container skin is deformed and there is the possibility of breaking the structure (Fig. 4). In the Fig. 5 one can see that the part of the body is critically stressed. The range of deformation of the container body is generally smaller than that of the energy-consuming elements.

2.1. Digital simulation of the explosion under the mine roller

The numerical model was built basing on the CAD geometric model (Fig. 2). Then, the model was divided into finite elements and the physical characteristics were given by defining the materials, thickness and connections between different parts of the mine roller. Consequently numerical model of the mine roller (Fig. 6) was developed.

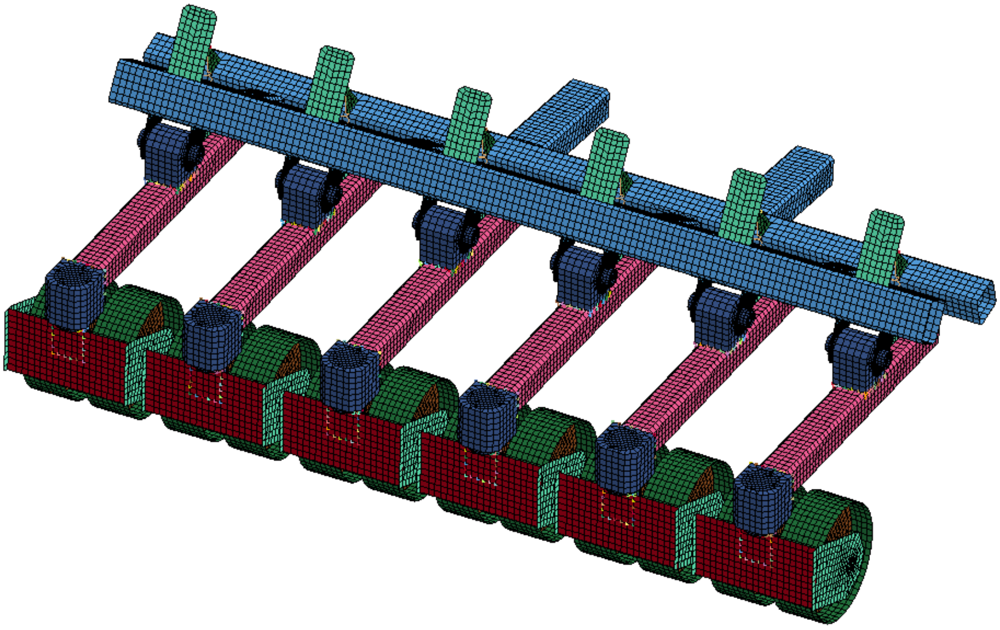

Fig. 6 Numerical model of the mine roller – general view

The explosion of 1 kg TNT applied under the middle wheel set was assumed for the computer calculations. The results are presented (Fig. 7) in the form of distribution of reduced stresses acc. to Huber hypothesis. The results are expressed in MPa.

