Interaction of the stream of the striking elements with barriers and cumulative ammunition

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Abstract. This paper is aimed at working out the algorithm of multi-contact interaction of solid bodies; it studies the influence of the shape of projectile (damage agent) on its penetration capability. Steel projectiles of different shape have been considered as damage agents: sphere, regular tetrahedron, cube, cylinder and plate. The weight of projectiles has been kept the same. Antitank grenade has been used as a target. The study has been conducted by means of numerical simulation using finite element analysis. The simulation is three-dimensional. Behavior of materials has been described by elastic-plastic model taking into consideration the fracture and fragmentation of interacting bodies. The speed of interaction has been considered within the range of 800 to 2000 m/s. Research results demonstrated significant influence of the projectile shape on its penetration capability. Projectile in the shape of elongated cylinder has shown better penetration capability. Considering the weight of damage agents (except for sphere and plate) their maximum penetration capability has been reached at the speed of 1400 m/s. Increase of the speed of interaction has been followed by intensive fracture of damage agents and their penetration capability thus has worsened.

1. Introduction
State-of-the-art level of anti-tank weapons enables to conclude about ineffective protection of almost any object of armored vehicles provided that it is not equipped with additional protection systems (dynamic, active, etc). The most developed countries (Israel, the Republic of Korea, Russia, the United States of America, France, Germany, Czech Republic, Sweden and others), as well as Ukraine currently have ongoing studies on development of active protection systems (APS) and their components. APS are intended for protection of objects of armored vehicles (tanks, armored infantry fighting vehicles, armored personnel carriers) from attacking anti-tank weapons (antitank rocket grenades, antitank guided missiles, and artillery shaped charges).

Grenade launchers are one of the widespread anti-tank weapons. Lightweight and heavyweight grenade launchers remain in service of almost every country in the world. Hand-held antitank grenade launchers have been actively used in all the armed conflicts and local wars within the last 50 years. Their simplicity, reliability, high mobility, secrecy of using, and power when it comes to approaching the target (armor penetration 600 mm and more) make grenade launchers severe and dangerous weapon. As an example, hand-held antitank grenade launcher RPG-7 is used in more than 100 countries of the world [1]. Among its targets are: M2 Bradley, M1A1 Abrams tanks, etc. Therefore one can see the relevance of research devoted to processes of interaction of damage agents of APS with attacking antitank grenade [2].
Figure 1. Problem statement: (a) longitudinal cross-section, (b) transverse cross-section: 1—sphere with diameter 4.54 mm; 2—regular tetrahedron with the edge 7.48 mm; 3—cube with the edge 3.67 mm; 4—cylinder with diameter 3 mm, height 7 mm; 5—plate with height 2 mm, width 4.95 mm, length 5 mm.

A crucial issue while solving those kinds of objectives is choosing the research methods. In this case numerical modeling would be quite effective and informative. Simulation experiment has the number of advantages over the physical one, such as: obtaining information on stress fields, velocities, and the nature of material fracture at different stages; moreover simulation experiment requires less financial expenses. Numerical simulation does not replace the physical experiment but it supplements it. However, the basic points of applying numerical simulation are in elaboration of adequate models of materials behavior under dynamic loadings and development of calculation procedure that would enable to consider real loading conditions to the maximum extent [3].

2. Problem statement
The two objectives have been solved in the present study. The first objective considers interaction of the flow of damage agents with steel barrier. Simultaneous regular interaction of 360 projectiles made from Steel 3 in the shape of a sphere, 0.34 g weight with the barrier also made from Steel 3, 1.5 mm thick is simulated. The distance between the centers of spheres comprised 10 mm. The range of interaction velocities was between 800 and 2000 m/s.

The second objective refers to simultaneous impact interaction of five fragments of the similar weight, of different shape projected by bursting charge of protective ammunition APS with the model of antitank shaped charge grenade RPG-7. Figure 1(a) illustrates longitudinal cross-section of shaped charge grenade. The grenade consists of the shell made of aluminum alloy D16T, explosive component and copper lining. Figure 1(b) illustrates transverse cross-section of grenade and shows the scheme of its interaction with projectiles. The shell of grenade in the conical portion is two-layered. The exterior layer is 2 mm and the internal layer is 1 mm thick. The material of projectiles is steel ShKh15, the weight of projectiles is the same and comprises 0.39 g. The thickness of copper lining (crater) is 1 mm. We studied the interaction of grenade with projectiles of different shape, figure 1(b). Impact velocity has been studied within the range between 800 and 2000 m/s. At the initial point of time the velocity vector of projectiles comprises 30 degrees to the longitudinal axis of grenade.

