Numerical analysis of impact of a bullet with cumulative head onto the rod armour with the circular cross section in the aspect of strain of armour elements made of selected steel types

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Abstract

On the base of the observation of military actions in the world, especially Polish army participation in stabilisation missions, it can be observed the change of the way of the equipment application and conducting the actions. Nowadays the biggest threat is posed by the two types of ammunition. First of them includes any types of mines and improvised explosive devices in which the main destructive factor is a pressure wave formed due to explosion of the explosive material. The other group includes bullets with cumulative heads. These bullets, due to their low production costs, usage simplicity and great penetration (reaching even to 900 mm of RHA armour steel [1]), are frequently used to destroy, among others, military armoured vehicles. Due to great penetration of these bullets, the essential problem is protection against such type of weapons. One of the method are rod armours. The paper presents the results of numerical analyses of impact of a bullet with the cumulative head of PG-7G type onto the rod armour built of elements with the circular cross section. There will be performed an estimation of the application possibilities of the selected material type of rods.

Keywords: numerical analysis, finite element method, armour, impact

1. Wstęp

While observing the currently waged military conflicts, a change of the way of fighting and using the equipment can be noticed. Nowadays, the greatest threat is from two kinds of firing assets. The first group includes bullets with cumulative heads and mines of any kind as well as improvised explosive devices (IED). In this case, the main destructive force is the pressure wave originated as a result of explosive material detonation. The other firing asset, bringing the greatest threat, is a bullet with a cumulative head. In this case, the essential destruction factor is a cumulative stream capable to penetrate up to 900 mm of RHA armour steel [1]. This bullets are characterised by: high effectiveness, relatively small mass, small dimensions and low production costs. All these features make it a very popular firing asset with the partisan and terrorist detachments.

Due to great penetration of the bullets with cumulative heads, it is very import ant to develop an effective method of protection against such a firing asset. Nowadays, to reach this aim, there are applied four types of armours: reactive armours, active armours, thick steel armours (specific armour) and rod armours. The latter type is, due to its relatively small mass, simplicity of construction and low price, is frequently implemented to protection of the vehicles which have to be characterized by high mobility. They include, among others, light-armoured tactical vehicles and patrol ones. Their common feature is high durability and high capability to move. Therefore, each additional load decreases capability to perform their fundamental task.

In order to maintain high mobility of a vehicle, it is necessary to minimise the mass of the elements of additional equipment including the armour protecting against rocket bullet equipped with cumulative heads. However, it cannot be performed in an uncontrolled manner causing hindering realization of fundamental tasks executed with the aid of this equipment. Therefore, in the process of designing a rod armour it is very important to understand the principle of operations of this type of protection asset as well as its operations mechanism. It is necessary also to minimize its mass.

The further part of the paper will present analysis of behaviour of a rod armour, made of two types of steel, during contact with the bullet equipped with a cumulative head.

2. Boundary condition

To perform analysis of behaviour of a rod armour during contact with the bullet equipped with a cumulative head, there were conducted numerical simulations based on a finite element method. During the simulations, a previously developed numerical model of PG-7G bullet was used [2]. It was assumed that the armour consisted of rods of 500 mm length distant by 83 mm from each other. This distance constitutes 80% of maximum diameter of the bullet head part. All degrees of freedom were removed from the rods ends (fig.1), and the whole bullet was given the initial velocity of 200 m/s. It is average velocity the bullet moves with after leaving the grenade launcher. It was assumed that the bullet impacts at the half of the rods length, exactly between them.

To represent behaviour of the analysed materials of the armour (St3 steel and steel of high strength with the plasticity limit amounted to 2000 MPa), in both of the cases there was applied a bilinear model of material with reinforcement. To represent the model reinforcement under high velocity of deformations, Cowper-Symonds model was used, in which the plasticity limit is calibrated by the coefficient determined with the formula [3]:

$$1+\left(\frac{\dot{\varepsilon}}{C}\right)^{1/p} \tag{1}$$

where: $\dot{\varepsilon}$ – strain rate, C, p – coefficients dependent on material

