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Criteria of material selection for ballistic shields in the context of chosen degenerated models

M. Kulisiewicz [a], M. Bocian [a], K. Jamroziak [b,*]
[a] Institute of Materials Science and Applied Mechanics,
Wroclaw University of Technology, Wroclaw, Poland
[b] Combat Technology Department, The General Tadeusz Kosciuszko Land Forces Military Academy, Wroclaw, Poland
* Corresponding author: E-mail address: krzysztof.jamroziak@interia.pl

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Analysis and modelling

ABSTRACT

Purpose: The models come from complex rheological models that static and quasi-static loading analysis was presented in the following publications. The main conception of the research is determination of the mechanical properties of ballistic shield materials with the use of the complex constitutive compounds.

Design/methodology/approach: In the paper criteria of material selection for ballistic shields in the context of chosen degenerated models are described.

Findings: Based on the research in direction of the first phase analysis of the punching process the final result gives designing criteria for the new effective ballistic shields. The results of the presenting analysis give specific technical solution in the context of material selection for the ballistic shields.

Practical implications: The article exemplifies the importance of material selection that is responsible for the first punching phase. That data is necessary to design the optimal ballistic shields.

Originality/value: The new conception based on degenerated model finds application in analysis of punching process. Nevertheless application of the technical solution will be possible after the new material testing methods are curried out (identification methodology in the dynamic conditions). This is the main goal in the next step of the research.

Keywords: Computational mechanics; Impact load; Impact, Composites

1. Introduction

Preliminary research of materials use for ballistic shields (e.g. Kevlar, Twaron, Dyneema, etc.) punched with different velocities of the bullet demonstrates non-linear punching characteristics dependent on penetration velocity [1-5]. There is no way to describe the effect based on the linear rheological models usually use in strength description according to Hook's model theory. In that reason the new conception based on degenerated model finds application in analysis of punching process. The models come from complex rheological models that static and quasi-static loading analysis was presented in the following publications [6-8]. The models characteristics are represented by the complex constitutive compounds. The main conception of the research is determination of the mechanical properties of ballistic shield materials with the use of the complex constitutive compounds. According to the conception there is a problem with identification and modeling of non-linear systems and materials under the impact load. Many other researchers [9,10] tried to determine the characteristics of non-destructive phase. Unusual modeling methods with the use of many various models and their sensitivity, synthesis and analysis are presented in the following publications [11-15]. The main direction of the research involves the first phase of the punching process. The material properties of the ballistic shield in that phase are stable (non-destructive deformation phase). In accordance with the results [16-18] the material reaction in the non-destructive phase may have essential influence of the subsequent punching process. Evidently the more energy dispersion in the first phase of the punching process is, the less material destruction in the impact point is. Based on the research in direction of the first phase analysis of the punching process the final result gives designing criteria for the new effective ballistic shields. In the article the modification of model [18] is also presented. It consists of implementation so-called compound element as a description of the non-destructive phase. Consequently the accurate approximation of punching characteristics *S(u)* in the phase is possible to determine in the case of any non-linear relation between resistance force S and bullet position u in the ballistic shield material.

2. Problem description

In accordance with the publication [16], where the bullet movement in the material of ballistic shield is represented by the function $x(t)$:

$$x(t) = x_0(t) + u(t) + \xi(t) \tag{1}$$

where:
x_0 – function of global movement of entire shield mass m_0,
$u(t)$ – function of non-destructive material deformation (up to the yield stress),
$\xi(t)$ – function of destructive material deformation (over the yield stress)

Sum of the functions:

$$z(t) = u(t) + \xi(t) \tag{1}$$

describes complete deformation of the material in the impact point. The deformation depends on material properties (MP) and the properties are represented by the assumed "a priori" model (Fig. 1). This methodology is given in previous publication [16] where material properties in the phase of destructive identification present two parameters: h, k. On the other hand in the phase of non-destructive identification the are three parameters: c_1, c_0, k_0 (look the pattern 3).

$$MPN = \{c_1, c_0, k_0\}, \qquad MPD = \{h, k\} \tag{3}$$

where:
c_1 – variable of material static stiffness in the range if *MPN*,
c_0 – variable of material dynamic stiffness in the range if *MPN*,
k_0 – dumping in the range if *MPN*,
h – dry friction in the range if *MPD*,
k – dumping in the range if *MPD*.

