

# Effects of the impact of 7.62 mm small-arms projectiles on various building materials

**J Kratochvíl<sup>1</sup>, O Koutný<sup>1</sup> and M Drdlová<sup>2</sup>**

<sup>1</sup> Brno University of Technology, Faculty of Chemistry, Purkyňova 118, 612 00 Brno, Czech Republic

<sup>2</sup> Senior Researcher, Research Institute for Building Materials, Hněvkovského 65, 617 00 Brno, Czech Republic

E-mail: xckratochvilji@fch.vut.cz

**Abstract.** The presented study deals with the experimental assessment of the effects (i.e. penetration depths) of 7.62 mm x 39 and 7.62 mm x 54 R multipurpose projectiles on various structural and shielding/cover materials. The materials selected for testing were hardwood, softwood, brick and sand. The primary focus of the testing was the effect of projectiles on samples during perpendicular impact at different impact velocities and therefore various impact energies. The secondary aim was to determine and observe projectile properties after target perforation. The observed parameters include the residual energy/velocity and structural properties of the projectiles (e.g. fragmentation).

## 1. Introduction

The security situation in Europe is rapidly worsening. There have been several severe terrorist attacks in European countries and political relations between NATO and Russia are deteriorating. The higher risk of terrorism in particular means the protection of critical infrastructure has become a key issue. The majority of critical infrastructure consists of civilian structures/buildings which therefore usually lack any form of ballistic and blast protection. The aim of this paper is to evaluate some common building materials such as bricks and wood from the point of view of their behaviour under ballistic load. Also, one type of natural material was tested, namely siliceous sand. Testing was performed using assault rifle calibre and sniper rifle/universal machine gun calibre ammunition. The calibre of the selected assault rifle ammunition was 7.62 mm x 39, while 7.62 mm x 54R was the calibre of the chosen universal machine gun/sniper rifle ammunition. The official designation of these cartridges often varies. The 7.62 mm x 39 cartridges are marked 7.62–43, M43 or simply Kalashnikov, while the 7.62 mm x 54R cartridges are labelled 7.62–59, 7.62 Mosin – Nagant or Dragunov. Both selected projectiles are designated as Multipurpose ball-type ammunition [1]. This slightly contradicts established ballistic testing standards. For example, STANAG 4569 usually requires armour piercing (AP) or armour piercing incendiary (API) ammunition. On the other hand, testing mode was selected to simulate an attack performed by an individual or a group, both of which tend to be usually far less well-equipped when compared to military troops and don't have access to specialized ammunition. Ball ammunition is widespread: during the Cold War billions of such cartridges were manufactured, and they are often available for civilian use.



The mechanical response of solids during high speed dynamic loads can be described using formulas commonly used for liquids. Rankine-Hugoniot formulas are especially useful for this purpose. These formulas describe change of momentum, change of mass and internal energy [2],[3],[5].

Mass conservation:

$$\rho_0 U_s = \rho(U_s - u_p) \quad (1)$$

Momentum conservation:

$$p = \rho_0 U_s u_p \quad (2)$$

Energy conservation:

$$\Delta e = \frac{p}{2} \left( \frac{1}{\rho_0} - \frac{1}{\rho} \right) \quad (3)$$

where  $\rho$ ,  $p$  and  $\Delta e$  are density, pressure and change in internal energy of the shocked material. Subscript stands for ambient conditions.  $U_s$  is shock velocity and  $u_p$  is particle velocity.

The basic empirically based approach to the calculation of the penetration or perforation of a selected projectile into a given material is based on energy equilibrium. The usual “starting” point for such calculations is the following formula:

$$E = kd^m t^n \quad (4)$$

The loss of kinetic energy of the projectile after sample perforation can be calculated using the following empirical formula:

$$E_R = E_I - sk = 0.5mv_I^2 - sk = 0.5mv_R^2 \quad (5)$$

where  $E_R$  is the residual kinetic energy of the projectile (J),

$E_I$  is the impact energy of the projectile (J),

$s$  is the thickness of the sample (if the sample was perforated) or depth of penetration (if the sample was penetrated) (mm),

$k$  is the material coefficient ( $J \cdot mm^{-1}$ ),

$m$  is projectile weight (kg),

$v_I$  is impact velocity ( $m \cdot s^{-1}$ ),

$v_R$  is residual velocity ( $m \cdot s^{-1}$ ).

If the projectile does not perforate the sample, residual velocity is zero ( $v_R = 0$ ) and depth of penetration can be calculated from the following formula:

$$s = 0.5mv_I^2 k^{-1} \text{ (mm)} \quad (6)$$

The material coefficient depends on two main factors. The first factor is the type of projectile – its geometry, velocity and weight, while the second factor is the impact energy of the projectile. This means that material coefficients can be gained for same type of projectile with different impact energies.

