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Modelling and Numerical Analysis of Explosion Under the Wheel of Light Armoured Military Vehicle

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The article presents a method for numerical modelling of a blast shock effect on unsprung parts of the military vehicle suspension. An explosive charge during the tests was placed under a vehicle wheel according to STANAG 4569 requirements. The mass of the charge is 10 kg of TNT, which corresponds to the highest level of safety – 4a. During the research, there was also tested an influence of application of Run Flat in the Tyre-Run Flat-Rim system on the propagation of a shock wave under the vehicle chassis. A model and numerical calculations were carried out with the use of the following programs: CATIA, HyperMesh, LS-PrePost, LS-Dyna. To describe an effect of a pressure wave on the structure, ALE approach was applied, which allowed mapping such processes as: detonation, wave propagation, interaction with a structure and ORFF system response.

Key words: shock wave, Run Flat, Light Armoured Vehicle (LAV).

1. Introduction

During international stabilization missions, logistic vehicles LV and light armoured vehicle are exposed to, among others, AT (Anti-Tank) mines and IEDs (Improvised Explosive Devices). Detonation of such charges take place through direct running with a wheel or in a short distance from the vehicle. IED and AT charges are most frequently buried in the soil, which, during their detonation, causes that the most subject subsystems to damage are unsprung parts.

The objective of the presented paper is to develop a methodology for numerical modelling of a shock wave effect on the structure of a LAV vehicle and to verify an application of Run Flat on splash and a shock wave shape.

2. Requirements concerning military vehicles resistance to detonation of mines and IEDs

LV and LAV vehicles moving in the area of an armed conflict should satisfy relevant requirements concerning ballistic, splinter-proof, counter-mine and counter-IED protection. Documents of NATO and institutes collaborating with NATO constitute a base for determining the requirements for crew members protection [1–3].

Document [1] defines the levels of LV and LAV crew members protection against a shock wave of AT mines explosion (Table 1). Levels 2–4 concern AT land mines detonated under a wheel/caterpillar or under the vehicle centre. Position of an explosive charge under the vehicle wheel according to STANAG 4569 standards is presented in Fig. 1.

Table 1. Levels of protection against a shock wave of AT mines explosion [1].

Level		AT mine explosion	
4	4b	explosion under the vehicle centre	AT 10 kg TNT
	4a	explosion under the wheel/caterpillar	
3	3b	explosion under the vehicle centre	AT 8 kg TNT
	3a	explosion under the wheel/caterpillar	
2	2b	explosion under the vehicle centre	AT 6 kg TNT
	2a	explosion under the wheel/caterpillar	

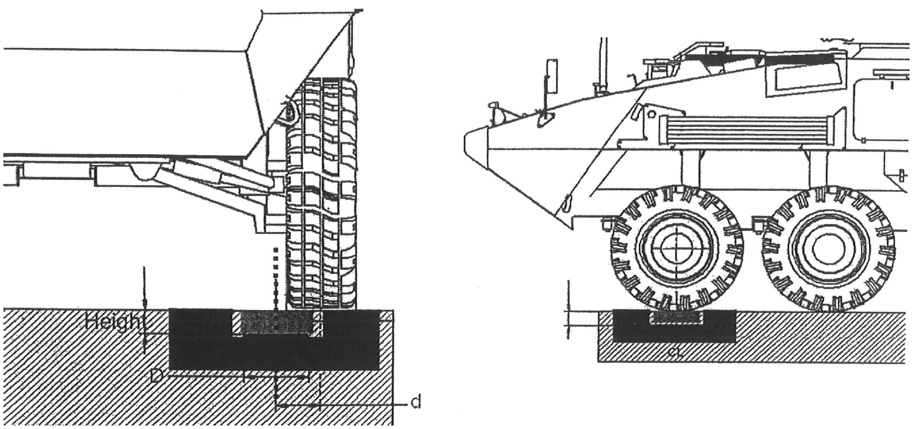

Fig. 1. Position of an explosive charge under the vehicle wheel in the steel foundation, where: S – tyre width, d – distance between wheel symmetry axis and explosive material, D – diameter of explosive material [1].

3. Research object

In order to verify a shock wave effect on a the vehicle structure, a simplified numerical model of a light military vehicle was developed. An essential detailed element was suspension parts, i.e., suspension arms with the places for mounting to the frame, tyre, rim and a wheel hub (Fig. 3). Connection mapping interaction of pivots and suspension elements was modelled using spherical joints and revolute joints. A model of the tyre was simplified through neglecting a cords system which is in a real tyre. Pressure supposed to occur in the tire has been neglected during the tests.