The results of experiment on the Polish ballistic laminate named LIM (Table 1 and Fig. 2) show that in the destructive phase there is substantial non-linear relation between impact force S and deflection u, moreover the characteristic depends on punching velocity v_d [18].

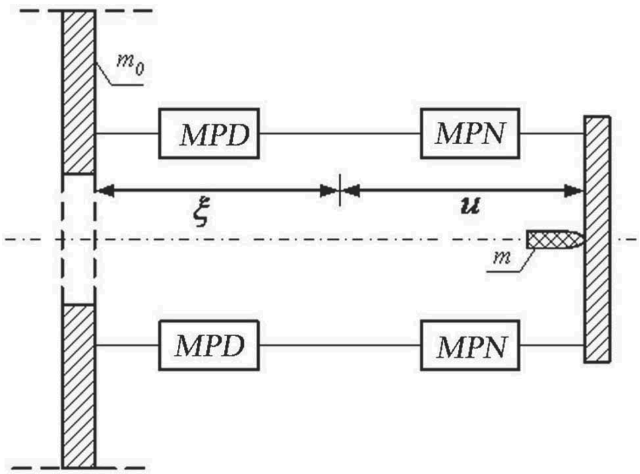


Fig. 1. Diagram of The Model Conception in The Punching Process: *MPD* – model of destructive phase , *MPN* – model of non-destructive phase, m – mass of bullet, m_0 – mass of shield, u – non-destructive deformation, ξ –destructive deformation

Table 1.
The characteristic of Polish ballistic laminate named LIM

Parameter	Laminate LIM	Aramid fabric	Aramid matrix
Thickness [mm]	5,0	0,6	0,2
Surface density [kg/m^2]	5,2	0,46	0,02
Density [g/cm^3]	1,135	0,766 (66 thread/10cm)	-
Fiber proportion [%]	70,8	-	-
Tensile strength [MPa]	309,3	466,7[1]	-
Young's modulus [MPa]	7458	7500	-
Strain by the mximum load [mm]	10,24	11	-
Tensile stress [MPa]	303,4	500	-
Tear strength[1] [kN]	0,0893	-	-
Shear strength [2] [kN]	1,42	-	-

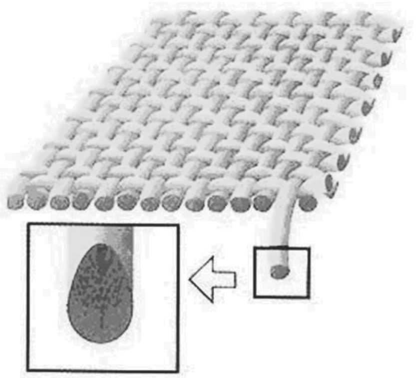
[1] test with the width dimension of sample - 50 mm
[2] test with the surface dimension of sample - 25 x 25 mm.

For the accurate analysis of the punching process the model was updated on the compound element $\dot{u}u^2$ that physical value is represented by the constant parameter κ. Generally it is assumed that in the punching process the material reaction is comparable to non-linear model with Maxwell element (Fig. 3.)