A similar formula was determined for softwood and hardwood:

Softwood:

$$k = 1.8037 + 2.501 \cdot 10^{-4} E_I - 1.51273 \cdot 10^{-7} E_I^2 \quad (7)$$

Hardwood:

$$k = 2.8756 + 3.95775 \cdot 10^{-4} E_I + 9.07583 \cdot 10^{-8} E_I^2 \quad (8)$$

The determination of the material coefficient for bricks (and generally for other hard and brittle materials) is much more difficult due to two factors:

1) The projectile often breaks and fragments upon impact – this leads to an increase in the diameter of the damaged zone, but also a much lower depth of penetration.

2) The sample often disintegrates, preventing measurement of the depth of penetration of the projectile. Therefore, the formula for depth of penetration was not calculated using the material coefficient  $k$ ; instead, impact energy was used (note that this formula is available for 7.62 x 54R):

$$s = -0.0269603 + 0.0152704 E_I - 3.10331 \cdot 10^{-4} E_I^2 \quad (9)$$

The main purpose of this paper is to determine the terminal ballistic properties of various structural materials.

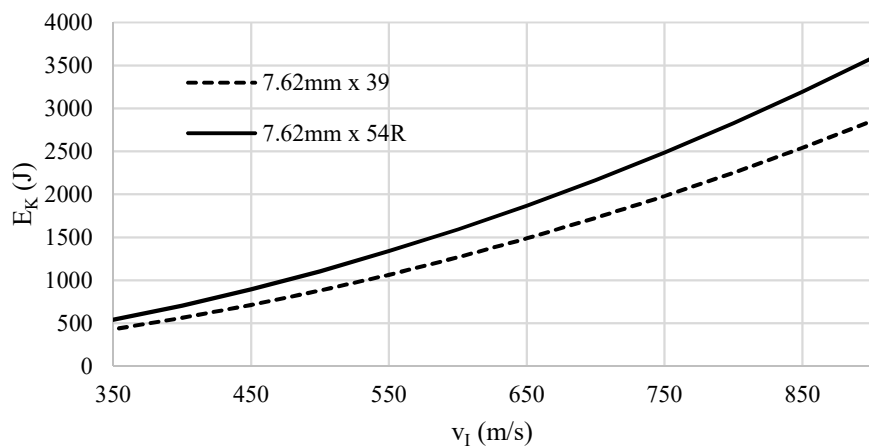
## 2. Experimental programme

The presented study deals with the determination of the response of various structural materials to ballistic load expressed as kinetic energy loss of a projectile after perforation of a panel. The tested wooden samples were fabricated from softwood and hardwood and of a defined thickness. The loss of projectile kinetic energy was determined using the known mass of the projectile and the measured impact velocity and residual velocity of the projectile after target penetration. The correlation between impact velocity ( $v_i$ ) and kinetic energy ( $E_k$ ) loss was monitored. The Depth of Penetration (DoP) test was performed for the same materials. The DoP test was also performed for the brick and sand sample as they represent other common types of structural and shielding materials. The DoP value corresponds to the total kinetic energy of the projectile absorbed during the process of penetration into the tested material. The ratio of the total kinetic energy of the projectile to the DoP value represents the material's capability to resist the penetration of the selected ammunition.

## 3. Materials and methods

Common structural materials were selected for ballistic testing, namely hardwood (oak), softwood (spruce) and brick. Siliceous sand was chosen as a representative of shielding materials. Wooden beams were glued together in order to achieve thicknesses of 100, 200 and 300 mm. The same approach to sample preparation was chosen for the DoP test, for which wood samples with a thickness of 800 mm were prepared. CP-20 bricks were used for the tests, with the dimensions 240 x 140 x 60 mm. Assuming that brick is an isotropic material, ten bricks were placed in a row one behind another to reach a total length of 600 mm and screwed together into a steel frame to prevent any disintegration of the whole assembly. One shot was fired for each such brick assembly. The sand was dried to a constant weight and sieved through a 5 mm sieve before being placed in wooden box with the dimensions 600 x 600 x 2000 mm.

