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Deformation of Ballistic Protection Vest Panel

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Abstract:

This article deals with an analysis of the resistance against projectile penetration and bending of ballistic protection vest made of a ballistic textile. A mechanical model of the core of ballistic protection vest is designed, theoretically solved, and experimentally verified. The stiffness characteristics of the ballistic protection vest core were obtained from the technical test utilising a free fall weight. These characteristics allow a prediction of a chosen small calibre projectile movement in the same material during a firing experiment. The shape deformation of ballistic protection vest core layers is analytically expressed by their bending in the direction of the projectile movement.

Keywords:

Terminal ballistics, ballistic protection vest, mechanical model, small arms

1. Introduction

The ballistic protection of an individual protects endangered persons against small arms projectiles, fragments, and stabbing, cutting or striking weapons. The most important means of personal ballistic protection on basis of the ballistic textiles are the ballistic protective vests (BPV). The core of the BPV consists of several layers of ballistic textile (Kevlar, Twaron, Dyneema, or others).

The most important and most wide spread group of BPV is composed of the bullet proof vests. The main functional characteristic of the BPV is its resistance against the projectiles. The resistance of the BPV is based on high strength and minimal ductility of the ballistic textile fibre under a tension load [1]. Most of the common projectiles deform after impact on the BPV and simultaneously rotate around its longitudinal axis. During the penetration through the BPV the projectile catches the fibres and tries to stretch them during its motion through the individual layers but their extreme strength acts against it. Going through several layers of ballistic textile of BPV gradually flattens the projectile, its front area increases, and finally the projectile

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is caught, even though several layers of BPV are damaged. The result of the interaction between projectile and the BPV is bending of the fibres and deformation of the projectile accompanied with an absorption of the remaining impact energy of the projectile by human body, often with use of the anti-trauma panels.

The resistance function of the BPV is based on the absorption of kinetic impact energy of the projectile, which is connected with spreading the longitudinal and shear waves in the body and the dissipation (dispersion, transfer into heat) of energy by friction during the penetration of the projectile into ballistic material. About 50 % of the projectile's impact energy is absorbed by spreading of the waves in the fibre structure surrounding the entry hole.

During testing the ballistic resistance by firing, the tested BPV is placed on a base material (usually plasticene), which simulates a human body by its stiffness – live tissue. The level of plastic deformation of the base material (size of the shock imprint) is one of the criteria for the evaluation of ballistic resistance of the BPV.

It is possible to describe the behaviour of the BPV either numerically, utilising the numerical simulation means, or analytically. The following article shows the analytical mathematical description of the BPV behaviour during impact of a heavy, slowly moving weight, and during impact of a light but quickly moving projectile; in both cases are impacting bodies caught by vest and the bend of layered ballistic textile is analysed.

2. Theoretical Analysis of Deformation of Ballistic Protection Vest

The theoretical analysis of the BPV deformation comes out from certain analogy between behaviour of BPV during the impact of a projectile and during the impact of the test weight with significantly lower impact velocity and comparable impact energy. It is also assumed that the mechanical characteristics of the core of the ballistic protection, obtained from the technical tests with use of the falling weight, enter the equations describing the motion of a small calibre projectile in this pseudo-elastic material. Theoretical assumptions used during derivation of this model were verified by firing tests of chosen small calibre projectiles.

2.1. Behaviour of Material of Ballistic Protection Vest During Impact of Test Weight

The modified elastic model was chosen for the analysis of BPV function [2]. The model is characterised by the power function of the resistance against the weight movement $R(x)$ in the form of

$$R(x) = a x^{n} \tag{1}$$

where: a [N m^{-n}] – the pseudo-stiffness of a spring (BPV),
x [m] – the axial displacement – movement of the weight in the direction perpendicular to the impact plane,
n [1] – the stiffness index.