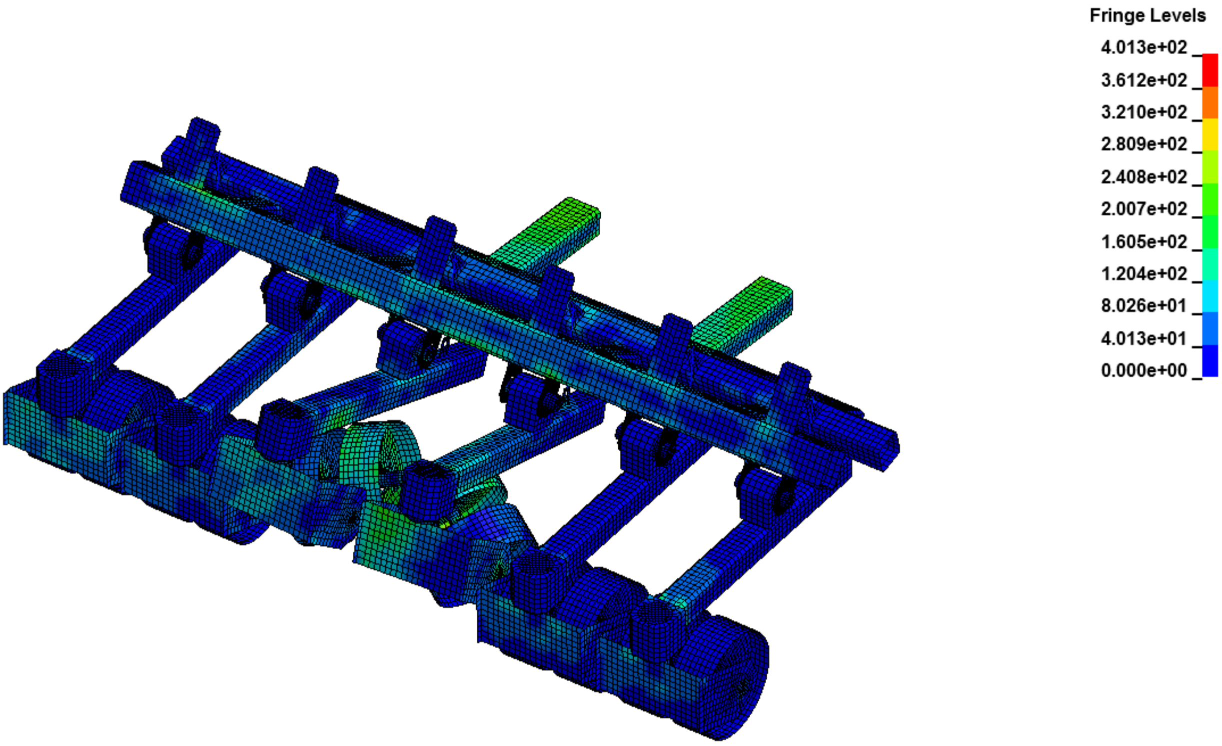

Fig. 7 Distribution of reduced stresses

It is possible that the roller which will be directly over the explosive charge can be completely destroyed. The whole mechanical construction of the mine roller will not be destroyed, because during the explosion the rocker arm together with the wheel set are to be thrown into the air (Fig. 7) and the energy is not transferred to the main part of construction. This phenomenon is confirms the design basis.

The damaged rocker arm should be replaced after the explosion. The mine clearance can continue.

3. EXPLOSION TESTS ON THE PROVING GROUND

The subject of the study were also the field tests of the container for transport and temporary storage of hazardous objects and the mine roller carried out on the proving ground. The subject is part of the TIRAMISU project.

3.1. Explosion tests inside the container carried out on the proving ground

The proving ground stand for testing the container is presented in Fig. 8. The black foil placed on the ground and four control shields deployed around the container were used to assess the fragment scatter. The shield height was 3 m and its width was 2 m. The distance from the shields to the container axis was 6.5 m. The ICP 137A23 pressure sensors were used to measure the pulse and overpressure parameters at the front of the shock wave. The distance from the container axis to the first pressure sensor was 3.25 m, to the second sensor − 6.5 m and to the third sensor − 10 m.