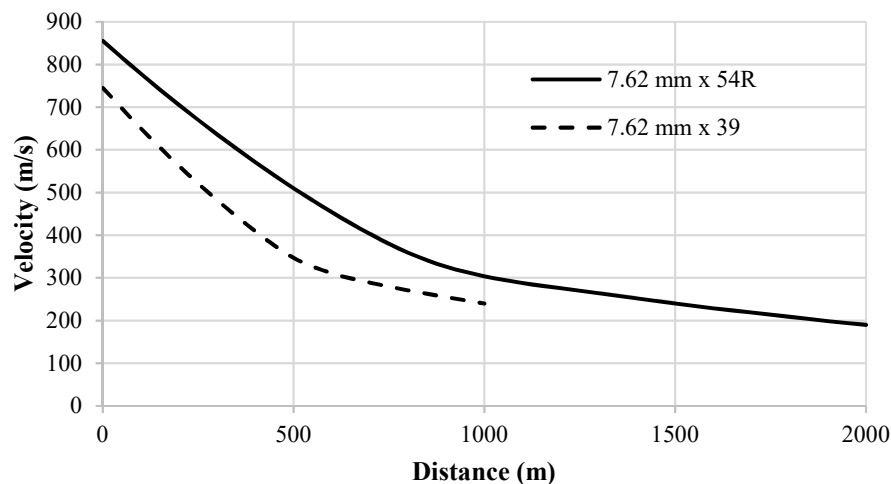
The aim of this paper is to describe the ballistic testing of materials using normal impact. The testing was performed using ballistic test barrels placed in a UZ-2002 universal breech mounted on a firing rest. The barrels used for testing were a 7.62 mm Soviet Model 1943 for 7.62 mm x 39 testing and a 7.62 mm Mosin – Nagant for the 7.62 mm x 54R. Figure 1 shows the kinetic energy of the observed projectiles based on their impact velocity.



**Figure 1.** Kinetic energy of 7.62 mm x 39 and 7.62 mm x 54R projectiles based on their impact velocity.

The tests were performed on an indoor range. The air temperature was between 18–22°C, with the test munitions being tempered to the air temperature. Humidity was between 60 and 80%. Impact velocity was measured using LS-06 optical light gates. Distance from muzzle to target was 10 m; the velocity of the projectile was measured at 8 m from the muzzle. Residual velocity was determined

from the high-speed camera record. The standard velocity at 8 m from the muzzle is 855 m/s for the 7.62 mm x 54R and 695 m/s for the 7.62 mm x 39 projectile. These were also set as the higher limit of impact velocity for each projectile. These velocities are assumed to be nominal, i.e. the most probable impact velocity which can be reached in a real situation according to STANAG 4569.

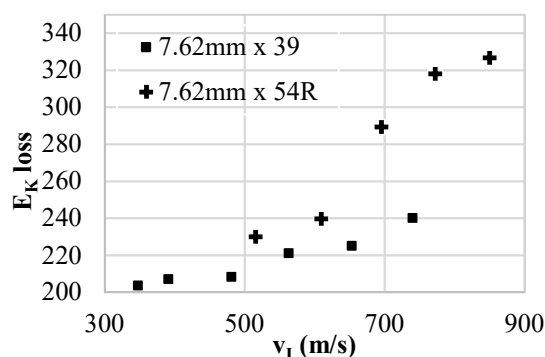


**Figure 2.** Projectile velocity at specific distances.

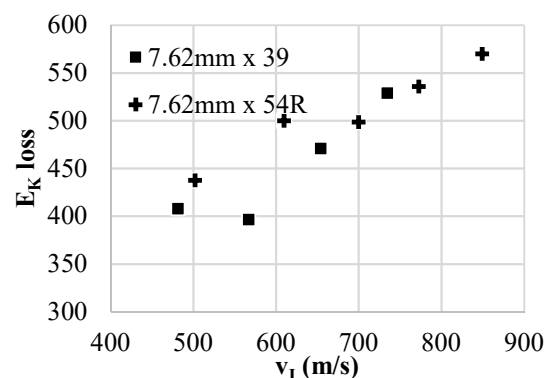
In order to achieve lower  $v_i/E_i$ , the powder charge was reduced according to ballistic tables. Lower  $E_i$  simulates shots being fired at longer ranges. The lower limit of projectile impact velocity was set as low as possible while keeping it high enough to provide perforation of the sample.

#### 4. Results and discussion

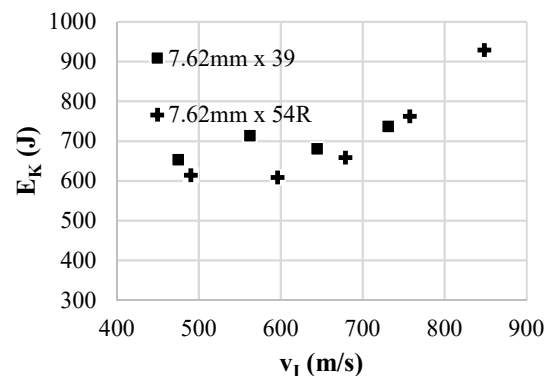
The residual velocity of each projectile after perforation of the target was monitored. The kinetic energy loss was determined in comparison to the impact velocity. This value represents the absorbed energy of the projectile during the perforation process through a target of defined material and thickness. Figure 3, Figure 4 and Figure 5 show the dependence of absorbed kinetic energy on the impact velocity of chosen projectiles for softwood panels with thicknesses of 100 mm, 200 mm and 300 mm. It is necessary to note that both projectiles have the same cross-section geometry, i.e. they are both 7.62 mm in diameter.