The weight of mass m falls from the height h on the spring, which substitutes the BPV. The kinetic energy of the weight is completely accumulated by the spring. The motion equation of the weight during its contact with the spring whose mass is neglected is in the shape

$$m\frac{\mathrm{d}^2 x}{\mathrm{d}t^2} = m\,g - R(x) \tag{2}$$

with the initial conditions $x = 0, \quad \frac{\mathrm{d}x}{\mathrm{d}t} = v = \sqrt{2gh}, \quad t = 0.$

Multiplication of both sides of Eq. (2) with $\mathrm{d}x/\mathrm{d}t$ and following integration gives

$$\frac{m}{2}\left(\frac{\mathrm{d}x}{\mathrm{d}t}\right)^2 + \int_0^x R(x)\,\mathrm{d}x = mgx + \frac{m}{2}v^2 \tag{3}$$

Maximum total displacement – movement of the weight x_K corresponds with the situation when $\mathrm{d}x/\mathrm{d}t = 0$, i.e. the weight stopped after the maximum deformation of the spring (bending of the BPV) had been reached. Utilising the relation from the theory of free fall weight, where $h = v^2/(2g)$, it is obtained for $R(x)$

$$\frac{1}{m\,g}\int_0^{x_K} R(x)\,\mathrm{d}x = x_K + h \tag{4}$$

Substituting the resistance function $R(x)$ with the Eq. (1) allows determination of the maximum weight displacement x_K after integration of Eq. (4)

$$\frac{1}{m\,g}\,\frac{a}{n+1}\,x_K^{n+1} = x_K + h \tag{5}$$

The characteristics a and n can be calculated from the Eq. (5) with utilisation of results of free fall experiments (weight falling from two different heights of fall h_1 and h_2)

$$\frac{1}{m\,g}\,\frac{a}{n+1}\,x_{K1}^{n+1} = x_{K1} + h_1 \tag{5a}$$

$$\frac{1}{mg}\,\frac{a}{n+1}\,x_{K2}^{n+1} = x_{K2} + h_2 \tag{5b}$$

Dividing both equations and after taking a logarithm, the relations for both constants are obtained

$$n = \frac{\log\dfrac{x_{K2} + h_2}{x_{K1} + h_1}}{\log\dfrac{x_{K2}}{x_{K1}}} - 1 \tag{6a}$$

$$a = \frac{\left(x_{K1} + h_1\right) mg\,(n+1)}{x_{K1}^{n+1}} \tag{6b}$$

Mean resistance of the spring (BPV) is defined by the equation $R_{\text{mean}} = \dfrac{a}{x_K} \int_0^{x_K} x^n \, \mathrm{d}\, x$,

hence

$$R_{\text{mean}} = \frac{a}{n+1} x_K^n \tag{7a}$$

It follows from the Eq. (1)

$$R_K = a \, x_K^n \tag{7b}$$

and for the ratio of maximum (final) and mean load it holds true

$$\frac{R_K}{R_{\text{mean}}} = n+1 \tag{8}$$

Knowing both constants a and n, the maximum displacement – weight movement x_K can be determined from the Eq. (5). This displacement corresponds to the fall height h and also to the maximum bending of the BPV.

For the experimental part of this work it is necessary to design such a falling weight that will be, due to its mass and shape, suitable for the determination of pseudo-stiffness a and stiffness index n of the ballistic material with respect to the subsequent small arms ammunition firing tests.

The falling weight should have comparable impact energy as the small arms projectiles, but must allow to carry out the fall tests from a reasonable height (the falling height $h = 3.0$ m in this experiment). It resulted from the analysis of the ballistic characteristics of the small arms projectiles that mass m of the falling weight should be more than 10.0 kg.

The shape of the falling weight is chosen as a cylinder with one hemispherical forehead (Fig. 1). This geometrical shape can be easily described mathematically. The falling weight acts on the ballistic material with its head in the shape of the spherical cap (active area of the weight). The instantaneous diameter of the base circle of the spherical cap is defined as

$$D_X \equiv D(x) = 2\sqrt{xD - x^2} \tag{9}$$

where x – the height of active part of the spherical cap that is in touch with front layer of the ballistic material (equal to the bend of material of the BPV),
D – the diameter of the cylindrical part of the falling weight.

