Modelling of Bulging Steel-Elastomer Armour Applied Against Long-rod Projectiles

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Abstract. A protection concept, so-called bulging armour, applied to mitigate effects of kinetic-energy penetrators is hereby discussed basing on an experimental and numerical study. The laminated steel-elastomer armours take advantage of the rubber interlayer that deforms rapidly under an impact causing bulging of the side steel plates. Long and slender kinetic-energy projectiles made with a tungsten alloy tend to fracture disturbed by an asymmetric contact with the deforming plates. In the performed experimental study, the laminates with the natural rubber interlayer of different thicknesses are impacted by the kinetic-energy penetrators with the initial velocity above 1500 m/s. The numerical analysis accompanies the ballistic test complementing it by a detailed insight into the defeat mechanism. The performed investigation proves a protective efficiency of the discussed passive armour and explains its physical background.

1. Introduction

To improve the ballistic efficiency of a protection system applied against kinetic threats, the following defeat mechanisms are maximized: deceleration, fragmentation, erosion or deflection of a threat. These defeat mechanisms constitute the basis of design principles of modern armours mitigating kinetic-energy (KE) penetrators, which belong to one of three groups: active, reactive and passive armours. In the reactive and active systems, a part of the armour is propelled against the incoming threat either at some distance away from a protected combat vehicle (active) or at the moment of an impact (reactive). In the active armour concept, a small plate (or some other projectile) is launched towards the kinetic threat. Explosive reactive armours (ERA) are composed of a high-energy explosive sandwiched between two steel plates adjusted at an angle. When hit by a shape-charge jet or by a kinetic-energy (KE) projectile, the explosive detonates forcing the front plate to move. The accelerated plate reduces the threat effective velocity and changes its angle of incidence. An asymmetric impact destabilizes a striker inducing an angular momentum in it so that it can turn to high yaw before the contact with the target or be fragmented.

Instead of using an external energy source (such as an explosive layer) to move the side plates against a threat, passive armours or non-explosive reactive armours (NERA) reuse the energy of an impact. The explosive interlayer is changed to another material, which enforces a rapid deformation of the side plates against the threat. Two steel or metal plates may sandwich then an elastomer or polymer liner. When struck by a jet, it changes its shape rapidly causing a localized bending or bulging of the side plates in the area of the impact. As the plates bulge, the impact point shifts with the plate deformation, increasing the effective thickness of the armour and destabilizing a kinetic threat. The bulging is a less powerful effect than the plate movement caused by a detonation in an explosive...
reactive armour. Thus, it offers a lower level of protection than a similarly-sized ERA. However, passive solutions may be lighter and safer to handle. Typically, this protection solution is used against shape-charges warheads, e.g. [1-2]. In reference [3], rubber composite and explosive reactive armours were compared and it was concluded that the former offered good protection and were more environmentally friendly. The study described the interactions between the rubber composite armour and shape-charge jets. In [4], the resistance capability of sandwich composite armours with different sandwich materials was analysed in a 2D simulation. It was concluded that the material strength and density are the relevant factors in the resistance of composite armours. A mechanism describing the target/threat interactions based on a theoretical approach was discussed by [5]. Whereas, in [6] effects of the rubber layer thickness and obliquity of an armour applied against shape-charges were studied through a theoretical modelling and ballistic experiments. A discussion about KEPs fracture caused by the contact with a flying plate may be found in [7]. The shape and motion of the residual projectiles were determined and the effect of the interaction was quantified in terms of changes in its length, velocity, momentum and kinetic energy. It was shown that the parameters of the largest influence on the disturbance of the projectile were the plate thickness, its velocity and the movement direction.

In the current study, the discussion concerns a passive armour solution comprises of the natural rubber interlayer between the side armour steel plates. As the threat, tungsten heavy alloy Y925 long-rod (KEP) projectiles are used. In the experimental campaign, the down-scaled rods are shot against targets but their length to diameter ratio is the same as for threats used to evaluate the protection level, i.e. $L/D = 20$. Several configurations with the natural rubber interlayer of different thicknesses are prepared and tested against the KE projectiles with the impact velocity above 1500 m/s. Due to a multi-flash X-ray radiography, the images depicting the threat and target behaviour in different time steps are obtained allowing observations of the defeat mechanism provided by the tested armour concept. The experimental results are then completed by a numerical simulation in the Ls-Dyna explicit code, which provides an analysis of the experimentally observed deformation and fracturing of the rod and plates. The study proves the protective efficiency of the presented passive armour concept and analysis behaviour of a protection solution which takes advantage of the mechanism of bulging to mitigate kinetic-energy penetrators.