**Figure 3.** Kinetic energy loss – 100 mm softwood panel.



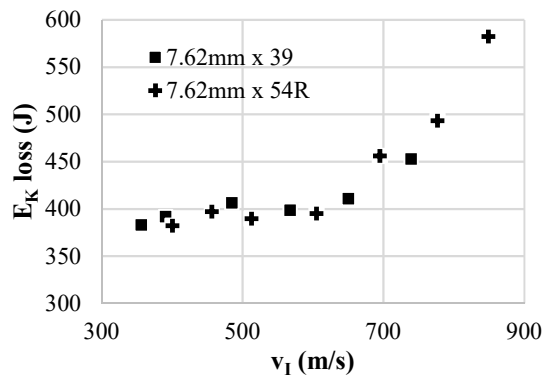
**Figure 4.** Kinetic energy loss – 200 mm softwood panel.



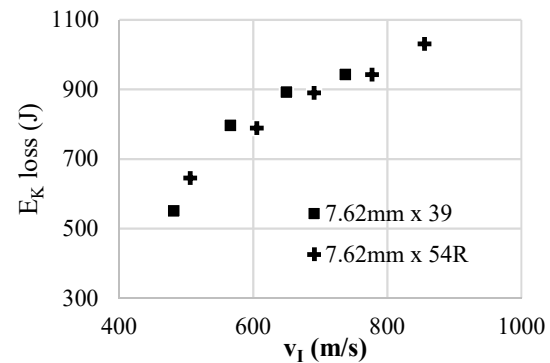
**Figure 5.** Kinetic energy loss – 300 mm softwood panel.

Generally, it can be concluded that with increasing impact velocity the kinetic energy loss increases. With softwood the kinetic energy loss rises in proportion to increasing impact velocity. This effect could be related to the fact that nearly no deformation of the projectile occurs, and neither is there almost any destabilization of its trajectory. Moreover, no hardening mechanism can be assumed in the softwood material [6]. This behaviour is fully compliant for both projectiles up to an impact velocity of approx. 700 m/s. For the higher impact velocity which was used for the 7.62 mm x 54R projectile there is a substantial deviation from the linear trend of the plotted dependence. This deviation is more evident in the case of the samples with higher thickness. This behaviour can be attributed to the secondary effects occurring during the penetration process; namely the destabilization of the projectile and the separation of the projectile jacket. The first of those effects makes a major contribution when the value of kinetic energy loss is higher than that which is expected according to the linear trend. Due to the destabilization of the projectile, the cross-section perpendicular to the flight trajectory is higher and therefore more energy is absorbed during penetration. The second effect occurs when the kinetic energy loss is lower than the expected value given by linear approximation. Due to jacket separation, the cross-section of the projectile is reduced, which results in higher pressure at the tip of the penetration tunnel and consequently lower dissipation of kinetic energy. Comparing the resistance of the tested material against the penetration of projectiles for different thicknesses it can be concluded that the kinetic energy of a 7.62 mm x 39 projectile with a nominal impact velocity of 695 m/s can be reduced by 14% by a 100 mm softwood panel. The reduction in kinetic energy seems to be proportional to panel thickness according to the test results: a 29% reduction for the 200 mm panel and a 42% reduction for the 300 mm panel. Similar behaviour can be observed in the case of the 7.62 mm x 54R projectile with a nominal impact velocity of 855 m/s. For the panel thicknesses of 100 mm, 200 mm and 300 mm, the reduction of kinetic energy was determined to be 10%, 18% and 29%, respectively.

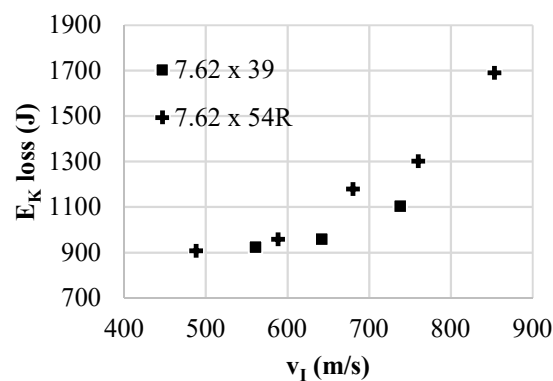
Figure 6, Figure 7 and Figure 8 display the results from the ballistic testing of hardwood panels with thicknesses of 100 mm, 200 mm and 300 mm.