It is well known from the firing tests that the bend of hit ballistic material usually occurs on the area of diameter larger than the calibre of projectile d. Similar situation is assumed also in the case of the bend of the ballistic material caused by the impact of the falling weight, when the front hemispherical part of the weight is crushed into the ballistic material. The mean diameter of the spherical cap bottom can be expressed as

$$D_S \equiv D(x)_{\text{mean}} = \frac{2}{x_K} \int_0^{x_K} \sqrt{xD - x^2} \, \mathrm{d}\, x \tag{10}$$

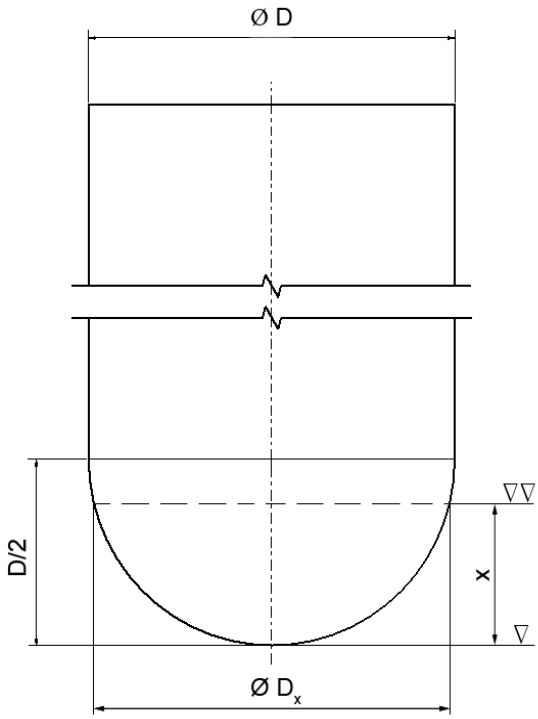

Fig. 1 Geometrical characteristics of interaction between weight's head and the ballistic material

After integration, the mean diameter of bottom of the spherical cap is given by

$$D_S = \frac{2x_K - D}{2x_K}\sqrt{D\,x_K - x_K^2} - \frac{D^2}{4x_K}\left(\arcsin\frac{D-2x_K}{D} - \frac{\pi}{2}\right) \tag{11}$$

The Eq. (9) is utilised for the determination of the depth of mean bend of the ballistic panel $x_{K\text{-}S}$ corresponding to the mean diameter of bottom of the spherical cap D_S. From the Eq. (9) are obtained roots of quadratic equation

$$(x_{K\text{-}S})_{1,2} = \frac{D}{2} \pm \frac{1}{2}\sqrt{D^2 - D_S^2} \tag{12}$$

where the root with minus sign is valid, i.e. bending of the BPV cannot be bigger than $D/2$ (the falling weight is in contact with the BPV only by the head part).

$$n_S = \frac{\log\dfrac{x_{K2\text{-}S} + h_2}{x_{K1\text{-}S} + h_1}}{\log\dfrac{x_{K2\text{-}S}}{x_{K1\text{-}S}}} - 1 \tag{13a}$$

$$a_S = \frac{\left(x_{K1\text{-}S} + h_1\right)mg\left(n+1\right)}{x_{K1\text{-}S}{}^{n+1}} \tag{13b}$$

It follows from the mathematical expression of the mean diameter of the spherical cap D_S (11) and its corresponding depth of the bend of ballistic material $x_{K\text{-}S}$ (12), i.e. that $D_S < D_X$, $x_{K\text{-}S} < x_K$, therefore the pseudo-stiffness $a_S\,(13\text{b}) > a\,(6\text{b})$. As a final implication it is valid for the bending of ballistic material $x_{K\text{-}S} < x_K$.