During the tests, 1/4 of a model was adopted (Fig. 2). Usage of a quarter of the vehicle considerably simplified the vehicle model, shortened computation time and did not influence the results in the form of interaction of detonation on the subsystems of LAV suspension.

Steel elements of the vehicle were modelled using MAT_PIECEWISE_LINEAR_PLASTICITY constitutive model.

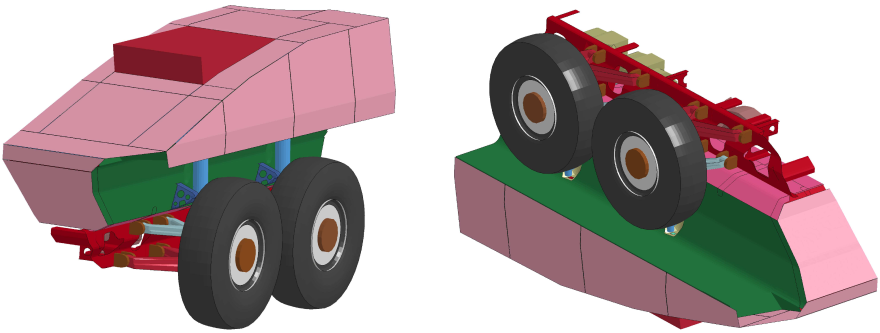

Fig. 2. A quarter of LAV vehicle model adopted to numerical simulations.

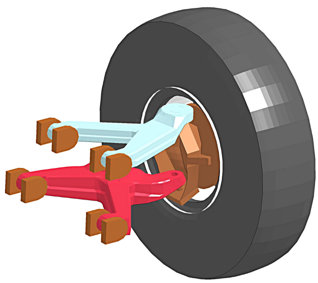

Fig. 3. Multi suspension arms system utilized in LAV model.

In the first stage of modelling methodology development, there was verified a study of model susceptibility to a size of finite elements composing Euler domain in which a pressure wave propagates. For this purpose, models differing with an elements size and a division method were built. In the first approach, a division into four finite elements using a 'transition' method was applied (Fig. 4a). The second approach during division was based on radial propagation of finite elements (Fig. 4b).

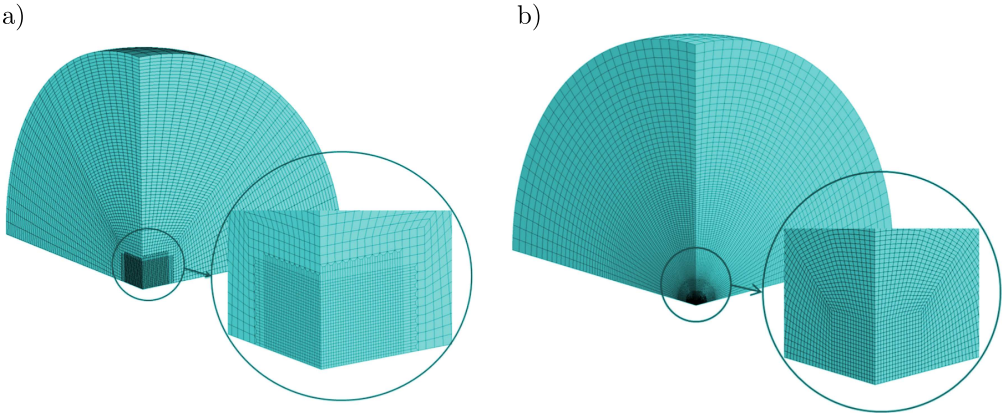

Fig. 4. Model of POT-TNT system with cubic elements: a) "transition" method applied, b) radial propagation "butterfly" method.

The aim of the second stage was to verify and analyse of three variants of a detonation products propagation manner in the case of explosion under:

- tyre – rim – wheel hub (Fig. 6a),
- tyre – triangular Run Flat – rim – wheel hub (Fig. 6b),
- tyre – parabolic Run Flat – rim – wheel hub (Fig. 6c).

For each of the presented variants, loading was realized in the same manner according to STANAG 4569 at 4a level (detonation of 10 kg of TNT under the vehicle wheel – Fig. 5).