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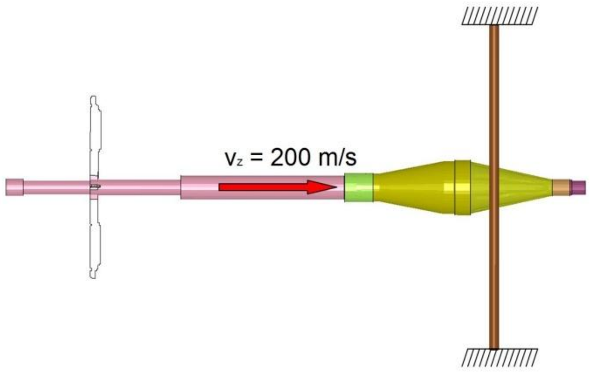

Figure 1: Boundary conditions

The boundary condition was defined between steel rods in the form of contact based on a penalty function of automatic_single_surface type. This contact is widely applied in analysis of such type of phenomena as crash since it assumes the possibility of contact among all the elements as well as the elements of the same body, what is possible in the case of large deformations occurring during crashes.

3. Algorithm of solution determination

All calculations were carried out with the use of LS-Dyna code which is purposed for calculations of the strongly non-linear and dynamic problems using, among others, the finite elements method. On the basis of the information included in the numerical model, it builds the dynamic equation of motion in the general form [3]:

$$M\ddot{q} + C\dot{q} + Kq = f \tag{2}$$

where: M – inertia matrix, C – damping matrix, K – structure stiffness matrix, q – vector of the generalized displacements of nodes of calculation model, f – vector of outer forces reduced to nodes of the model.

Matrixes M, K as well as vector f are determined in the inner node systems of coordinates through aggregation of the matrix elements. Damping matrix C is frequently defined as a function dependent on the inertia matrix and stiffness matrix:

$$C = \alpha M + \beta K \tag{3}$$

where: α, β – are constant coefficients.

Equation (2) should be supplemented by initial conditons at the start of the simulation t_0:

$$q\big|_{t=t_0} = q_0, \quad \dot{q}\big|_{t=t_0} = \dot{q}_0 \tag{4}$$

The differential equation (2) with boundary conditions (4) is next integrated in order to determine the displacements of the model nodes. LS-Dyna code uses an explicit algorithm of integration, called also "step by step" method or direct integration. It is applied to equations which were not subjected to any transformations.

The direct integration method is based on two assumptions. First of the them claims that the equation of motion is to met only in the selected time moments "t" between which a certain distance, called an integration step Δt , exists. It means that only the assumed moments are considered:

$$0, \Delta t, 2\Delta t, \ldots, t, t+\Delta t, \ldots, T \tag{5}$$

where: Δt – integration step, t – selected time moments, T – the end of integration range.

The other assumption assumes the specific changeability character of displacements, velocity and accelerations The equation of integration comes down to searching the only in selected moments $t_0 + i\Delta t$ with the use of the given values of the function in the previous moments t_0, $t_0 + \Delta t, \ldots,$ $t_0 + (i - 1)\Delta t$ The values of displacements, velocities and accelerations at the initial moment t_0 are given and r result from the initial conditions, however in the further integration steps they change according to the dependency:

$$\begin{aligned} \dot{d}_t &\cong \frac{1}{2\Delta t}\left(d_{t+\Delta t} - d_{t-\Delta t}\right) \\ \ddot{d}_t &\cong \frac{1}{\Delta t^2}\left(d_{t-\Delta t} - 2d_t + d_{t+\Delta t}\right) \end{aligned} \tag{6}$$

After introducing the differentia operators into the equation of motion (2), the following equation is obtained:

$$\begin{aligned} &\frac{1}{\Delta t^2}\left(d_{t-\Delta t} - 2d_t + d_{t+\Delta t}\right)M \\ &+ \frac{1}{2\Delta t}\left(d_{t+\Delta t} - d_{t-\Delta t}\right)\left(\alpha M + \beta K\right) + Kd_t = P_t \end{aligned} \tag{7}$$

From the above equation, displacements $d_{t+\Delta t}$ in moment $t + \Delta t$ are determined.