**Figure 6.** Kinetic energy loss – 100 mm hardwood panel.



**Figure 7.** Kinetic energy loss – 200 mm hardwood panel.

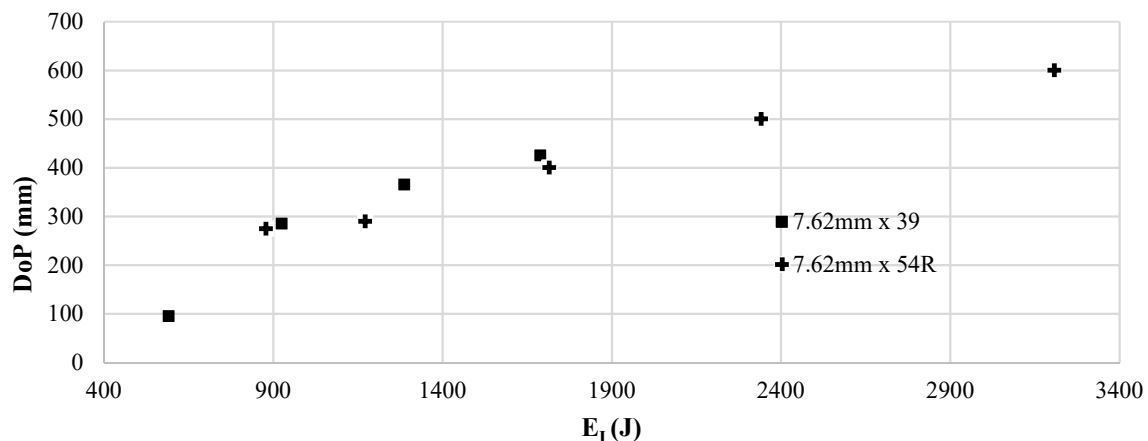


**Figure 8.** Kinetic energy loss – 300 mm hardwood panel.

The kinetic energy of projectiles absorbed by hardwood is approximately two times larger compared to softwood panels of 100 mm thickness. This ratio proportionally decreases with increasing panel thickness to a factor of 1.55 for 300 mm thickness. It is evident that there is a similar trend to that of the previous experiment with regard to rising kinetic energy loss with increasing impact velocity for both projectiles. However, the trend cannot be designated as proportional i.e. linear to the increasing impact velocity. For the 100 mm panel it seems to be the case that the difference in kinetic energy loss is constant in the range of impact velocity up to 600 m/s for both projectiles. It is necessary to note that a projectile with an impact velocity lower than 350 m/s is not able to perforate the sample. The kinetic energy loss of projectiles with an impact velocity larger than 600 m/s proportionally increases with impact velocity. The results for hardwood panels with thicknesses of 200 mm and 300 mm correspond to the results for softwood, i.e. a similar effect which is responsible for positive or negative deviation from the linear trend occurs. The negative deviation of the linear trend is evident from the larger impact velocities for the 200 mm hardwood and softwood panels. This could be also attributed to the destabilization of the projectile and therefore the increase in cross-section perpendicular to the flight trajectory. For the 300 mm thick hardwood panel a positive deviation in the linear trend occurs at larger impact velocities. This effect could be attributed to the partial separation of the jacket and the subsequent decrease in projectile cross-section, resulting in better penetration capability, as in the case of the 300 mm softwood panel. Comparing the material's resistance against the penetration of projectiles for different thickness it can be concluded the kinetic energy of a 7.62 mm x 39 projectile with a nominal impact velocity of 695 m/s can be reduced by a 100 mm hardwood panel by 25%. The reduction in kinetic energy is proportional to the panel thickness up to 200 mm, which reduces the projectile's kinetic energy by 52%. For larger material thicknesses, a negative deviation from the linear trend arises, which is evident from the kinetic energy reduction of 62% for the 300 mm panel.

Similar behaviour can be observed with the 7.62 mm x 54R projectile, with a nominal impact velocity of 855 m/s. For the panel thicknesses of 100 mm, 200 mm and 300 mm, the reduction in kinetic energy can be determined as 18%, 32% and 33%, respectively, and again a negative deviation from the linear trend is seen for the largest thickness.

The depth of penetration of selected projectiles was monitored in wooden samples via the DoP test. The results from the DoP testing of softwood are summarized in Figure 9, which expresses the dependence between DoP and  $E_I$ .