2. Threat-target configuration
A combination of tungsten (wolfram) properties – resistance to high temperatures, hardness, density and strength, make it an important raw metal for the military industry. More than half of the extracted tungsten is consumed for the production of tungsten carbide alloys. A large part of raw tungsten is compounded with cobalt and nickel and known as tungsten heavy alloys (WHA). Less than 10% of raw tungsten is used in other chemical compounds. Tungsten heavy alloys are two-phase composites consisting of about 90% pure tungsten in a matrix of nickel, iron and cobalt. Addition of these elements improves the ductility and machinability of the non-alloyed tungsten. In consequence, the WHA alloys are characterized by a unique combination of high density, high strength, moderate hardness and ductility, moderate electrical and thermal conductivity and good corrosion resistance, [8].

The WHA alloys are produced by powder-metal and sintering processes since the consolidation of pure tungsten (density 19.3 g/cc) requires excessively high temperatures. During sintering, low melting additives form a liquid and the material thickens rapidly to form a fully dense two-phase structure. The mechanical properties of WHAs can be tailored through compositional changes influenced both by tungsten content and the Ni:Fe ratio, and processing conditions.
In the current investigation, the WHA known under the grade name Y925 (prod. Kennametal Mistelgau) is used to manufacture the KE projectiles. In this alloy grade, dissolved tungsten grains are embedded in the matrix consisting of nickel, iron and cobalt - tungsten is 92.5% of the total element contain. This particular alloy is present on the market for decades and has been described in several studies regarding its mechanical and ballistic behavior. In the references [9-10], there are given results of material tests on the grade Y925 of the Kennametal Mistelgau production, the same alloy which is investigated in the present study. According to the studies [9-10], at quasi-static conditions, the linear elastic behavior of the Y925 WHA grade ends up about 1300 MPa. The Young modulus determined by the authors is equal to 347 GPa and the ultimate tensile stress for 12 tested samples varies between 1292 and 1400 MPa, with the average 1343 MPa.

For the shots, the targets are inclined at 60° NATO, Fig. 1. In the down-scaled configuration, the projectiles with the diameter and length of 4 and 80 mm are shot against the targets with the size 40 x 200 mm. The targets are laminates composed by the 4 mm thick front steel plate – the rubber interlayer – and the 4 mm thick back steel plate. The side plates are made with the rolled homogenous armour steel (RHA). The RHA armour steel grade is a high strength martensitic steel with the standardized composition (e.g. [11]) and material properties (i.e. hardness about 380 HB, UTS about 1200 MPa) produced by most of armour steel manufactures. The natural rubber with different thicknesses is chosen to evaluate the behavior of the elastomeric interlayer in the protection system. To allow a free expansion of the rubber layer and thus, a movement of the plates, no adhesive is used to bond the components. The natural rubber used in the presented test configuration is characterized by the hardness 70 Shore (scale A) and the tensile strength of 25 MPa at the maximal elongation reaching 700%,[12].

3. Experimental investigation

To a shot, a KE projectile is inserted in a plastic sabot, which stabilizes the projectile in a barrel and during the first flight phase. The sabot’s mass is 19.4 g and the mass of the KE projectile made with the tungsten alloy Y925 is 19.1 g. The total mass of the KE projectile in the sabot is 38.5 g. The aluminum cup stabilizes the rod during a flight without affecting its behavior while target penetration. The down-scaled projectiles are inserted in sabots and launched by a powder gun cal. 25. A target is prepared to a shot in an instrumented catch box – as presented in Fig. 2, which depicts the testing stand.

Figure 1. (a) Down-scaled KEP with $L/D = 20$ and its sabot, (b) target configuration.
Figure 2. Experimental stand: 1 – powder gun, 2 – optical light barrier, 3 – tested target in the catch box, 4 – shots are recorded by multi-anode X-ray radiography from the side.