The integration method is conditionally stable so application of small integration steps Δt is required. In order to assure the method stability, Courant-Friedrischs-Levy condition has to be met:

$$\frac{u \cdot \Delta t}{\Delta x} \le C \quad \Rightarrow \quad \Delta t \le \frac{C \cdot \Delta x}{u} \tag{8}$$

where: u – velocity of propagation of sound waves in the material, Δt – integration step, Δx – characteristic length of a finite element, C – constant.

As a result of integration of the equation of motion, the values of displacements, velocities and accelerations for the particular nodes are obtained. The values of parameters in any place of the model are interpolated on the basis of the values in the nearest nodes.

4. Results

As a result of the conducted numerical simulations, the course of behaviour of rods made of two steel types during contact with a bullet equipped with a cumulative head. Figures 2 – 4 present deformation of rod made of St3 steel for the subsequent moments of time. A very strong deformation of the Middle part of the rod is visible in figure 2. After of bullet crosses between the rod elements of the armour (fig.3), the middle part of the rods is slightly deformed. The increase of deformation of the rest part of the material is visible in the subsequent moments. At the final stage of analysis (fig.4), the rod deflection is very similar to the deflection in the case of static loads. Rod deflection for time moment t=0.7 ms – rod made of steel of high strength

Figure 2: Rod deflection for time moment t=0.46 ms – rod made of St3 steel

Figure 3: Rod deflection for time moment t=0.7 ms – rod made of St3 steel

Figure 4: Rod deflection for time moment t=1 ms – rod made of St3 steel

Figures 5-7 present the course of deformation of the rod, made of steel of high strength, determined on the base of the result of numerical simulations The course of deformation has a different character than in the case of St3 steel. Rods elements are subjected to deformation in their middle part (fig. 5), and at the further stage, an impact impulse causes practically parallel displacement of the rod material (fig. 6). The state of deformation in the last recorded time moment has a similar character as in the case of St3 steel.

Figure 5: Rod deflection for time moment t=0.46 ms – rod made of steel of high strength

Figure 6: Rod deflection for time moment t=0.7 ms – rod made of steel of high strength

Figure 7: Rod deflection for time moment t=1 ms – rod made of steel of high strength

Different character of the deformation course of two types of steel is reflected in maximum displacements. Figure 8 presents the maximum displacement of the Middle part of the rod. It can be seen that, in the case of high strength steel, the course of displacement is softer and more close to a linear one. Bucklings and folds in the graph can be related to the wave effects occurring in the rod material. The material of high strength steel plasticizes itself at rather high strains value which was additionally raised through introducing the effect of strengthening of the material itself. In the case of material made of St3 steel, the graph of a change of displacement of the middle part of rod has a bilinear character. During contact of armour elements with a bullet, displacements grow very fast, however, after the bullet head crosses between them they significantly slow down. This effect should be explained by the fact that at the initial stage of analysis, the bullet head jostles the rods causing the plasticizing of the material. At the further stage of analysis, the bullet does not interact on the rods elements, however the inertia of the material, low stiffness of the plasticized material and high accelerations to which the material was subjected at the initial stage, cause further deformations of displacements.

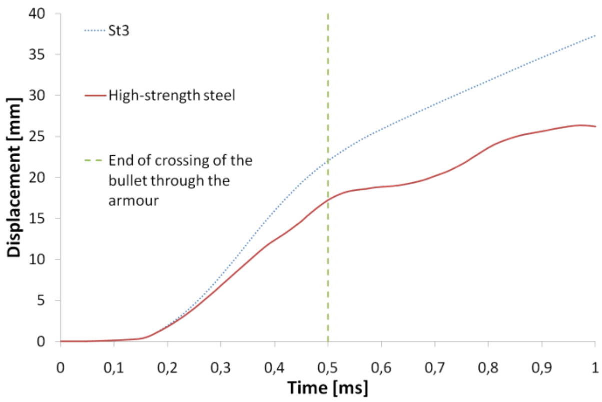

Figure 8: Comparison of maximum acceleration of the middle part of the rods

Highly great displacements and their fast growth during the bullet impact caused occurring of strains of a significant value. It should be noticed here that in the case of numerical simulations conducted for both of the materials, the possibility of material destruction was not taken into consideration.