In the end it is assumed that:

$$MPN = \{c_1, c_0, k_0, \kappa\} \tag{4}$$

a)



b)

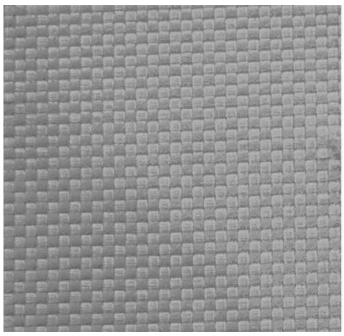


Fig. 2. Polish Ballistic Laminate Named LIM: a) – aramid fabric, b) – ballistic laminate

3. Model analysis

In the case of quasi-static loading with the constant velocity v_d , the impact force is equal to resistant force of the material:

$$S(t) = S[u(t)] = S(v_d t) \tag{5}$$

That force is also a sum of following summands:

$$S = S_M + F_s(u, \dot{u}) \tag{6}$$

where S_M - resistant force of Maxwell element that in the case of quasi-static loading the force is equal to [18]:

$$S_M = k_0 v_d (1 - e^{-au}) \tag{7}$$

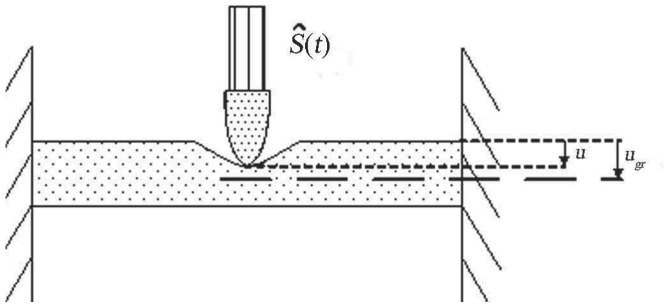
Parameter a is constant and equal to:

$$a = \frac{c_0}{k_0 v_d} \tag{8}$$

The force $S(u)$ in the quasi-static force has the following form:

$$S(u) = k_0 v_d (1 - e^{-au}) + c_1 u + \kappa v_d u^2 \tag{9}$$

a)



b)

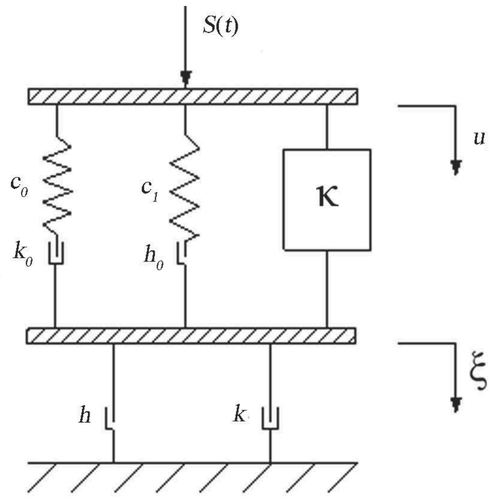


Fig. 3. Diagram System (b) of Punching Process Modeling (a)

The function describes reaction force of the material for:

$$u < u_{gr} = \frac{h_o}{c_1} \tag{10}$$

where u_{gr} is the assumed boundary value of deformation. All the effects of deformation over the u_{gr} cause material destruction. (The elasticity degradation value may be determined by the experiment with the low velocity loading ($v_d \approx 0$)). The force S over the value of h ($h >> h_o$) causes the second step of material destruction. In that moment the Maxwell and compound element κ does not exist any more and the force $S(t)$ is equal to:

$$S(t) = S[\xi(t)] = hSgn\dot{\xi} + k\dot{\xi} \tag{11}$$

The next consideration involves the range of $u < u_{gr}$. The non-linear characteristic $S(u)$ may run in different way depending on numerical value of non-destructive deformation c_1, c_0, k_0, κ (Figs. 4~5).

The assumed model is universal and it may be use for identification of dynamic characteristics for a wide range of materials.