During the impact test, the initial velocity is measured by a light barrier. Each shot is recorded by a multi-anode flash X-ray radiography Fig. 3, which follows the projectile trajectory from the side view. In the case of high-velocity KEP impacts, it is difficult to extract residual fragments of projectiles after the shot. The X-ray radiography captures interactions between the threat and target during a shot and these images are often the only evidence of the experimental investigation. The images have an improved quality because each time step is separately recorded. [13]. Fragments and debris, which cannot be found after a test, are detected and distinctly visualized on the images. Finally, the X-ray images are used to calculate the residual velocity of the projectiles and debris.

3.1. Experimental results

In the experimental investigation, the configurations based on the discussion given in [14] are tested against the down-scaled long-rod penetrators. Firstly, two 4 mm thick RHA steel plates with a 15 mm air gap between them are prepared to a shot. This configuration is considered as the reference to show effects of the rubber application. In the subsequent configurations, the rubber interlayer with different thicknesses is sandwiched between the RHA steel plates. To allow a free expansion of the rubber layer and thus, a movement of the plates, no adhesive is used to bond the components. The rubber layers have the thicknesses 5, 10, 15 mm and also two times 10 mm, respectively. All laminates are inclined at the NATO angle 60°. At this obliquity, the line of sign (LOS) along which a projectile perforates the target is equal to 28, 38, 48 and 58 mm, respectively. At the moment of impact, the rods have a velocity higher than 1500 m/s. The impact velocities and selected characteristics of the shots are collected in Table 1.

Comparing the velocity loss measured for the configurations with different rubber thicknesses and the configuration without the rubber, it may be noticed that the interlayer does not affect greatly the residual velocity of the rod fragments. An average 5% decrease of the rod velocity after the sandwich perforation is not significantly high to be considered as a proper defeat mechanism. However, on the flash X-ray images presented in Fig. 3, it may be seen that the rods which passed thought the steel-elastomeric laminates are fragmented. This effect does not occur when the KEP perforates the configuration without a rubber but with the air gap instead – in that case, the penetrator is undisturbed and undamaged. The strongest fragmentation of the rod occurs when a 2 x 10 mm thick rubber is inserted between two steel plates. The rod cracks in four smaller pieces. In the case of the laminate with the 5 mm thick rubber interlayer, only the rear part of the striker is separated from its main length after the perforation. It might be seen thus, that the remaining front part is strongly bent. On all images, a plug ejected from the rear steel plate might be recognized (it is a piece slightly below the shape of fragmented threats).
Figure 3. (a) Experimental stand with the details of the X-ray device. (b) Schema of the fast multi-frame X-ray imaging: a sequence of short X-ray pulses is converted by a scintillator to a visible light registered by a fast multi-frame camera.

| Interlayer     | Angle | LOS [mm] | \(v_0\) [m/s] | \(E_{\text{kin}}\) [J] | \(v_R\) [m/s] | \(V_R/V_0\) [-] |
|----------------|-------|----------|----------------|----------------|--------------|----------------|
| 15 mm AIR      |       | 48       | 1606           | 2463           | 1525         | 0.95           |
| 15 mm rubber   |       | 48       | 1520           | 2206           | 1462         | 0.95           |
| 10 mm rubber   | 60°   | 38       | 1526           | 2224           | 1451         | 0.95           |
| 5 mm rubber    |       | 28       | 1540           | 2264           | 1464         | 0.95           |
| 2 x 10mm rubber|       | 58       | 1586           | 2402           | 1472         | 0.92           |

The rubber expands and shrinks during the KEP penetration of the laminate, which is well captured by the X-ray images presented in Fig. 4. The expanding rubber causes bending of the steel plates, which
were initially parallel and after the perforation, they are bent in opposite directions. This mechanism is called ‘bulging’.

| Rubber thickness [mm] | X-ray images at subsequent time steps |
|-----------------------|--------------------------------------|
|                       | 0μs | 25 μs | 100μs |
| No rubber             | ![Image](image1.png) | ![Image](image2.png) | ![Image](image3.png) |
|                       | 0μs | 75μs  | 125μs |
| 5                     | ![Image](image4.png) | ![Image](image5.png) | ![Image](image6.png) |
|                       | 0μs | 50μs  | 125μs |
| 10                    | ![Image](image7.png) | ![Image](image8.png) | ![Image](image9.png) |
|                       | 0μs | 75μs  | 125μs |
| 15                    | ![Image](image10.png) | ![Image](image11.png) | ![Image](image12.png) |
|                       | 0μs | 75μs  | 125 μs |
| 2x10                  | ![Image](image13.png) | ![Image](image14.png) | ![Image](image15.png) |