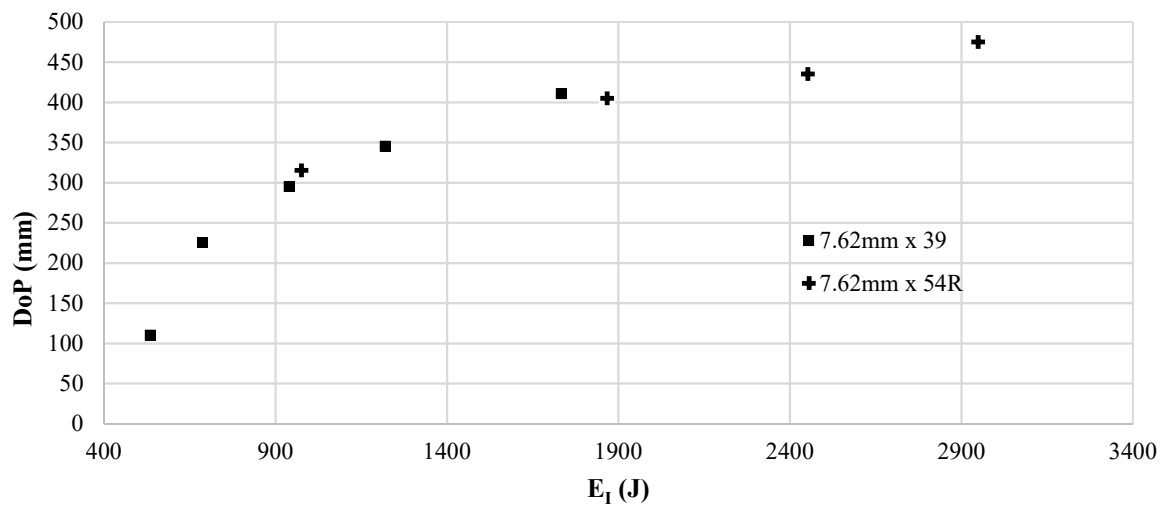


**Figure 9.** DoP test results for softwood.

As can be seen, the perforation of softwood material by selected projectiles can be related to their impact kinetic energy in the selected range of impact velocities. Generally, it is evident that over 430 mm of softwood is necessary to stop a 7.62 mm x 39 projectile at its nominal impact velocity of 695 m/s, i.e. with an impact kinetic energy of 1700 J. In the case of the 7.62 mm x 54R projectile, over 600 mm of softwood is necessary to stop it at its nominal impact velocity of 855 m/s, i.e. with an impact kinetic energy of 3200 J. The higher slope of the DoP –  $E_I$  dependence is evident at low impact kinetic energy (up to approximately 1000 J). In other words, there is a negative deviation from the linear trend resulting in a lower DoP than could be expected. According to the statement that the mechanical properties of wood are not strain-sensitive, i.e. that there is no physical reason for any strain hardening or strain softening behaviour by wood-like materials at assumed strain rates ( $10^4 - 10^6 \text{ s}^{-1}$ ), a different effect responsible for the decrease in DoP from linear trend is presented: The destabilization of the projectile and increase in yaw may be attributed to this effect due to the lower impact velocities involved, which are far below the nominal velocities. Lower impact velocity and therefore lower momentum causes high yaw and the projectile is more sensitive to destabilization from its flight trajectory. This results in a higher cross-section perpendicular to the flight trajectory and a lower DoP due to the faster absorption of the projectile's kinetic energy by the surrounding material.

The results from the DoP testing of hardwood are summarized in Figure 10, which expresses the dependence between DoP and  $E_I$ .