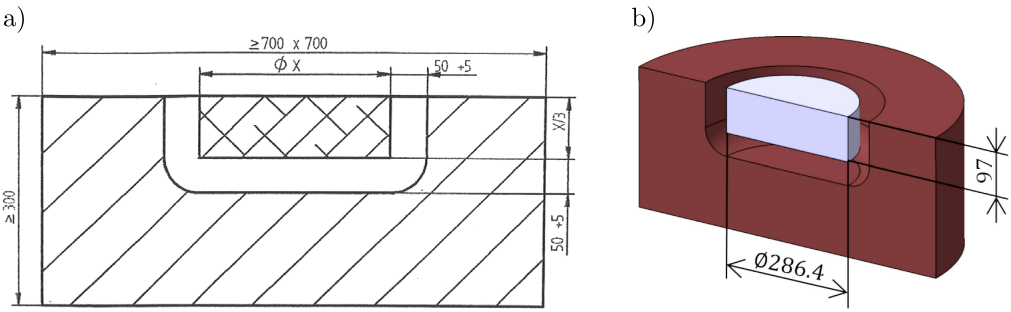

Fig. 5. Dimensions of steel cylindrical foundation depending on explosive material size: a) requirements according to STANAG 4569, b) prepared CAD model of TNT explosive material – steel cylindrical foundation.

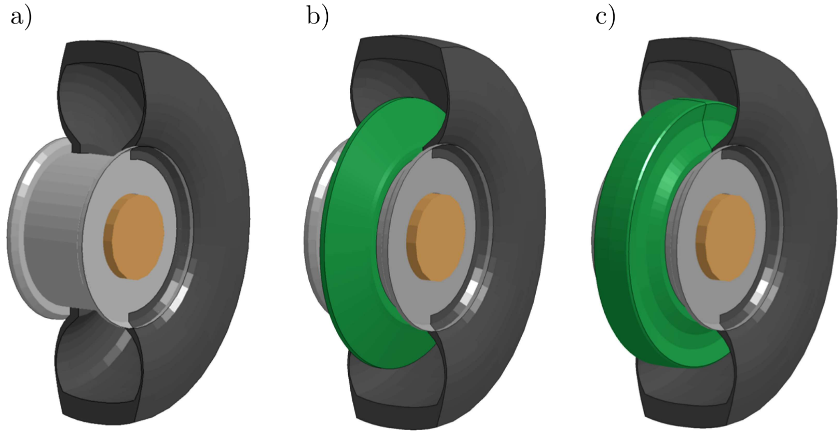

FIG. 6. Model of system: a) system without Run Flat insert, b) ORFF – Run Flat with a triangular cross section, c) ORFF – Run Flat with a hyperbolic cross section.

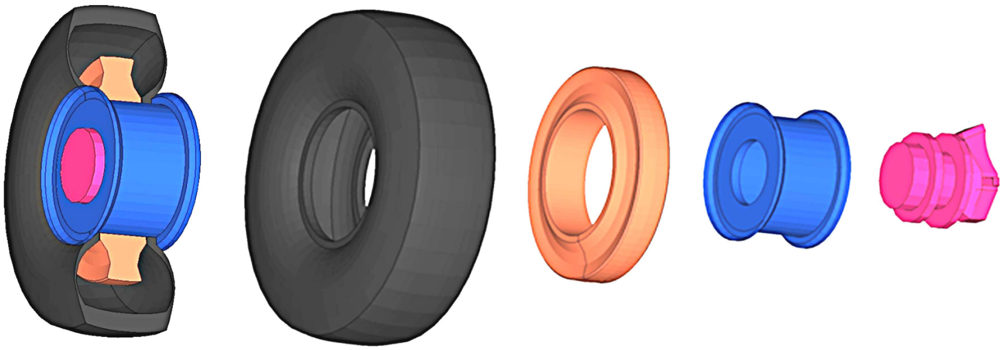

FIG. 7. Elements of steering knuckle – wheel hub – rim – Run Flat (hyperbolic cross section) – tyre system.

Dynamic simulations were carried out using LS-Dyna code, whereas a process of interaction between a wave and the rest of LAV vehicle elements was mapped numerically using gas – solid body coupling based on MM-ALE procedure. The first stage of explosion, i.e., a detonation process was described by Jones Wilkins Lee equation of state (Table 2), whereas the second stage is propagation of a detonation wave. Both of them are realized in Euler description. Each time the detonation place was under the right front wheel.

$$p = A\left(1-\frac{\omega\eta}{R_1}\right)e^{\frac{-R_1}{\eta}} + B\left(1-\frac{\omega\eta}{R_2}\right)e^{\frac{-R_2}{\eta}} + \omega\eta\rho_0 e,$$

where η – ratio of gas density ρ at the given moment to initial density ρ_0, e – specific internal energy of the explosive, A, B, R_1, R_2, ω – experimentally determined coefficient.