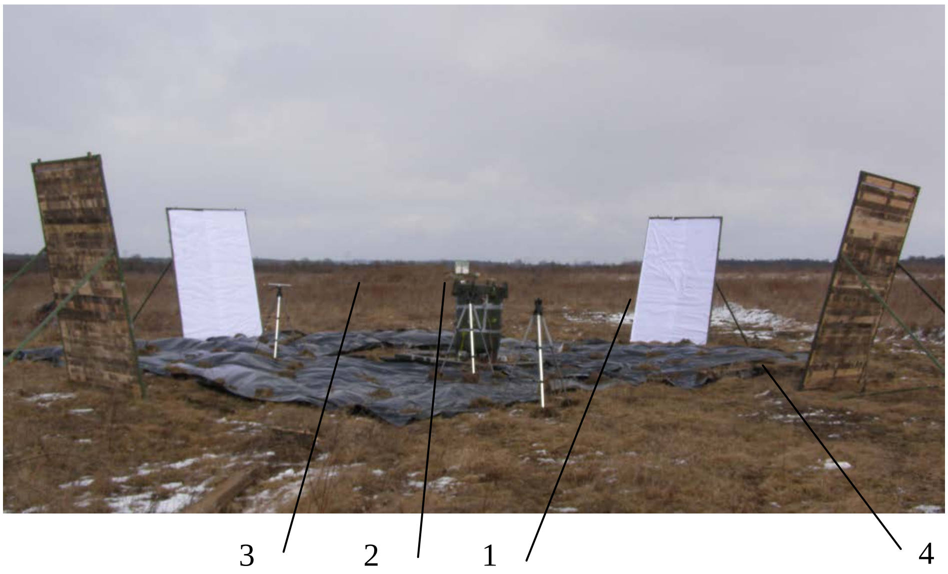

Fig. 8 The proving ground stand for container tests.
1-container; 2-pressure sensor; 3-shields, 4-foil.

The explosive charges used for testing included lethality enhancers. These charges were made of TNT pressed blocks weighing 75 g (11 elements) and a single 200 g block (1 piece). The lethality enhancers were steel balls (bearing balls) with the diameter of 6 mm. The total number of balls amounted to 2000. The 200 g TNT block has a body made of 2 mm steel sheet. The explosive charges were placed in the container and then armed with the “ERG” electrical detonators. Then they were connected to the measuring apparatus. The explosive charges were detonated by means of a TZK-100A electric blasting machine.

The effect of detonation of explosive charges is presented in Fig. 9. The container inspection was carried out after the trial and deformations of the container side surface in two areas were noted: larger, in the middle part (Fig. 10) and a minor one − of the container cover.

Fig. 9 Effect of detonation of explosive charges in the container
1-steel balls; 2-pressure sensor; 3-control shield

The inspection of the area covered with foil and of the control shields was carried out after the detonation. A dozen or so steel balls were found on the foil with a radius of 4.0 m from the container axis. Some wooden splinters of the damaged boards and of the cover of the cavity for explosive charges were present too. Not one steel ball had hit the control shields. The obtained results indicated that the substantial majority of balls remained in the container, only a few were ejected outside and fell around it. As a result of the impact of the high temperature of the post-explosion gasses, the wooden and rubber components inside the container had incinerated.

The experiment showed that the container was not damaged as a result of detonation of fragmentation explosive charges and that the explosion had no impact on the safety of its use. Tensile stresses of the side part of the container body, eye bolts and the frame of the container did not exceed the limit values for tensile strength. The probable cause of deformation of the container side surface in two places the impact of the 200 g block of TNT, which after detonation divided into two parts.

Fig. 10 Deformation of the container side surface-front view (top figure) and side view (bottom figure).

The maximum deformation values (Fig. 11) were 10÷11mm and 4÷5mm, respectively.

The courses of pulse and overpressure at the front of the shock wave registered by sensors are presented in Fig. 11.