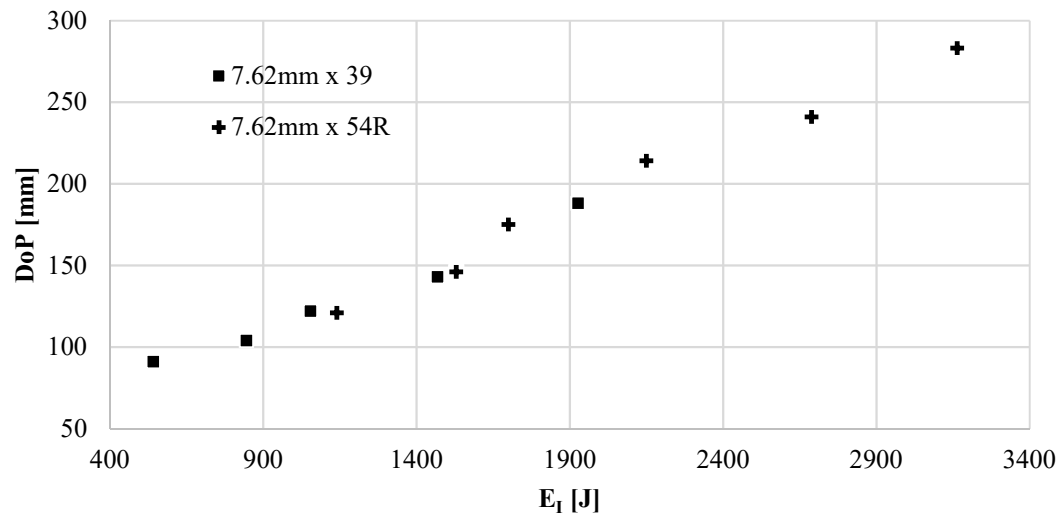


**Figure 10.** DoP test results for hardwood.

Just as with softwood, the DoP of hardwood can be directly attributed to the impact kinetic energy of a projectile independent of its mass for the same calibre. Generally it is evident that over 400 mm of hardwood is necessary to stop a 7.62 mm x 39 projectile at its nominal impact velocity of 695 m/s, i.e. impact kinetic energy is 1700 J. At the same time, over 470 mm of hardwood is necessary to stop a 7.62 mm x 54R projectile at its nominal impact velocity of 855 m/s, i.e. impact kinetic energy is 3200 J. It is evident that the same DoP was obtained for both types of wood up to an impact kinetic energy of 1000 J. From this value a linear trend is evident. The slope of the linear trend for hardwood is twice as steep as in the case of softwood. This parameter can be directly attributed to the material properties responsible for ballistic loading resistance. A similar trend occurs in the development of DoP with increasing projectile impact kinetic energy. At low impact velocities, i.e. low projectile kinetic energies of up to 1000 J, a negative deviation from the linear trend is evident. This phenomenon can be attributed to low projectile stability due to its lower impact velocity and the destabilization of the projectile's flight trajectory at the initial phase of penetration due to low momentum, just as in the case of the softwood samples. This results in higher absorption of the projectile's kinetic energy by surrounding material. This assumption can be confirmed by the same DoP up to 1000 J of impact kinetic energy for both types of wood, as was mentioned above.

The DoP test was also performed on brick, another common structural material. The results are summarized in Figure 11.

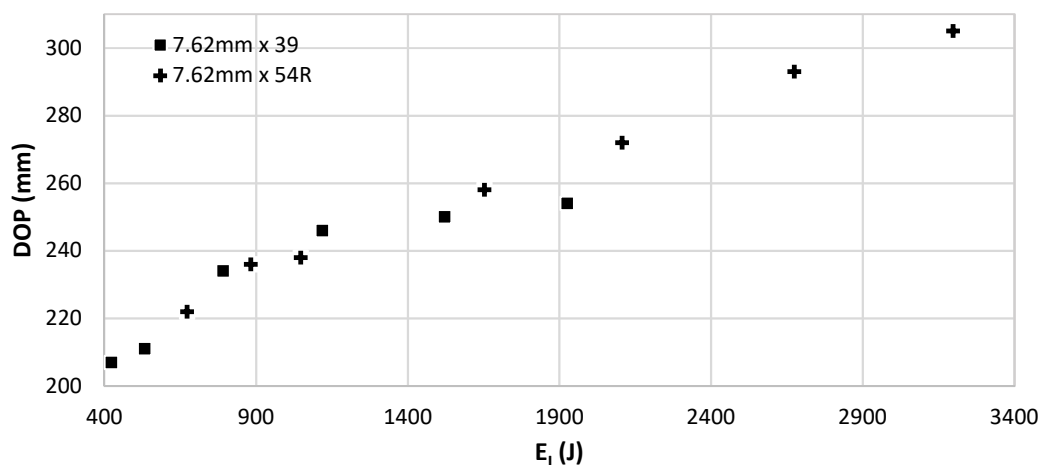




**Figure 11.** Depth of Penetration – brick.

The DoP of brick can be directly attributed to the impact kinetic energy of a projectile independent of its mass for the same calibre, which corresponds to the previous assumption applied to the results for the wooden samples. According to the DoP results it can be concluded that the minimum thickness of a standard brick wall that will stop a 7.62 mm x 39 projectile moving at its nominal velocity of 695 m/s is more than 190 mm. The minimum thickness of a brick wall that will stop a 7.62 mm x 54R projectile moving at its nominal velocity of 855 m/s is more than 280 mm. In contrast to the previous tested materials (softwood and hardwood), the linear trend of the DoP is evident throughout the whole range of monitored impact kinetic energy. In other words, no negative deviation of DoP occurs at low impact velocity (i.e. low impact kinetic energy), in contrast to the wooden samples. No severe destabilization of the projectile in the initial phase of penetration can be considered. As the brick has much higher mechanical properties than any wooden materials, the destabilization of the projectile during the initial phase of penetration is suppressed by the surrounding material. The DoP –  $E_i$  dependence and its linear character show that no strain strengthening or strain softening mechanism occurs. This corresponds to the general assumption that a brittle or quasi-brittle material mechanical response will occur under high-rate dynamic loading. [7]

The last considered material from the testing session is a siliceous sand, which was selected as the material most likely to be used in temporary shielding systems. The results from the DoP test are summarized in Figure 12.



**Figure 12.** Depth of Penetration – sand.

From the DoP results it can be concluded that there is a direct relation between DoP and  $E_i$  for projectiles of the same calibre. However, due to the heterogeneous character of sand there are visible deviations from the general trend in contrast to the other tested materials, which is especially valid for the 7.62 mm x 39 projectile. At high impact velocities the expected DoP for this projectile should be higher. According to the DoP results it can be concluded that the minimum sand layer thickness needed to stop a 7.62 mm x 39 projectile moving at its nominal velocity of 695 m/s is more than 250 mm. The minimal sand layer thickness necessary to stop a 7.62 mm x 54R projectile moving at its nominal velocity of 855 m/s is more than 310 mm. The negative deviation of the linear trend is visible from the low impact velocity (i.e. low impact kinetic energy), just as with the wooden samples. The same effect is assumed to occur due to the low mechanical properties and stability of the tested sample, which is a particulate material. [8]

## 5. Conclusion

In the first part the loss of kinetic energy of 7.62 mm x 39 and 7.62 mm x 54R projectiles during the penetration of softwood and hardwood panels was monitored and the following conclusions can be derived.