Table 2. Parameters of TNT material and JWL equations adopted to numerical analyses.

ρ [kg/m^3]	D [m/s]	A [MPa]	B [MPa]
1630	6930	3.71E5	3.23E3
R1 [–]	R2 [–]	ω [–]	E0 [MPa]
4.15	0.95	0.3	7000

Table 2 includes values of the mentioned constants found in the JWL equation [6] for the TNT used for the computations. The air was modelled with the *MAT_VACUUM card when for density $1.200 \cdot 10^{-12}$ t/mm^3.

MAT_PIECEWISE_LINEAR_PLASTICITY was used for the steel constitutive model. The input parameters are shown in Table 3. CONTRAINED LAGRANGE_IN_SOLID card was coded to produce the interaction between the air domain and the Lagrangian bodies (Table 5) [7]. MAT_HYPERELASTIC_RUBBER was used for the rubber element (Table 4).

Table 3. Material constants for steel used to build the elements of suspension and undercarriage.

ρ [kg/m^3]	E [GPa]	ν [–]	SIGY [MPa]
7.8e3	210	0.3	350
EPS1 [MPa]	EPS2 [MPa]	ES1 [MPa]	ES2 [MPa]
0	0.22	350	600

Table 4. Material constants for rubber elements.

ρ [kg/m^3]	ν [–]	C10 [MPa]	C01 [MPa]
1.1e3	0.499	0.55	0
C11 [MPa]	C20 [MPa]	C02 [MPa]	C30 [MPa]
0	−0.05	0	0.95

Table 5. Parameters of LAGRANG_IN_SOLID coupling.

NQUAD	CTYPE	DIREC	PFAC
6	4	2	0.7
FRCMIN	ILEAK	PLEAK	PFACMM
0.1	2	0.2	3

A layer of elements with NON_REFLECTING boundary conditions was defined on the outer walls of the Euler domain.

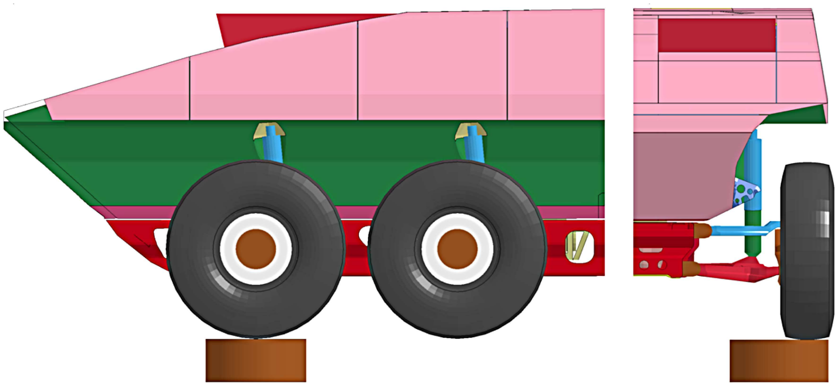

FIG. 8. Model of LAV vehicle with an explosive charge placed in the steel cylinder under the vehicle wheel.

4. Effect of explosion wave realized with the use of MM-ALE method

The most advanced method used for describing an effect of a pressure wave on structures is MM-ALE coupled approach allowed mapping in one model such processes as detonation, explosive waves propagation, interaction with a structure and structure response. Behaviour of a solid body domain (e.g. structural element) is defined with the use of a classic FEM method, whereas behaviour of a gas environment (products of detonation and air) is simulated with the use of ALE method.

Contrary to classic Lagrange formulation, in ALE method the material movement is connected to the movement of nodes and elements. The method is based on possibility of mutual movement of the material of a gas environment and a FEM mesh. A material flow between finite elements is possible [4].

Similarly as for FEM classic method, also for ALE system a critical time step is limited by conditions resulting from the maximum frequency of free vibrations of the system, however, it is additionally limited also by velocity of material flow between the elements and is equal to [5]:

$$\Delta t^{\mathrm{CFL}} = \min\left[\frac{L^e}{c};\ \frac{L^e}{4\nu^{flux}}\right],$$

where L^e – characteristic size of element (equation), c – sound velocity in the material, $\nu^{flux} = \max|\nu^e - \dot{x}^e|$ – velocity of material flow between elements, v^e – velocity of material for an element, x^e – velocity of mesh nodes.