2.2. Behaviour of Material of Ballistic Protection Vest During Impact of Projectile

Total impact energy of the projectile, after neglecting all loses, consumed on work during compression – bending of ballistic material on the trajectory $x_{K,}$ can be expressed using formula

$$\frac{m_q v_D^2}{2} = \int_0^{x_K} R(x)\,\mathrm{d}x \tag{14}$$

For the determination of the right side of the equation, the modified Eq. (1) with the mean characteristics of ballistic material a_S and n_S is utilised

$$R(x) = a_S\, x^{n_S}$$

After the substitution into Eq. (14) it is obtained

$$\frac{m_q v_D^2}{2} = a_S \int_0^{x_K} x^{n_S}\,\mathrm{d}x = \frac{a_S}{n_S+1}\, x$$

from where the relation for the maximum compression of the ballistic material caused by projectile is expressed

$$x_K = \left[\frac{m_q v_D^2 (n_S+1)}{2a_S}\right]^{\frac{1}{n_S+1}} \tag{15}$$

Maximum resistance during compression of the ballistic material can be expressed as follows

$$R_K = a_S\, x_K^{n_S} = a_S \left[\frac{m_q v_D^2 (n_S+1)}{2a_S}\right]^{\frac{n_S}{n_S+1}}$$

and after algebraic modifications

$$R_K = \left[\frac{m_q v_D^2 (n_S+1)\, a_S^{\frac{1}{n_S}}}{2}\right]^{\frac{n_S}{n_S+1}} \tag{16}$$

A pressure of the projectile on the front of BPV can be determined according to the relation

$$p_K = \frac{4R_K}{\pi d^2} \tag{17}$$

and for the specific impact energy of the projectile it can be stated

$$e_D = \frac{4E_D}{\pi d^2} = \frac{2m_q v_D^2}{\pi d^2} \tag{18}$$

The velocity $v(x)$ and time $t(x)$ related to the bending of the BPV are under assumption of evenly decelerated motion of projectile given by the following equations

$$v(x) = v_D \sqrt{1 - \frac{x}{x_K}} \tag{19}$$

$$t(x) = \frac{2x_K}{v_D}\left(1 - \sqrt{1 - \frac{x}{x_K}}\right) \tag{20}$$

For the determination of the maximum compression x_K and the other characteristics of the ballistic material R_K, p_K, and e_D it is necessary to know the mechanical properties of this material a_S and n_S calculated with use of Eqs (13a) and (13b) from the results of the free fall tests.

3. Comparison of Calculations with Experiments

3.1. Results of Free Fall Tests [3]

The steel weight of mass of m = 10.2 kg, cylindrical shape of diameter D = 70.0 mm, and hemispherical head was used for the free fall tests. It follows from the geometry of the weight's head that maximum (final) bend of ballistic material has to be smaller than 35 mm (x_K < 35 mm). In the case of the maximum achievable falling height h = 3.0 m, the maximum impact energy of the falling weight is E = 300 J. The falling weight was released from two heights h_1 = 1.0 m and h_2 = 2.5 m during the experiment.

The evaluated material was a sample of the panel of BPV, whose resistance corresponds to the class III-A according to standard NIJ 0101.06 (i.e. with guaranteed resistance against the projectiles of calibre 44 Magnum and also 9 mm Luger), consisting of Dyneema SB and 2 pcs of laminated Kevlar (bend preventing) of the overall thickness of 18.0 mm.

The base material, to which the ballistic sample was attached, was the block of a plasticene of the thickness of 105.0 mm. The bend of this ballistic sample is defined as a displacement of its bottom surface attached to the base material and copying its deformation.

From the free fall tests the following results were obtained; 3 attempts for each height of fall were carried out:

- h_1 = 1.0 m; x_{K1} = 19.4 mm,
- h_2 = 2.5 m; x_{K2} = 30.5 mm.

First of all the mean values of the mean diameters of bottom of the spherical cap $D_{1\text{-}S}$ and $D_{2\text{-}S}$ from two falling heights h_1 and h_2 are determined with use of relation (11):

$$D_S = \frac{2x_K - D}{2x_K}\sqrt{Dx_K - x_K^2} - \frac{D^2}{4x_K}\left(\arcsin\frac{D - 2x_K}{D} - \frac{\pi}{2}\right)$$

After substitution of the values of the bend, the following values of the mean spherical cap diameters were obtained $x_K = x_{K1}, D_{1\text{-}S} = 44.8\,\text{mm},$ and $x_K = x_{K2}, D_{2\text{-}S} = 52.8\,\text{mm}$.