- It can be concluded that with rising projectile impact velocity the kinetic energy loss linearly increases. However, at impact velocities of over 700 m/s in the case of softwood and 600 m/s in the case of hardwood a deviation occurs in the linear trend. Two effects are assumed to be responsible for this behaviour. Positive deviation from the linear trend is attributed to the destabilization of the projectile during the penetration process and an increase in the projectile cross-section perpendicular to the flight trajectory. Negative deviation from the linear trend can be related to the separation of the projectile jacket during the penetration process and the subsequent decrease in the projectile cross-section perpendicular to the flight trajectory.
- The loss of kinetic energy is proportional to the thickness of the panel for softwood samples, which corresponds with the results observed for the hardwood samples up to panel thicknesses of 200 mm. For thicker hardwood panels a negative deviation from the linear trend should be expected.
- According to the data obtained for kinetic energy loss, the ability of a material to resist damage from ballistic loading by assumed projectiles is two times higher in the case of hardwood compared to softwood when panel thickness is 100 mm. This ratio proportionally decreases with increasing thickness to a factor of 1.55 for 300 mm thick panels.

In the second part the Depth of Penetration (DoP) was monitored for softwood, hardwood, brick and siliceous sand impacted by 7.62 mm x 39 and 7.62 mm x 54R projectiles. The following conclusions can be drawn.

- Generally, it can be concluded that the DoP is a linear function of impact kinetic energy for projectiles with the same calibre. However, negative deviation from the linear trend occurs at low impact kinetic energy. This effect could be attributed to the low stability of the projectile due to its low momentum and destabilization during the initial phase of penetration. The second effect is significantly reduced in the case of the brick sample because the material surrounding the projectile during the penetration process has sufficiently high physical-mechanical properties to prevent any severe destabilization.
- The DoP test provides a basic assumption regarding the minimum layer of monitored material which is needed to stop the selected projectiles. From the DoP results it can be concluded that the minimum softwood panel thicknesses needed to stop 7.62 mm x 39 and 7.62 mm x 54R projectiles are 430 mm and 600 mm, respectively. In the case of hardwood, the minimum thicknesses are reduced to 400 and 470 mm respectively for the selected projectiles. Brick has the greatest ability out of all the investigated materials to resist damage from ballistic loading. 190 mm of brick material is necessary to stop a 7.62 mm x 39 projectile, while 280 mm is needed for 7.62 mm x 54R ammunition. The DoP results also show that particulate materials such as siliceous sand of the 0–5 mm fraction provide relatively good protection against the selected projectiles: a 250 mm layer of sand is needed to stop a 7.62 mm x 39 projectile and a 310 mm layer is needed for 7.62 mm x 54R.
- The results of the DoP are fully in accord with the general formulation of high-strain rate dynamic loading described by the Rankine-Hugoniot relation, where the density or volume weight of materials has a direct effect on the fracturing of the body of a material. Brick (i.e. the tested material with the highest density) shows the best performance under ballistic loading of all the materials investigated in this study.

### Acknowledgements

As doctoral students of the Materials Research Centre at FCH BUT- Sustainability and Development, REG LO1211, with financial support from National Programme for Sustainability I (Ministry of Education, Youth and Sports), authors want to thank the foundation for its financial support. The authors also wish to express their gratitude and sincere appreciation to the authority of The Technology Agency of the Czech Republic, project No. TE02000162 - Centre of advanced materials and technologies for protection and safety enhancement, for financial support.

### References

- [1] Carlucci D E and Jacobson S S 2013 *Ballistics: Theory and Design of Guns and Ammunition* Second Edition 2 (CRC Press)
- [2] Rosenberg Z and Dekel E 2012 *Terminal ballistics* (Berlin: Springer)
- [3] Buchar J and Vodička J 2003 *Terminální balistika* (Prague: Academia)
- [4] STANAG, STANAG 2280. 1. 2008 (Brussels: NATO Standardization Agency)
- [5] Morison C M 2004 Dynamic response of walls and slabs by single-degree-of-freedom analysis—a critical review and revision (DOI: 10.1016/j.ijimpeng.2004.11.008)
- [6] Johnson W Historical and present-day references concerning impact on wood (DOI: 10.1016/0734-743X(86)90003-5)
- [7] Gilbert M, Hobbs B and Molyneaux T C K The performance of unreinforced masonry walls subjected to low-velocity impacts: experiments (DOI: 10.1016/S0734-743X(01)00049-5)
- [8] Chian S C, Tan B C V and Sarma A Projectile penetration into sand: Relative density of sand and projectile nose shape and mass (DOI: 10.1016/j.ijimpeng.2017.01.002)