**Figure 4.** Fractured long-rods after targets perforation in the flash X-ray images.

3.2. **Bulging effect**
Elastomers are built up by long molecule chains that form a polymer. The raw material of natural rubber has no links between the molecule chains – they are formed during a process of vulcanization, due to which chains are connected with cross-links. Weak intermolecular forces that join chains of rubber molecules are responsible for the characteristic rubber properties, as an ability to a quick elastic deformation. The bulging armours take advantage of the rubber properties, [15-16].

Upon an impact, high pressure is transferred into the interlayer by a fast-moving striker causing rapid changes of the rubber shape. The elastomeric interlayer compresses under the projectile nose, then it expands rapidly during the penetration and finally, it bounces back to the initial shape. The side steel plates deform together with the rubber structure. The projectiles are strained between the front and rear plates deforming in the opposite directions. Front and back halves of the rods acquire different impulse because of a difference in the interaction time with the plates. The projectiles remain intact after the early penetration phase. The laminate is interacting longer with the backward half of the rods than with their front part, which left the armour. As it may be seen on the flesh X-ray images,
the KEPs are broken in the middle and the back part in consequence of this asymmetrical contact and the deformation induced by the layers of the laminate.

4. Numerical analysis

The configuration parts are modeled as deformable Lagrangian solids. The calculations have been performed with the explicit solver of the finite element Ls-Dyna software package v. 9.0.1. [17]. All components are discretized by reduced integration 8-node solid elements with stiffness-based hourglass control. The long-rod of the diameter and length 4 mm and 80 mm, is meshed by elements of the size 0.1 x 0.1 x 0.1 mm, which results in 1.192.000 elements. The plate 4 x 40 x 200 mm has a fine mesh of 0.1 x 0.1 x 0.1 mm in the central impacted zone (20 x 40 mm), whereas a coarser meshing is applied on the plate. Each plate is meshed by 441.000 elements. The rubber layer is discretized by regular elements of the size 0.2 x 0.2 x 0.2 mm, which gives in total 535.464 elements for the 15 mm thick layer. A very fine mesh of the rod and in the direct impact zone allows modeling of thin cracks leading to fracture and fragmentation, [18-20]. Between the rod and the parts of the laminate, the eroding contact is applied (*ERODING_SURFACE_TO_SURFACE). Without insight into friction conditions, an assumption of the frictionless contact between all components is taken. The target parts are in contact due to the option *AUTOMATIC_SURFACE_TO_SURFACE, which represents well a free contact between the layers in the experiment. To reproduce the test boundary conditions, the sides of the laminate are fully clamped. To the rod, the initial impact velocity is assigned. The similar conditions are assumed for the configuration without the rubber interlayer and with the different rubber thicknesses.

The popular models available in many codes, and in Ls-Dyna also, are applied to describe the tested materials. For the steel and the tungsten alloy – the Johnson-Cook flow and fracture model, and for the rubber – the Ogden model is chosen. The fracture model formulation and the discussion on it may be found in numerous works, primarily in the original papers of Johnson and Cook, [21-22].

As the material characterization, which describes the tungsten alloy Y925 does not account for characteristics of its fracture (c.f. [12-13]), the *MAT_SIMPLIFIED_JC (*MAT_98) is applied in the calculations. This implementation of the Johnson-Cook flow model does not describe temperature effects and is decoupled from the JC fracture model. To introduce fracturing in the modeled material, the material card has a simple fracture condition PSFAIL – the effective plastic strain at failure. Its value is set as 1.0. Additionally, the option *MAT_ADD_EROSION is active with a threshold of the minimum pressure at failure MNPRES. The pressure, i.e. the hydrostatic stress, is the average of the three normal stress components of any stress tensor:

$$\rho = \frac{1}{3} \rho_{kk} = \frac{\sigma_{11} + \sigma_{22} + \sigma_{33}}{3} \quad (1)$$

where \( k = 1, 2, 3 \). According to the Ls-Dyna theory manual [20], the hydrostatic pressure in the Ls-Dyna formulation is positive in compression. In the fracture criterion MNPRES, when the assumed minimal value pmin is obtained, the element is deleted from the model. Several examples presented in the literature prove that calculations with that option model well fragmentation and shattering of high strength cores of small-caliber rounds upon an unsymmetrical contact with a target, [23-24].