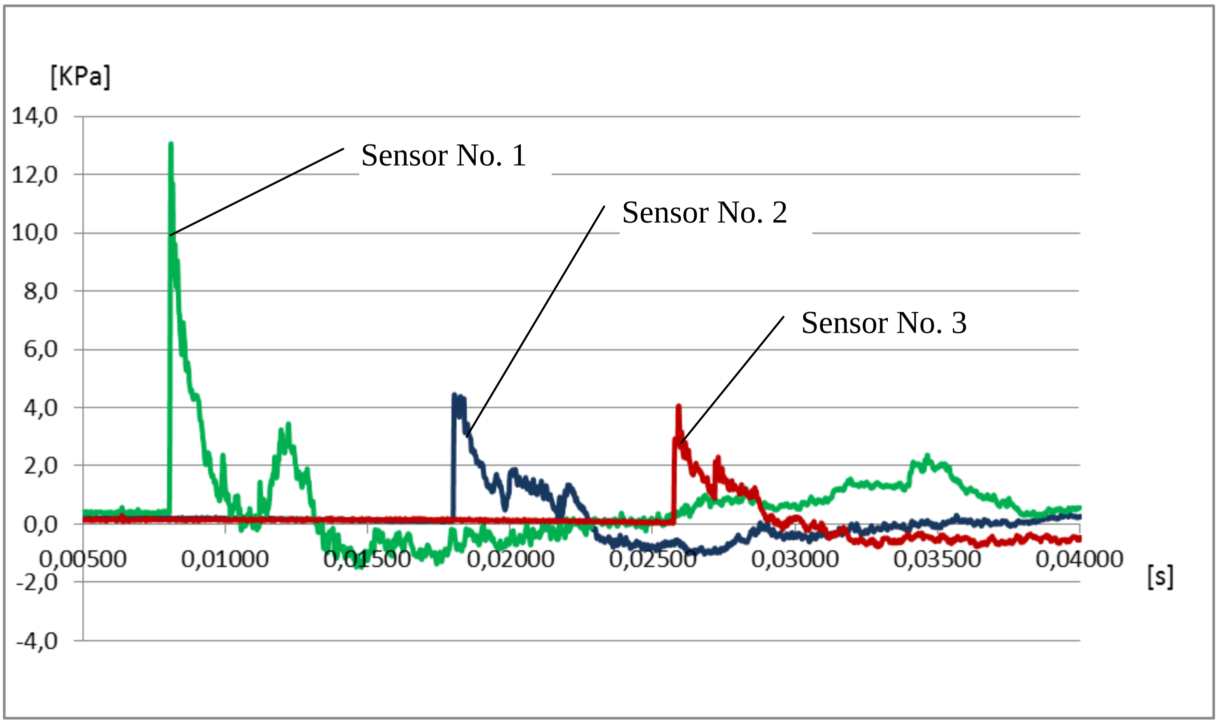

Fig. 11. The course of the pulse and overpressure at the front of the shock wave.

The peak values of the overpressure for the shock wave and reflected wave registered by separate sensors were as follows:

Sensor No. 1 – ΔP – max1 – 13.06 kPa; max2 – 3.45 kPa;
(distance from the container axis – 3.25 m)
Sensor No. 2 – ΔP - max1 – 4.45 kPa; max2 – 1.74 kPa;
(distance from the container axis – 6.5 m)
Sensor No. 3 - ΔP - max1 – 4.03 kPa; max2 – 2.14 kPa;
(distance from the container axis – 10 m).

Area hazardous to human health and resulting from the impact of shock-wave (atmospheric pressure exceeding 0.1 standard atmosphere) measured from the centre of the explosion should equal:

a) from 0 to 6.5m for a charge containing 2kg of TNT,
b) from 6.5 m to 9.0m for a charge containing 5kg of TNT

according to the Ordnance of Ministers of Internal Affairs, National Defense, Finances and Justice (Journal of the Laws, No. 165, item 992 dated August 2nd, 2011).

Thus it can be concluded that the **hazardous area for the tested container carrying fragmentation explosive charges up to 1 kg of TNT ranges from 0 m to maximum 4 m, which is well below the Ordnance regulation**.

4.1. Mine roller tests on the proving ground

The test stand was designed and erected to carry out explosive tests under the mine roller on the proving ground. The mine roller was presented in Fig. 12.