In the case of St3 steel, the highest strains were recorded on the direction overlapping with the rods axis (axis x in figure 9). They amounted to 1530 MPa. On the rest of the main directions, the strains were at least twice as much lower. While observing the course of maximum strains, it can be noticed that their value increases up to the moment of when the bullet crosses the armour. In the further part of analysis, the strains decreases despite the fact that displacements are still growing. It results from the fact that during analysis, up to the moment the bullet crosses between the armour rods, deformation was increasing mainly in the middle part of the rod where the highest strains were observed. At the further stage, the greatest part of the armour was moving, while the middle part was decreasing its displacement in respect to the system part surrounding it.

Highly similar course character of maximum strains of the middle part of the rod was observed during analysing the behaviour of the armour made of high strength steel. In this case, the strains on direction x (figure 10) are three times as much greater than on the rest of directions.

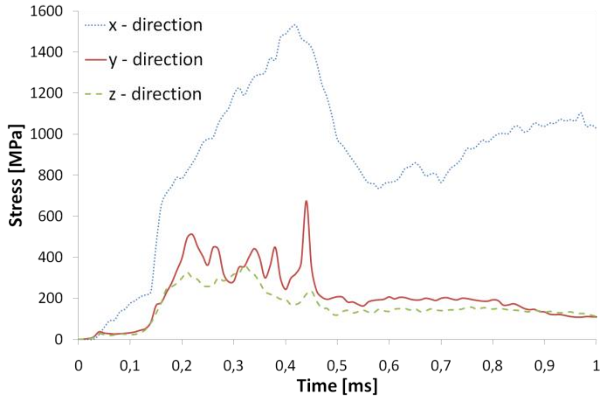

Figure 9: Courses of maximum strains of the middle part of the rod made of St3 steel for the main directions.

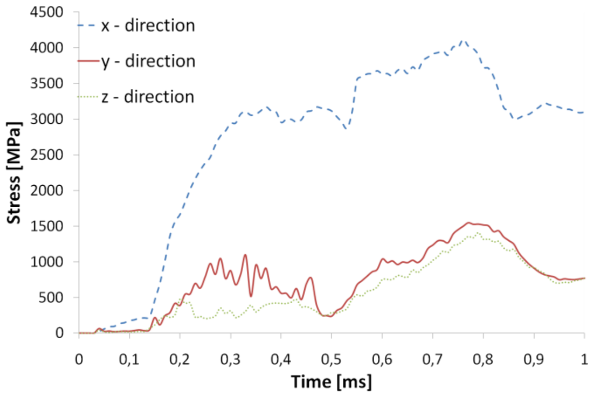

Figure 10: Courses of maximum strains of the middle part of the rod made of high strength steel for the main directions.

5. Summary and conclusions

The paper dealt with the results of numerical simulations of the impact of the bullet with cumulative head of into the rod armour built of circular rods made of two types of steel. The course of deformation of the armours elements as well as the graphs demonstrating maximum displacements and strains of the middle part of the rod were presented. On the basis of the enclosed results, it can be find out that both of the materials can be applied for constructing the rod armours since the differences in maximum displacements are so slight that the bullet would be subjected to destruction in both of the cases. However, due to the smaller drawing of the elements made of high strength, it should be assumed that the more recommended material for constructing the elements of this type are materials of higher plasticity limit and greater Young modulus. These materials, however, due to high velocity of deformation should be characterised by additionally low fragility.

A special attention should be paid to the graphs concerning the strains observed Turing the impact of bullet into the armour. In both cases, the strains on the axis overlapping with the axis of rods were at least twice as much higher than the strains on the other axes. It is a very precious indication for constructors involving in designing of such type of protection asset. The presented results of simulations showed that the armours of this type operates mainly for stress, what has a significant meaning for the selection of a proper cross section of the rods as well as for the proper cutting out the fragments of their surface in the case of optimizing the mass.

The results of the presented analyses will be used for demarcation of the optimizing direction of rod armours made of another cross sections developed in the Department of Mechanics and Applied Computer Science, Military University of Technology.

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