3. Results and discussion
Materials behavior is described using elastic-plastic model [4–7]. Intensity limit of plastic deformations is accepted as a local criterion of shear fracture [7]. Simulation is conducted
Figure 2. Configurations of damage agents and barriers at interaction velocity 800 m/s: (a) 10.5, (b) 18 and (c) 25 μs.

Figure 3. Total kinetic energy of particles.

Figure 4. Part of fractured material in flow of particles.

by finite element method, it is three-dimensional and author’s program software is used which allows describing fragmentation of interacting bodies [7, 8].

Figure 2 shows configurations of damage agents and barriers for the interaction velocity 800 m/s at sequential time points; this visually illustrates correct operation of the algorithm for calculation of contact boundaries and model of material fracture.

Curves in figures 3 and 4 show how total kinetic energy of particles is being changed as well as the part of fractured material in particles flow, accordingly. By impact velocity of 2000 m/s the process of barrier penetration by particles is finished by 1.5 μs (curve 3 in figure 3); in this case fracture of particles after barrier penetration continues due to tensile stresses (curve 3 in figure 4) and increases by 3.1 times. After unloading a striker damped oscillations occur, giving
rise to the tensile and compressive stresses with decreasing amplitude over time. The resulting tensile stresses lead to an increase in material fracture [9].

For the velocity of 1400 m/s full barrier penetration occurs at 3.2 µs (curve 2 in figure 3), in this case the part of fractured material of particles by the moment of barrier penetration makes 2.6% (curve 2 in figure 4) and exceeds a little the corresponding value for 2000 m/s which is 2.0%. This is conditioned by the fact that time of contact of particles and barrier at impact velocity of 1400 m/s is almost twice larger; thus it leads to increase of the volume of areas in particles where critical plastic deformations are formed. After barrier penetration one can observe fracture of particles material due to tensile stresses (curve 2 in figure 4) however it is less intensive than for the velocity of 2000 m/s (curve 1 in figure 4).

By interaction velocity of 800 m/s barrier penetration occurs at 4.7 µs (curve 1 in figure 3). Due to less interaction intensity the part of fractured material of particles by the moment of barrier penetration is less than for interaction velocity of 1400 and 2000 m/s (curve 1 in figure 4). Also, in this case particles fracture is not so intensive after barrier penetration.

Now we consider interaction of damage agents of different shape with shape-charge projectile. Figure 5 shows in section areas of interaction of projectiles with the shell after its penetration (for the initial velocity of 800 m/s). We can observe deformation and partial fracture of damage agents. Through-wall penetration of the shell does not occur for the tetrahedron-shaped projectile. Rebound of projectile from the second layer of aluminum shell can be observed.

For the rest projectiles (sphere, cube, cylinder, plate) one can observe through-penetration of two-layered shell. It should be noted that after interaction with the shell projectiles start to rotate which is clearly seen with cylinder in figure 5(d) and plate in figure 5(e); at the initial moment of time longitudinal axis of cylinder coincides with the vector velocity and makes the angle of 30 degrees with the longitudinal axis of grenade. After interaction with the shell both cylinder and plate have been turned by 60 degrees. When we increase the impact velocity (1400 and 2000 m/s) through-penetration of the shell is observed for all the projectiles; however the process of their fracture has also been intensified. With increase of velocity we can also note the decrease of cylinder deflection from the initial spatial orientation. Penetration capability of projectiles can be evaluated in figure 6, where one can see time dependence of the center-of-
Figure 6. Time variations of the center-of-mass velocity of projectiles with (a) 800, (b) 1400 and (c) 2000 m/s. Numbers denote damages from the corresponding projectile: 1—sphere; 2—tetrahedron; 3—cube; 4—cylinder; 5—plate.

Mass velocity of projectiles. All the curves have indicative step-wise view. Areas of the intensive velocity drop correspond to the period of interaction of projectiles with the shell and copper lining adjoining explosive component.