Fig. 12 Mine roller in the test stand

The test stand consisted of the mine roller mounted on the auxiliary frame loaded with the weight of 26.7 kN. Sequences of the selected registered images during the trial of dynamic load caused by the detonation of 8 kg cast TNT in form of 400 g 20 blocks placed indirectly under the mine roller wheel are presented in Fig. 13.

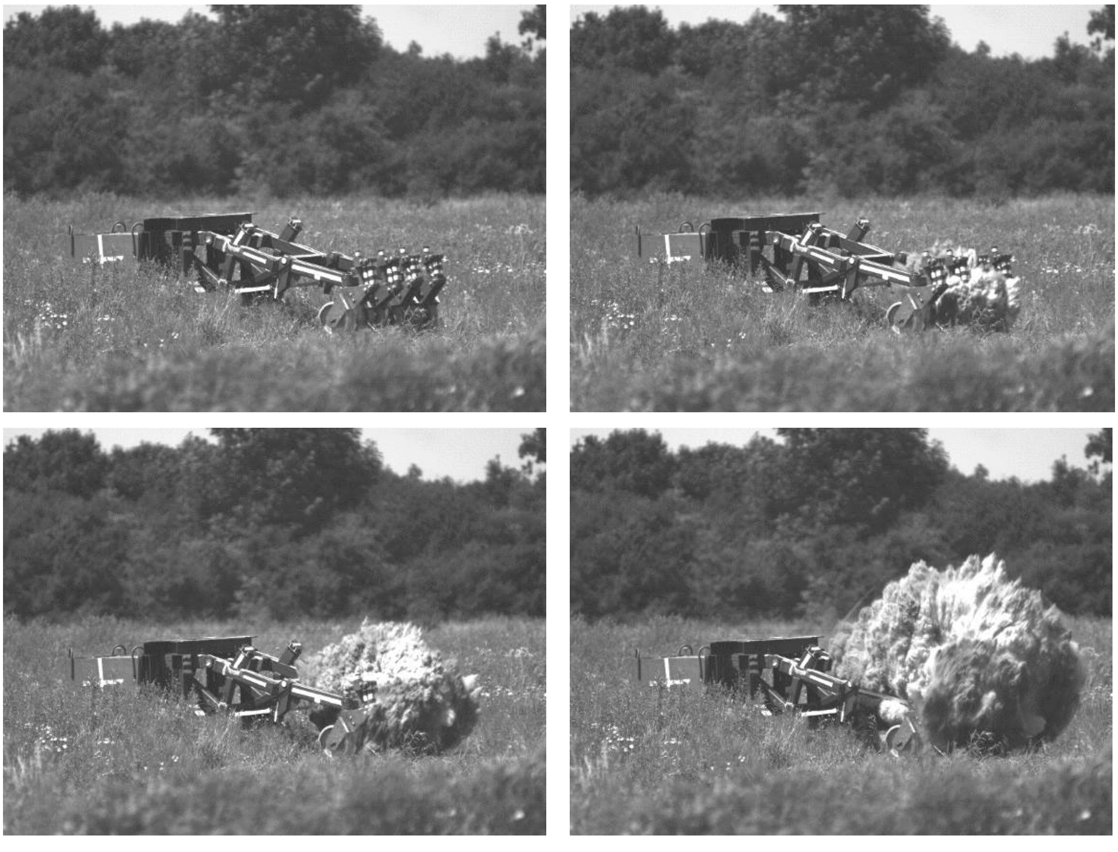

Fig. 13 Images registered during trial by the high speed camera No. 1

The above images were registered by means of a high speed camera.

Fig.14 Image mine roller after trial

Only a wheel set on the rocker arm directly over the explosive charge was destroyed. The remaining rocker arms and elements were in good condition.
The trial result confirmed earlier calculations.

4. Conclusions

The use of computer-aided design software allows the user to create models of devices and to perform simulations without having to build models in real terms. Such methodology can significantly reduce the cost of implementation of the devices. This way the design basics are also verified.