Another problem is mutual interaction between two domains (gas and solid body), which required introduction of an algorithm called numerical coupling. In the realized problem, an interaction process is realized with the use of a penalty function method, where interaction is only introduction of an artificial spring element between a gas element and a solid body node. Force of interaction is proportionate to the value of mutual penetration of both domain. It is worth mentioning that it is required to select the stiffness of this interaction as no significant penetration, and therefore, no "leak" occurs. A penalty function is a frequently applied approach during modelling of a problem of interaction between solid bodies as well as solid body – gas interaction.

5. Results of calculations

Figures 9–10 present characteristic of pressure wave propagation inside the air volume for the selected moments of time of the analysis with a steel cylinder for two analysed variants of division into finite elements. Application of two

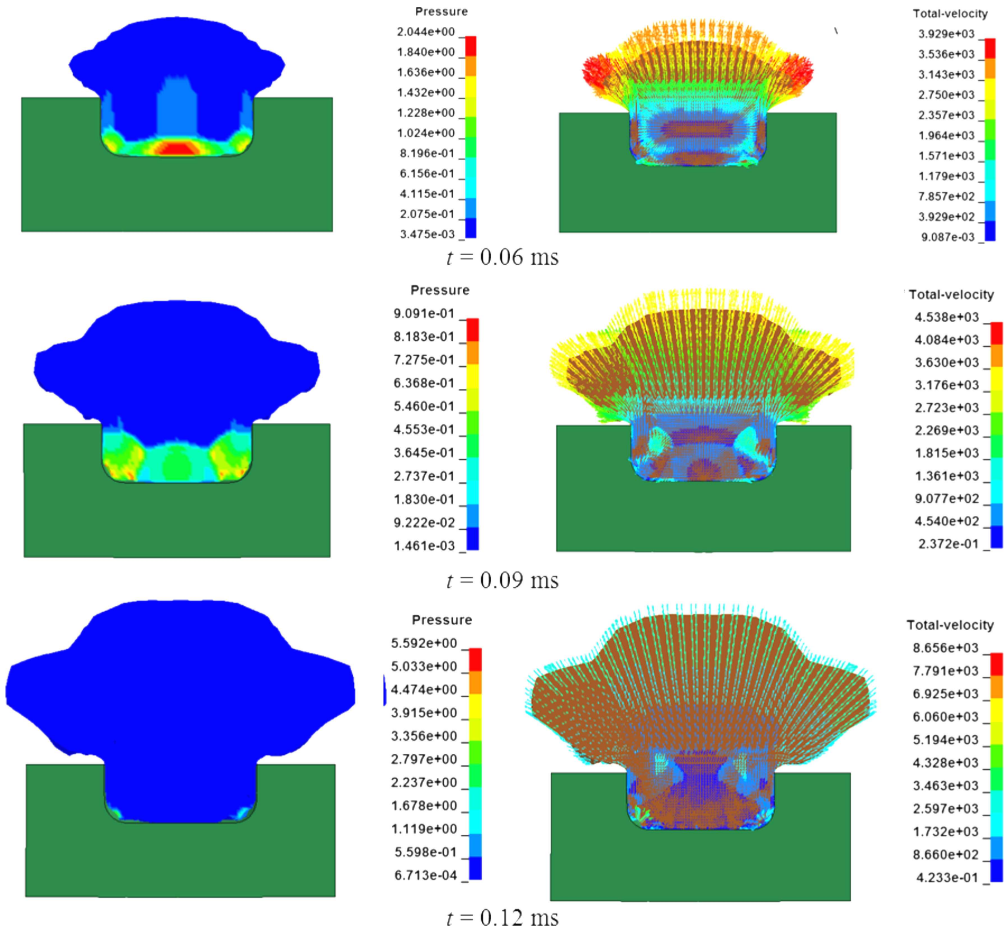

Fig. 9. Pressure wave propagation in the air for a test in which a "transition" method was used.