To these values of mean diameters of bottom of spherical cap $D_{1\text{-}S}$ and $D_{2\text{-}S}$ the corresponding depths of bend $x_{K1\text{-}S}$ and $x_{K2\text{-}S}$ are assigned using the relation (12):

$$(x_{K\text{-}S})_{1,2} = \frac{D}{2} \pm \frac{1}{2}\sqrt{D^2 - D_S^2}$$

After substitution of the mean diameters of bottom of spherical cap, the following values of the mean depth of bend were obtained $D_S = D_{1\text{-}S}, x_{K1\text{-}S} = 8.1\,\text{mm}$ and $D_S = D_{2\text{-}S},\ x_{K2\text{-}S} = 12.0\,\text{mm}$.

These corrected values of bends $x_{K1\text{-}S}$ a $x_{K2\text{-}S}$ (less than half in comparison with measured values x_{K1} and x_{K2}) are used for calculation of pseudo-stiffness a_S and stiffness index n_S (13a) and (13b).

$$n_S = \frac{\log \frac{x_{K2\text{-}S} + h_2}{x_{K1\text{-}S} + h_1}}{\log \frac{x_{K2\text{-}S}}{x_{K1\text{-}S}}} - 1$$ and after substitution of corrected bends $n_S = 1.33$,

$$a_S = \frac{\left(x_{K1\text{-}S} + h_1\right) mg \left(n_S + 1\right)}{x_{K1\text{-}S}{}^{n_S + 1}}$$ and again after substitution of corrected bends

$a_s = 17.453 \times 10^6$ [N m$^{-n_S}$].

Graphical expression of the resistance $R(x)$ of tested ballistic material is shown in Fig. 2. It is obvious from this figure that with increasing axial deformation x progressively increases the resistance force R.

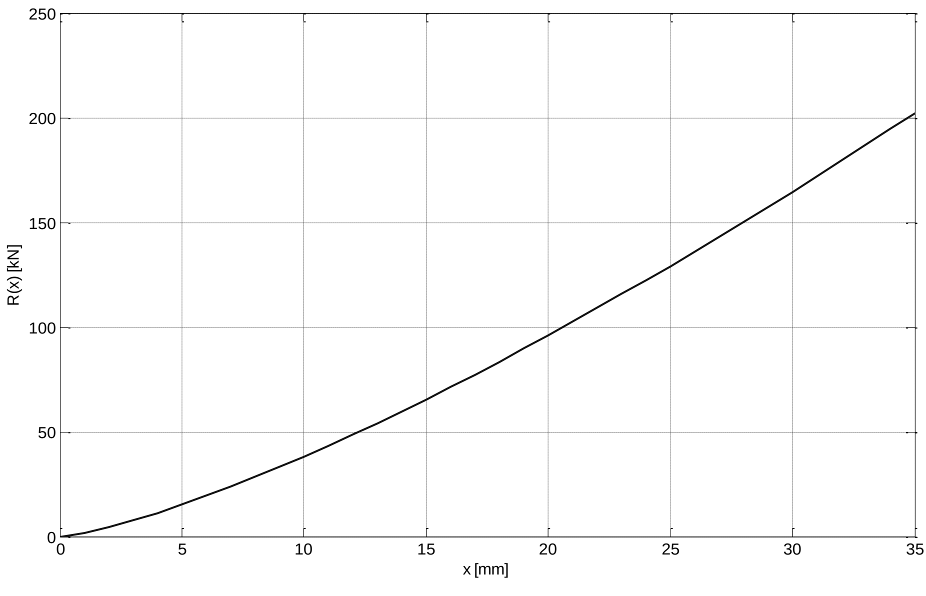

Fig. 2 Resistance of tested ballistic panel made of material Dyneema (considering the base material plasticene)

3.2. Results of Firing Tests [3]

The firing tests were carried out with two types of 9 mm calibre cartridges:

- cartridge with projectile in form of steel spherical ball of the mass of 2.97 g,
- 9 mm Luger cartridge with Full Metal Jacketed projectile of the mass of 7.50 g.

Steel Spherical Projectile

This projectile was fired from the dispersion measuring ballistic smooth bore barrel of the length of 125 mm, which was chambered for the 9 mm Luger cartridge. The velocity of a projectile was measured with the optical gates LS 020 (measuring base was 1 m) at the distance of 1.5 m from the ballistic sample.