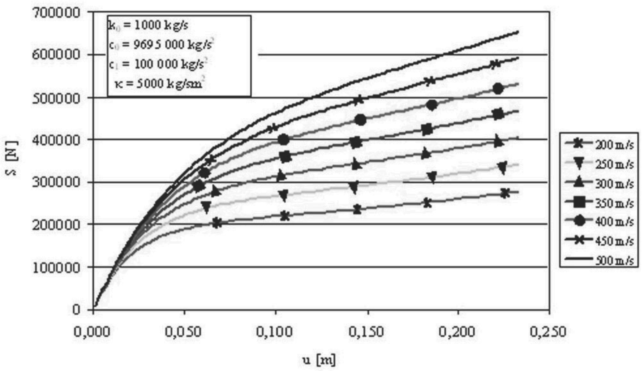


Fig. 4. Quasi-static Characteristics of Punching Process $S(u)$ with Different Velocity in The Range of Non-destructive Deformation According to The Assumed Parameters $MPN = \{c_1, c_0, k_0, \kappa\}$

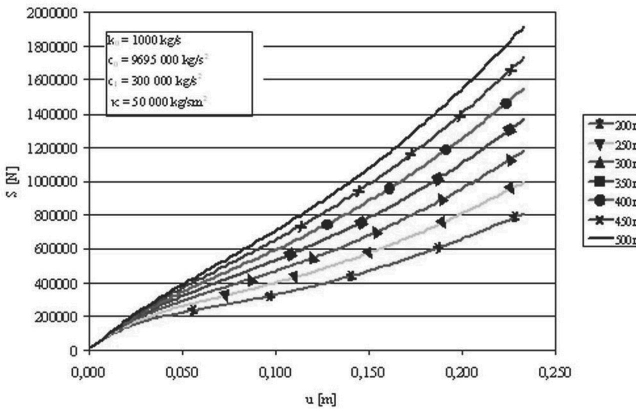


Fig. 5. Chosen Model Parameters Value Influence on Quasi-static Characteristics of Punching Process $S(u)$ with Different Velocity in The Range of Non-destructive Deformation

4. Usability material criteria in the context of punching process

In accordance with the assumption presented in publication [16,18] the highest energy dispersion in the range of non-destructive deformation gives the best material properties in the context of punching process.

$$E_{gr} = \int_0^{u_{gr}} S(u)du = \max \tag{12}$$

The function $S(u)$ (Eq. 9) used for calculation of yield energy gives the following relation:

$$E_{gr} = \int_0^{u_{gr}} c_1 u du + \int_0^{u_{gr}} \kappa v_d u^2 du + \int_0^{u_{gr}} k_0 v_d du - \int k_0 v_d e^{-au} du \tag{13}$$

As a result of the calculation with the use of relation (Eq. 10) the energy is:

$$E_{gr} = \frac{h_o^2}{2c_1} + \frac{\kappa v_d}{3} \cdot \frac{h_0^3}{c_1^3} + k_0 v_d \frac{h_o}{c_1} - \frac{k_o^2 v_d^2}{c_0}\left(1 - e^{-a\frac{h_o}{c_1}}\right) \tag{14}$$

Although the energy calculation (Eq. 14) is complicated for the analysis of optimization with respect to all material properties the result according to the criterion (Eq. 12) is useful for proper material selection.

Based on the calculations increase of the yield energy E_{gr} is noted when:

- the coefficient of elasticity c_1 describing the material stiffness in the static conditions decreases;
- the coefficient of elasticity c_0 (or relation c_0/k_0, (Eq. 14) describing the material stiffness in the dynamic conditions increases;
- the coefficient κ describing the characteristic of $S(u)$ increases;
- the material constant h_0 increases.

Apart from this the influence of dumping coefficient k_0 is not especially important, because the third and fourth summand approach infinity when the k_0 increases. But their difference approach the constant boundary value E_k

$$E_k = \frac{h_0^2 c_0}{2c_1} \tag{15}$$

5. Conclusions

The article exemplifies the importance of material selection that is responsible for the first punching phase. That data is necessary to design the optimal ballistic shields. The material properties can be determinate based on the complex rheological models, what considerably widest possibility of material tests in the range of dynamic loading. The results of the presenting analysis give specific technical solution in the context of material selection for the ballistic shields. Nevertheless application of the technical solution will be possible after the new material testing methods are curried out (identification methodology in the dynamic conditions). This is the main goal in the next step of the research.

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