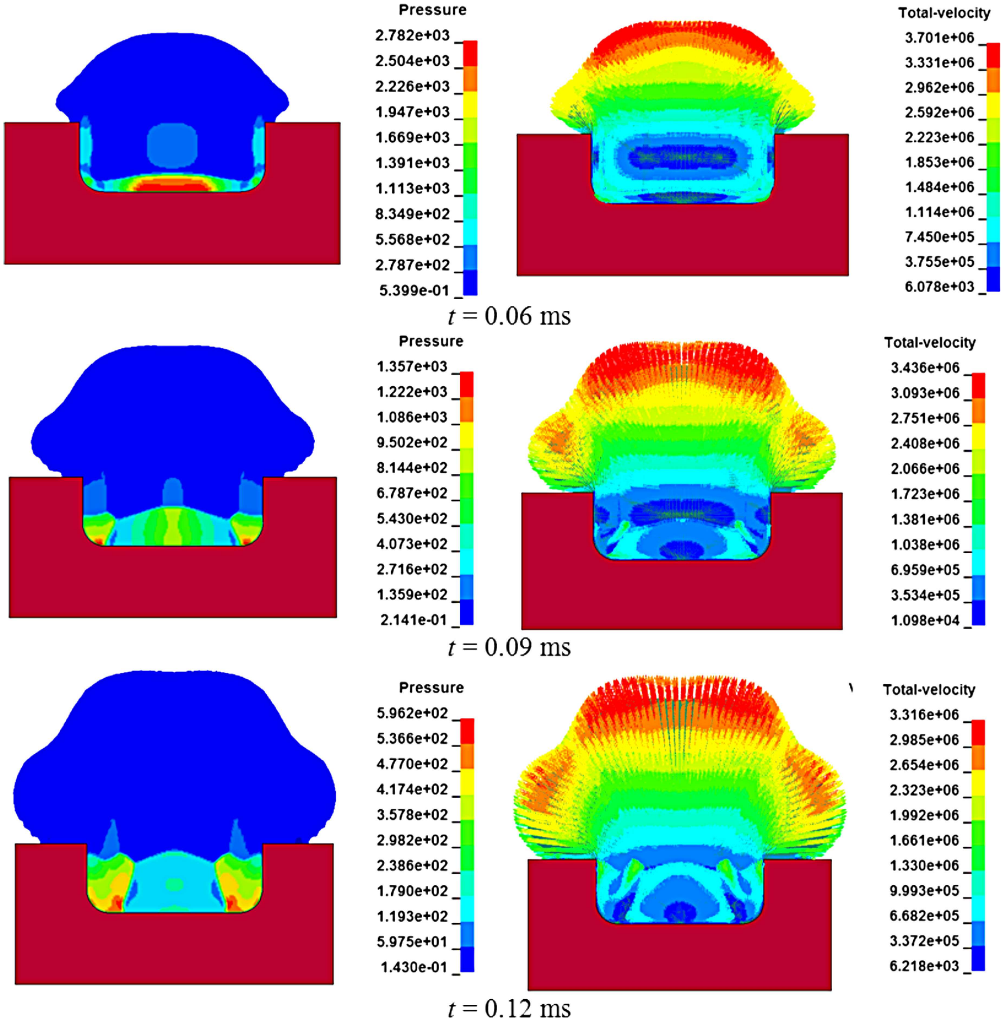

Fig. 10. Pressure wave propagation in the air for a test in which finite elements propagate in a radial way.

above mentioned approaches caused that wave propagation in the air took place in a different way. In the subsequent moments of time there are observed the differences in the shape, wave propagation, pressure and velocity in the air volume. In the case of the model in which in which the elements propagate in a radial way was used, the results are more approximate to the real ones. Owing to the above reason, for the second stage aiming at verifying a method of detonation products propagation, a model with division in which the finite elements propagate in a radial way was used for three variants – Fig. 11.

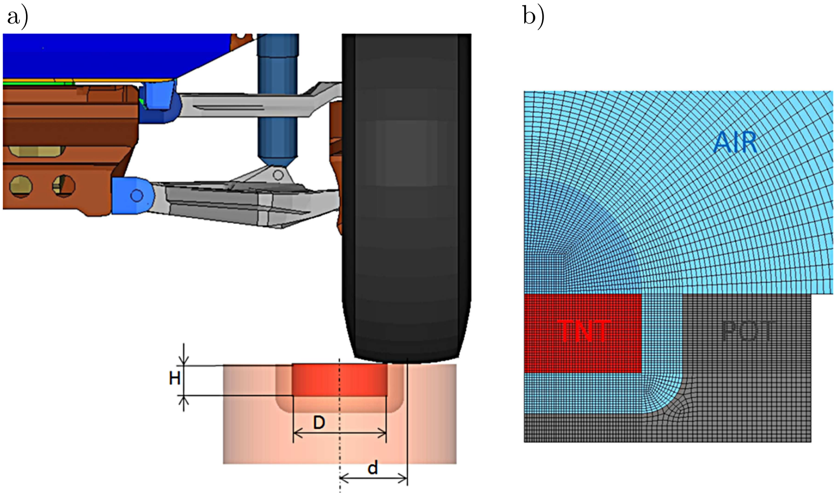

FIG. 11. a) Dimensions of explosive material placed under the vehicle: $H = 97$ mm, $D = 286.4$ mm, $d = 200$ mm, b) method of division of Pot-TNT system into finite elements propagating in a radial way.