It should be noted that as the shell is two-layered, the first two areas of intensive deceleration of projectiles velocity correspond to the periods when projectiles interact with the first and second layer of aluminum shell. After penetration of the shell velocity of projectiles has not been changed up to the moment of interaction with copper lining and explosive component. During the process of interaction with copper lining we can observe intensive fracture of projectiles and drop of center-of-mass velocity. For all considered interaction velocities projectile in the shape of cylinder has shown better penetration capability; moreover by increasing the interaction velocity the difference in penetration capability of cylinder in comparison with the other projectiles also increases. For example, for the impact velocity 800 m/s, figure 6(a), the difference in velocity between cylinder and sphere having the second large value of velocity comprises 8%; for the impact velocity 1400 m/s, figure 6(b), the difference with the second large value of velocity (plate, tetrahedron) is 25%; for 2000 m/s it is 33%. At the same time, with increase of interaction velocity the difference in penetration capability of sphere, tetrahedron, cube and plate becomes smaller. It should be noted that for all the projectiles through-penetration of grenade cannot be observed—projectiles have fractures and they stop in the copper shell or explosive component. This could be seen in figure 7 illustrating final pictures of destruction in copper lining and explosive component, figure 7(a–c), for different impact velocities and damages in the conical portion of the shell after interaction with the damage agents, figure 7(d).

The velocity of 800 m/s is characterized by damages from penetration of sphere, cube, cylinder and plate into lining and explosive component. By this initial velocity tetrahedron has not penetrated the second layer of the shell, figure 5(b). Interaction velocity of 1400 m/s is marked by damages from all of the projectiles. By velocity of 2000 m/s one can observe additional areas of destruction in copper lining as a result of impact of fragments that are formed after projectiles fracture.

Table 1 shows the values of the crater depth and the explosive component for the projectiles under study. As can be seen from the results not all the considered projectiles penetrate into the layer of explosive component. Depending on the shape of projectile and the interaction velocity their penetration capability also differs. Thus, penetration capability of the sphere is reduced with increase of the velocity and by the velocity of impact of 2000 m/s it does not penetrate the explosive component layer, forming the crater only in the copper lining.
Figure 7. Final pictures of destruction of elements of shaped charge grenade: (a–c) copper lining and explosive component; (a) 800, (b) 1400 and (c) 2000 m/s; (d) conical portion, 800 m/s.

Table 1. Depth of craters formed in the explosive component for different impact velocity.

| Projectile type | 800 m/s | 1400 m/s | 2000 m/s |
|-----------------|---------|----------|----------|
| 1 Sphere        | 11.88 mm| 7.79 mm  | —        |
| 2 Tetrahedron   | —       | 8.95 mm  | —        |
| 3 Cube          | 2.48 mm | 14.44 mm | 3.96 mm  |
| 4 Cylinder      | 6.81 mm | 14.62 mm | 13.38 mm |
| 5 Plate         | 4.28 mm | 1.66 mm  | —        |

Tetrahedron penetrates the explosive component only at the velocity of 1400 m/s. Velocity of 800 m/s leads to tetrahedron rebounding from the second layer of aluminum shell, by 2000 m/s it is destructed into fragments forming two small craters in the copper lining. Cube-shaped projectile demonstrates the maximum depth of crater in the explosive component by the velocity of 1400 m/s. Penetration capability of cylinder is largely influenced by its spatial orientation. At the velocity of 800 m/s cylinder projectile behaves as follows: it turns around after penetration of the aluminum shell and its further interaction with copper lining and explosive component occurs along the side face. The crater formed in that case is significantly smaller than the one formed by the sphere projectile. Cylinder spatial orientation settles with increasing the impact velocity and it interacts with the copper lining and explosive component by front face leading to formation of larger craters in the explosive component compared to other projectiles. Plate undergoes intensive fracture with increase of velocity and it is marked by the lowest penetration capability.

4. Conclusion
Conducted studies revealed that in the considered conditions of interaction the shape of damage agents influences significantly their penetration capability. Elongated projectiles (cylinder) are also largely influenced by their spatial orientation. The larger penetration capability under the considered conditions has been demonstrated by the cylinder-shaped projectile. Taking into account the weight of damage agents in this case their maximum penetration capability (except for sphere and plate) has been reached at the velocity of 1400 m/s. Further increase of interaction velocity shows intensive fracture of damage agents and their penetration capability therefore goes down.
Acknowledgments
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