The methods of digital prototyping and simulation of explosive phenomena were described in the paper. These methods were verified by experiments on the proving ground.

Generally speaking, the design basics were met. The assumed construction of the mine roller with modular structure consisting of quickly replaced elements which would be damaged as a result of explosion proved effective. In particular, the mine clearing elements (wheel sets) were designed so as to be placed on movable bars (the so-called rocker arms) which move back during the explosion thus minimizing the effects of the destruction on the device. Both the digital simulations and the proving ground tests indicate that this concept is sound and solid.

During the design of the container to transport explosives, it has been assumed that the part of energy of explosion should be absorbed by the material filling the container inside to protect the container against disintegration. At the same time, the overpressure of the shock wave will be released vertically upward through the shutter structure of the upper container cover. The design of the shutter/grate should not allow significant ejections of the solids from the container. Basing on the tests carried out, it can be concluded that the design basics have been met.

The designed container should comply with the legal document connected with the impact of the shock wave. In this paper, it has been shown that the hazardous zone for the tested container has a radius of 4 m, what is not only acceptable but well below the legal requirement.

On completion of the work, the following observations were made:

- calculations of explosion under the mine roller and the explosion on the proving ground confirm the accuracy of calculations;
- the explosion of the container on the proving ground did not confirm the calculations – the damage to the container was minor, while according to the calculations it should have been great.

Considering, the present state of knowledge it is necessary to experimentally confirm the results of digital simulation calculations related to the phenomena of explosives.

The applications (Fig. 17) of tested devices coupled with the Pierre Trattori (TIRAMISU Partner) remote-controlled tractor can be proposed.

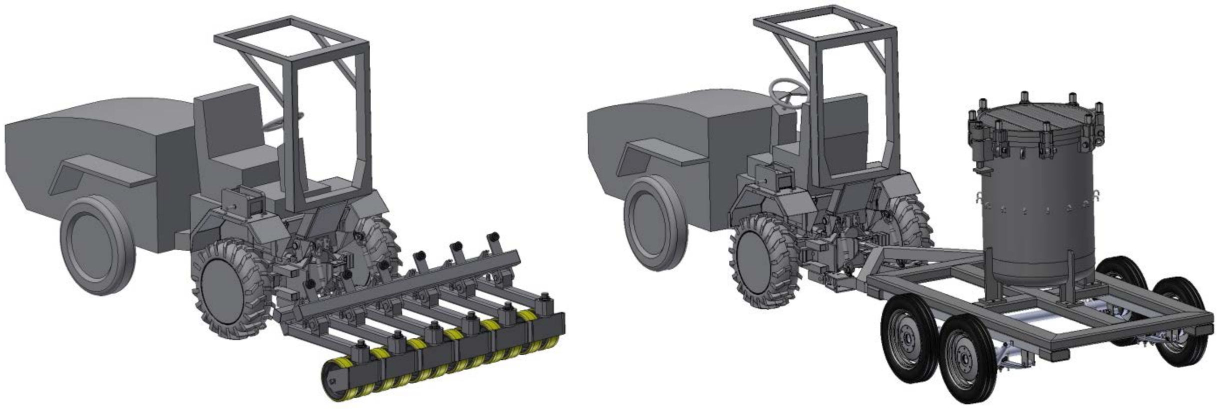

Fig.15. Application of devices tested on a tractor

Basic vehicle
tractor: Pierre Trattori
engine power: 58.1 kW
hydraulic pump: 180 bar, 36l/min
mounting: TUZ (three-point linkage)
with load bearing capacity of 1.350 kGm (relative to wheel axis)
unmanned operation – remote-controlled (wireless)
vehicle's resistance to explosions of anti-personnel mines (on steel wheels)

Literature

1. LS-Dyna Theory Manual, Livermore Software Technology Corporation, Livermore, 2006.
2. LS-DYNA Keyword User’s Manual (Version 971).

Acknowledgements:

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