The final part of work concerned LAV vehicle along with the detailed/specified elements of a suspension subjected to loading with an impulse wave from deto-

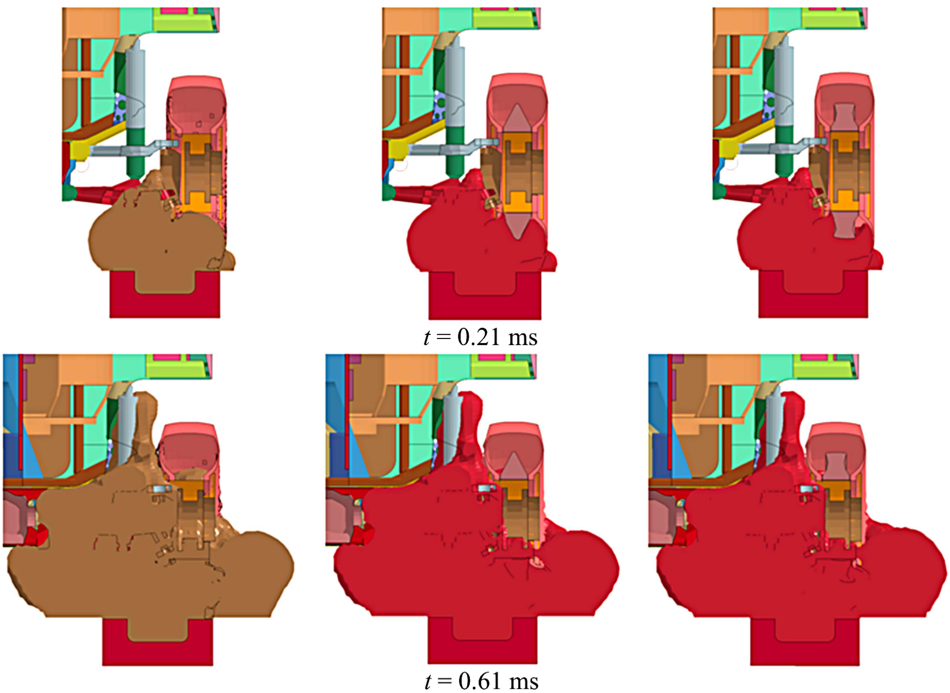

FIG. 12. Propagation of detonation products in the selected moments of time.

nation of an explosive charge according to STANAG 4569 standard. During the tests, there was adopted 1/4 part of the model and symmetry on two directions was assumed. The numerical model lacks a number of vehicle elements, and its main elements are the elements of the body metal plates. To map a real mass of the vehicle, density of the material constituting an outside shell was increased. The initial mass corresponded to the mass of Rosomak vehicle, i.e., 22 000 kg.

Most of the above mentioned elements was modelled with the use of Belytshko-Tsay shell finite elements with 5 points of integration on thickness. Some of the components were reflected with the use of the solid elements. In the tests, an explosive wave effect on the behaviour is going to be mainly analysed.

The results of simulations present characteristic of pressure wave propagation inside the air volume for the selected moments of time as well as values of pressure in the Euler domain – Figs. 12–13.