Having the fracture model identified for the RHA steel allows an application of the Johnson-Cook model implemented in Ls-Dyna by the classical material card *MAT 15. This model formulation requires the equation of state (EOS). The Gruneisen approach with a cubic shock velocity defines the pressure-volume relationship for a compressed material is then used, [25] (the *EOS_GRUNEISEN card in Ls-Dyna). The parameters of the JC model for the WHA alloy and the RHA steel, as well as the Gruneisen EPS parameters are presented in Table 2.
Table 2. Parameters of the JC flow model for the WHA Y925 grade\textsuperscript{[9]} and the RHA steel\textsuperscript{[11, 25]}.

|                | WHA grade Y925 | JC flow model | JC fracture model | Gruneisen EOS |
|----------------|-----------------|---------------|-------------------|---------------|
| \( A \) [MPa]  | 1258 ± 97       | 1193          | D\(_1\)           | 0.21          | C             | 4570          |
| \( B \)         | 0.092 ± 0.014   |               |                   |               |               |               |
| \( C \)         | 0.0013          |               |                   |               |               |               |
| \( n \)         | 0.014 ± 0.0003  |               |                   |               |               |               |
| \( m \)         | 0.940 ± 0.007   |               |                   |               |               |               |

RHA steel

|                | JC flow model | JC fracture model | Gruneisen EOS |
|----------------|---------------|-------------------|---------------|
| \( A \) [MPa]  | 500           | D\(_1\)           | 0.21          | C             | 4570          |
| \( B \)         | 0.0043        | D\(_2\)           | 7.21          | S\(_1\)       | 1.49          |
| \( C \)         | 6.77          | D\(_3\)           | -5.44         | S\(_2\)       | 0             |
| \( n \)         | 0.67          |                   |               | S\(_3\)       | 0             |
| \( m \)         | 1.17          |                   |               | \( \gamma_0 \) | 1.16          |
| \( \rho \) [g/cm\(^3\)] |               |                   |               | 7.85          |

The Ogden model (*MAT_77), proven many times as efficient in the modeling of hyper-elastic material behavior, is chosen to model the natural rubber layer. In the Ogden approach, the strain energy is a function of the elongation \( \lambda \) of the strain tensor. Thus, the strain energy according to the Ogden formulation is given as follows:

\[
W = \sum_{p=1}^{n} \frac{H_p}{\alpha_p^2} (\lambda_1^{\alpha_p} + \lambda_2^{\alpha_p} + \lambda_3^{\alpha_p} - 3)
\]  

(2)

where \( \alpha_p \) and \( \alpha_p \) are material constants and \( n \) indicates an order of approximation.

The model is formulated in a power form, so to fit an experimental stress-strain data to a desired degree of precision, a sufficient number of terms may be taken. Here, a set of the model parameters for \( n = 3 \) proposed by Yeoh\textsuperscript{[20]} describing a natural rubber, Table 3. Since the card *Mat_077 does not model material damage, the additional erosion criterion must be applied to introduce a failure in the perforated rubber. The criterion of the shear strain at failure equals 1.0 is then chosen in the card *Mat_add_erosion.

Table 3. The Ogden model parameters for the natural rubber,\textsuperscript{[26].}

|                | Natural rubber | Ogden model |
|----------------|----------------|-------------|
| \( \alpha_1 \) | 1.3            | \( \mu_1 \) | 0.618       |
| \( \alpha_2 \) | 5.0            | \( \mu_2 \) | 0.00118     |
| \( \alpha_3 \) | -2.0           | \( \mu_3 \) | -0.00981    |

The discussed configuration consists of 3 materials (tungsten alloy, armour steel and rubber) with different material properties. An in-house material characterization might result in a more reliable and detailed numerical simulation. Nevertheless, the material models available in the literature allow also for a first evaluation and an explanation of phenomena occurred during the target-threat interaction.