The sample of ballistic material, the same as used for free fall tests, was fixed on the same base material – plasticene of the thickness of 105.0 mm and supported by a steel plate. The projectiles were fired at two different velocities and thus two different impact velocities $v_{1.5} \approx v_D$ were measured. Following results were obtained:

1. Impact velocity $v_D = 245.0 \text{ m s}^{-1}$ and $x_K = 7.0$ mm. For this value of the measured final bend, the final bend was calculated with use of relation (15):

$$x_K = \left[\frac{m_q v_D^2 \left(n_S + 1 \right)}{2 a_S} \right]^{\frac{1}{n_S + 1}} = 7.7 \text{ mm}$$

that differs from the measured value by 10 %.

2. Impact velocity $v_D = 403.0 \text{ m s}^{-1}$ and $x_K = 11.2$ mm (measured final bend) and $x_K = 11.8$ mm (calculated final bend). In this case, the difference between two values is 5 %.

Full Metal Jacketed Projectile of Calibre 9 mm Luger

This standard projectile was fired from ballistic barrel under the same conditions and into the same ballistic material and the following results were obtained: $v_D = 353.0 \text{ m s}^{-1}$, $x_K = 14.1$ mm. After substitution of required characteristics into relation (15), the final bend $x_K = 15.7$ mm was calculated. The difference between the measured and calculated value of bend was 11 %.

The values of other calculated characteristics are shown in the table Tab. 1.

Tab. 1 Characteristics R_K, p_K, and e_D for tested 9 mm projectiles

Projectile	v_D [m s^{-1}]	Characteristic	Value
9 mm sphere	245	R_K [N] (16)	26972
	403		47606
9 mm Luger FMJ	353		69443
9 mm sphere	245	p_K [MPa] (17)	424
	403		748
9 mm Luger FMJ	353		1092
9 mm sphere	245	e_D [MJ m^{-2}] (18)	1.4
	403		3.8
9 mm Luger FMJ	353		7.3

4. Conclusions

The aim of this article is to introduce the derivation of the physical model of the deformation behaviour of the multilayer BPV material as a modified elastic material during dynamic load and determine its characteristics from the free fall tests carried out with the hemispherical head shape weight. The determined characteristics can be utilised for a prediction of the bend of ballistic material after impact of a small calibre projectile. The determined characteristics can be also utilised for the diagnostics of the stiffness and strength of these materials during their non-destructive tests [4].

The spring with the power resistance function described by pseudo-stiffness and stiffness index of the material was chosen as a substitution of the BPV. The analytical model was verified by the firing experiments during which 2 types of projectiles were fired – standard 9 mm Luger FMJ projectile and a steel ball of diameter of 9 mm. The measured values of the bend of the BPV are in very good agreement with the values obtained from the analytical model. The introduction and utilisation of the new variable D_S, and consequently derived characteristics a_S and n_S, is the authors' new contribution to the testing of the BPV materials.

The current and also new perspective ballistic materials can be evaluated with use of results of free fall test carried out with falling weight of suitable mass and shape, especially from the point of view of their stiffness that is one of the components of ballistic resistance against small arms projectiles, or its capability to eliminate deformation of rear side of BPV adjoined to the body. The deformation behaviour of the BPV is the essential criterion for the assessment of the ballistic resistance against small arms projectiles.

References

[1] BUCHAR, J. and VOLDŘICH, J. *Terminal ballistics* (in Czech). Praha: Academia, 2003.

[2] FUDZIJI, T. and RZALO, M. *Mechanics of failure of composite materials* (in Russian). [trans. from Japanese]. Moskva: Mir, 1982.

[3] NOVÁK, M. and PĚCHOUČEK, P. *Results of free fall and firing tests of ballistic panel of ballistic protective vest* (in Czech). Brno: Prototypa ZM, Ltd., 2010.

[4] LATISHENKO, V.A. *Diagnostics of stiffness and strength of materials* (in Russian). Riga: Zinatne, 1968.

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