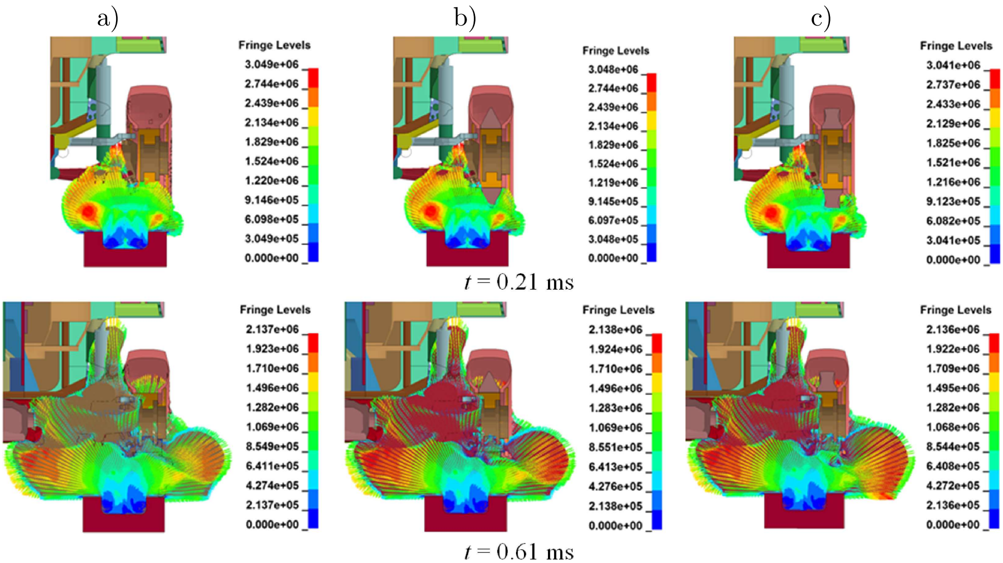

FIG. 13. Distribution of wave velocity in Euler domain [mm/s] for the selected moments of time for variants: a) system without Run Fast insert, b) ORFF – Run Flat with a triangular cross section, c) ORFF – Run Flat with a hyperbolic cross section.

6. Summary

The paper present a methodology for numerical modelling of a shock wave effect on the structure of a light military vehicle. Besides a very important problem, which is coupling of Lagrange and Euler systems realized in the LAGRANGE_IN_SOLID (Table 4) section, division of the environment into finite elements in the Euler reference system significantly influences the obtained results. It is recommended that a size of a finite element, when ALE method is used, is approximate, i.e., a size of the elements was approximate in both Euler and Lagrange domain. Application of big elements to build explosive material will not allow obtaining the parameters in the Chapman-Jouguet point (C-J).

In the conducted numerical analyses, the best results were obtained when division into finite elements using "Butterfly" division method was applied – Fig. 11b.

In the second stage of work, the conducted numerical analyses proved that:

1) Lack of "Run Flat" insert causes faster discharge of detonation products from the underside of the vehicle as compared to the other systems Figs. 12–13.
2) Application of inserts enabling driving after puncturing a tyre in the case of explosive material detonation under the wheel causes diminishing of energy transmitted to the whole system Fig. 14.

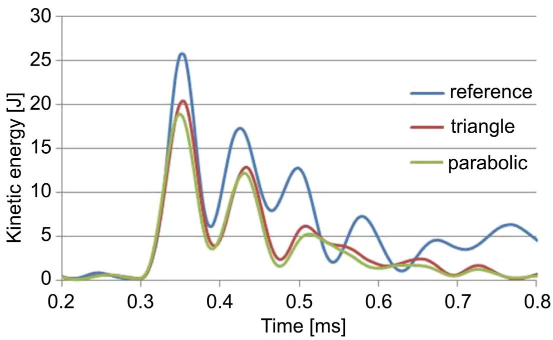

Fig. 14. Kinetic energy of the rim of the wheel under which detonation of explosive material took placed: a) reference – system without Run Flat insert, b) triangle – ORFF – Run Flat with a triangular cross section, c) parabolic – ORFF – Run Flat with a hyperbolic cross section.

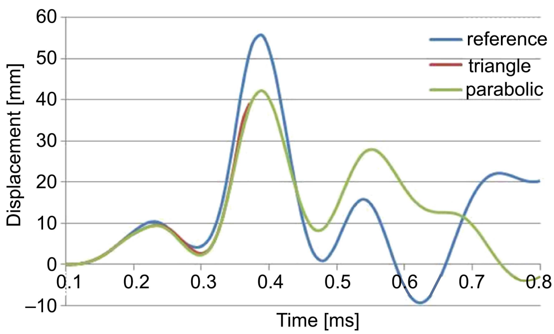

Fig. 15. Displacement of the rim of the wheel under which the detonation occurred MW: a) reference – system without Run Flat insert, b) triangle – ORFF – Run Flat of triangle cross section, c) parabolic – ORFF – Run Flat of hyperbolic cross section.

3) An insert shape does not significantly influences the amount of transmitted or dispersed energy. A more important factor is an amount of rubber material used to build the "Run Flat" system.
4) It is recommended to apply as big "Run Flat" inserts as possible. The inserts of a big size applied in the suspension system allow for better reduction of forces interacting on the whole system.

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