Based on the formerly described experimental investigation and the chosen material modeling, the laminate with the 15 mm thick rubber interlayer is analyzed numerically. The stages of penetration and the final perforation presented along the curve of the impact velocity reduction are given in Fig. 5. The high impact velocity, 1500 m/s, causes the ejection of small steel debris forming a characteristic ‘cloud’ of a quarter-circular shape at the moment when the projectile strikes the front plate (step 1, Fig. 5). In the test recorded on the images presented in Fig. 4, a cloud of fragments is larger and denser but
in the simulation, the Lagrangian representation of the model cannot provide such an extensive separation between elements. While the KEP pushes its way through the laminate, the rubber around the perforation channel is expanding around allowing its passage (steps 2 and 3), and then, it is returning to the initial position enfolding the rod tightly (step 3 and 4). The expansion of the rubber and the movement of the KEP cause the deformation of the front and the back steel plate (step 4). When the rod leaves the front plate, both plates are already bent in opposite directions (step 6). The crack initiates on the upper periphery of the projectile being in contact with the plate. The rear part of the rod is stabilized by the rubber already closed around it, whereas its front part is bent slightly down by the deformed back-plate. In the relatively brittle tungsten alloy susceptible to tension, the crack initiates easily and propagates down the rod diameter leading to the breakage of the long-rod into two pieces, Fig. 5(b). During the experiment (Fig. 6), the pictures taken at the time instant 125 μs, when the projectile is already about 70 mm behind the perforated target, visualize the separation of the fragmented rod pieces.

Figure 5. Penetration of the steel-elastomeric laminate: (a) impact velocity reduction and (b) threat after the target perforation (90 μs).

The initial KEP velocity assumed in the calculation as 1500 m/s is reduced to 1475 m/s after the target perforation. Comparing to the experiment, the result of the simulation is not very accurate. In the test, the decrease of the velocity is close to 5% with a reduction from 1520 m/s to 1465 m/s. The reason for that discrepancy are the material models taken assumed based on the literature, which might not fully correctly describe the material properties. Nevertheless, the numerical simulation follows a reduction
of the threat velocity in time indicating the characteristic phases during the passage of the long-rod through the target laminate. Consequently, several stages may be distinguished. The end of the first phase may be noted at 10 µs when the KE penetrator perforated the steel plate and starts penetrating the rubber interlayer. A change of the slope character is seen at 22.5 µs when the nose of the projectile touches the back-plate. Subsequently, another phase ends visibly at 40 µs, when the projectile perforates the back-plate and ejects a material debris, which in the experiment has an irregular plug shape – in the simulation the plugging is not so distinctly captured, a much thinner material piece is separated from the plate. At 62.5 µs, the crack leading to the rod breakage is fully developed and finally, at 80 µs the whole projectile is outside the plate – which on the curve is represented by a constant exit velocity.

![Simulation without the add-on erosion criterion: rod deformation.](image)

**Figure 6.** Simulation without the add-on erosion criterion: rod deformation.

To present more distinctly the strain state and bending which the rod undergoes while it penetrates the laminate, another simulation is performed in which, the option *Mat_add_erosion*, due to which the criterion of the minimum pressure at failure is introduced to the rod in the previous calculation, is not used. This time, only the failure condition available in the used material card describing the striker is
active, i.e. the effective plastic strain at failure here equals 1.0. Its application results in the projectile nose erosion because of the contact with the side steel plates.

In the maps of the pressure stress, it may be observed how the long-rod deforms and bends traversing the target layers, Fig. 6. After the laminate perforation, the deformed rod has a z-like shape (step 90 μs). There are two zones, where the KEP is strongly bent, one indicated by a filled arrow (pointing up) and then, the second one indicated by an unfilled arrow (pointing down). The simulation shows that the rear part of the rod is stabilized by the rubber (step 60μs) which enfolds it tightly, whereas the upper periphery of the front part is in contact with the perforation hole in the back steel plate. The plate is deforming due to the rubber expansion and pushes the penetrator downwards causing its bending. In the calculation where the erosion criterion is applied, the crack initiates at the first curvature (pointed by a filled arrow).

![Image](image_url)

**Figure 7.** Pressure in the rod cross-section – crack initiation.

To visualize better the long-rod fragmentation in the simulation, in which the additional fracture criterion is applied, the crack initiation is analyzed. Three subsequent time steps presenting the state of pressure in the cross-section of the KEP before and after the fracture occurrence are collected in Fig. 7. The simulation accounts for the additional fracture criterion, in which the minimal pressure at failure equals to -650 MPa. On the maps of the pressure, it is seen that the rod undergoes a local bending on the upper periphery which touches the deformed plate. The simulation calculates that the value of the minimum pressure threshold is reached firstly in that zone, which causes an element deletion and
initiates a crack. The meshing of the striker is very fine (the size of the elements is 0.1 mm$^3$), the modeled crack contains only a single elements layer.

![Figure 8](image_url)

**Figure 8.** Influence of the rubber thickness on the rod fragmentation – numerical and experimental results.

The question should be stated if it is necessary to apply an additional fracture criterion. The classical function of the Johnson-Cook fracture model is relatively simple e.g. [27-28] and does not cover all sensitivities of the critical stress states, which lead to material failure. High strength metals are usually
sensitive to tensile stresses and tend to fracture overloaded in that regime. Under this assumption, an application of the minimal pressure at failure may be then favored. When the assumed limit value of the criterion defined according to Eq. (1) is reached, the fracture condition is fulfilled and the element is deleted from the mesh. This simplified and based on the phenomenological observations approach allows modeling of the tungsten rod fracturing, which represents the experimental observations and is not inconsistent with the physics of the material.

Even if the numerical fragmentation of the long-rods is not identical with the results of the test, the simulation captures correctly differences in the influence of the different rubber layers on the projectile behavior, Fig. 8. According to the calculations, the maximal deformation of the laminate (the widest distance between two plates) increases with the rubber thickness. In the case of the laminate with the 5 mm thick rubber interlayer, its thickness (initially 14 mm) increases to 17.3 mm. Respectively for the other targets – with the 10 mm rubber layer to 22.7 mm (the initial thickness 18 mm), with the 15 mm thick rubber layer to 27.7 mm (the initial thickness 23 mm) and with the 20 mm thick rubber layer to 34.1 mm (initially 28 mm). The simulation shows that the 10 mm and 15 mm thick rubbers cause a similar deformation of the steel plates but the rod is more fractured due to the contact with the 5 mm thinner laminate. Thus, it may be considered as more efficient. Like in the experiment, the thinnest laminate with the 5 mm rubber blocks between its layers only the last part of the penetrator, which causes its separation from the longer, slightly bent front part. Both the simulation and the experiment show that the double rubber layer causes the strongest fragmentation of the KEP – it breaks into four pieces. Each rubber layers deforms independently from another, which strengthens the bending of the side steel plates.

5. Conclusions

Kinetic-energy penetrators are considered as one of the most dangerous kinetic threats. Long and slender projectiles, made of a high-density metal (like tungsten or depleted uranium alloy) use their kinetic-energy (as a function of the striker’s mass and velocity) to force the way through armour. The ballistic impact test concerns the down-scaled kinetic-energy penetrators ($L/D = 20$, rod diameter D = 4 mm) shot against four configurations with the rubber interlayer of different thicknesses (5, 10, 15 and 2 x 10 mm) and the configuration with an air gap instead of the rubber. The separated flash X-ray images show the KEP fragmentation and the deformation of the target layers during their penetration. Among the tested configurations, the most efficient – i.e. leading to the most serious rod fragmentation, is the configuration with the double rubber layer. The numerical simulation performed in the Ls-Dyna Lagrangian approach adds a complementary, detailed analysis of the experimental campaign. The simulation depicts the process of the rubber shape changes and its influence on the deformation of the plates. It is described how a crack initiates in the KE penetrator evoked by bulging of the steel plates.

Based on the presented experimental and numerical investigation, the influence of a steel-elastomer armour on kinetic-energy penetrators is discussed. In the presented protection concept, the bulging effect is considered as the main defeat mechanism leading to an efficient minimization of the piercing potential of KEPs. Hit by a long-rod projectile with a high impact velocity, the rubber deforms rapidly causing also a deformation of the side steel plates. The rod disturbed by the plates deforming in the opposite directions starts to bend and because it is long, slender and made with a high-strength tungsten alloy of a relatively low ductility, it tends to fracture more easily when it is destabilized and strained at tension.

The present investigation based on the ballistic experiment completed by the numerical simulation is proves an efficiency of the discussed protection system against kinetic-energy penetrators. Aside from providing an insight into the deformation and failure mechanisms of the high-velocity threat, the study explains the effect of bulging which improves protective performance of the armours applied against KEPs.

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