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MODELLING AND EXPERIMENTAL VERIFICATIONS OF ENERGY ABSORBED BY CONSTRUCTIONAL SHIELDS UNDER FIRING

In the presented work, the author introduces the ballistic energy absorbed by the shield $m_p V_{BL}^2/2$ to elaborate the results of firing on homogeneous plates and multi – layered constructional shields. The introduced criterion V_{BL}^2 is used to determine ballistic thickness h_{BL} and ballistic velocity V_{BL} under normal firing 7.62 mm ŁPS bullets.

The experimental tests were performed on an unified test stand to investigate ballistic resistance of materials in field conditions. The stand was developed at the Naval University of Gdynia and then patented. The design of this test stand was based on the construction of ballistic pendulum arranged for measuring: the impact forces, the turn angle of ballistic pendulum φ, initial and residual velocities of the bullet. All the measurement data were transmitted to a digital oscilloscope and personal computer. The energy absorbed by the shield was subject to further analysis of $V_{BL[R]}^2$ according to Recht's and Ipson's method and of $V_{BL[Z]}^2$ according to author's method. The verification of the above-mentioned dependences was based on the results of the tests. The ballistic velocities $V_{BL[R]}$ and $V_{BL[R]}$ of the steel and steel – aluminium alloy shields with air interlayer thicknesses of 0, 6, 12 mm were approximately equal, however, they were quite different for aluminium alloy multi – layered shields, according to the results of firing 7.62 mm ŁPS bullets. These properties were confirmed by the average mass coefficients α_s^2 and average effectiveness coefficients β_s of the V_{BL}^2 for the tested methods.

NOMENCLATURE

E_{abs} – ballistic energy absorbed by the plate and the bullet, $(m_{BL} V_{BL}^2/2)$, kgm^{2}s^{-2},

E_k – kinetic energy of the bullet, $(m_p V_p^2/2)$, kgm^{2}s^{-2},

h_{BL} – ballistic thickness, m,

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I – momentum of force transferred to the dynamometer of ballistic pendulum, Ns,
m_{BL} – ballistic mass, ($m_{BL} = m_p$), kg,
m_p – mass of the bullet, kg,
V_r – residual velocity, ms^{-1},
V_{BL} – ballistic velocity ($V_r = 0$), ms^{-1},
$V^2_{BL[R]}$ – proper absorbed energy according to Recht's and Ipson's method, m^2s^{-2},
$V^2_{BL[Z]}$ – proper absorbed energy according to author's method, m^2s^{-2},
α^2_s – average mass coefficient,
β_s – average effectiveness coefficient.

1. Introduction

Diverse opinions about ballistic resistance of constructional shields can be formulated depending on the performed tests:

- standard tests e.g. for delimitation of ballistic velocity V_{50},
- laboratory tests for qualification of behaviour of materials under dynamic loading,
- field – laboratory tests for simultaneous qualification of ballistic resistance of materials as well as verifying information for analytical – computational simmulation,
- evaluation ground tests in sea conditions for estimation of ballistic resistance of studied shields.

The standard tests of ballistic resistance of plates under firing gun and rifle bullets are well-known. The value of velocity defined as V_{50} is obtained when perforation of target under normal fireing is executed with approximately 50% probability, accordingly to STANAG 2920 for NATO. A fundamental question remains, however, how can one determine ballistic velocity V_{BL} of the shield, particularly under normal fireing 7.62 mm AP bullets. The initial and residual mass of the bullet, residual mass of the shield as well as the bullet's velocity at the inlet and outlet from the shield are used according to Recht's and Ipson's method [6], 10]. An analytical – experimental evaluation of ballistic velocity V_{BL} has been presented in many survey works [1], [5], [10]. We are interested in the impact velocity of the bullet below 1000 ms^{-1}, where hydrodynamic models are not obligatory. Based on this assumption, an improved method to evaluate ballistic velocity V_{BL} is presented in this article.

2. Experimental procedure on ballistic pendulum

The experimental tests are performed on an unified test stand to investigate ballistic resistance of materials in field conditions. The stand was developed at the Naval University of Gdynia [3] and patented [4]. This test stand is based on the construction of ballistic pendulum arranged for measuring: the impact forces, shield's acceleration, initial and residual velocities of the bullet. The set-up placed on the line of fire is equiped with a target, 50 mm in diameter, which is fastened and protected in the front surface of dynamometer. The bullet impacts into the target causing its deformation. Simultaneously, parts of energy and momentum are transferred to the dynamometer, which registers the impact force F(t). This causes a turn of the pendulum around its axis. The set-up for measuring the impact velocity of the bullet V_p is installed between the outlet of the barrel and the target. Additionally, a measuring set-up for the residual velocity of the bullet and splinters V_r is installed after the target.

The acceleration sensor is placed on the target. Electromechanical transducer for measuring turn angle of the pendulum arm is placed in the axis of the pendulum. All the measurement data are transferred to a digital oscilloscope and a personal computer.

Optoelectronic and electric dual – gate devices are used to measure the bullet's velocity within the range of 20 to 1000 ms^{-1}. The transducers for velocity measurement on the inlet and outlet of the bullet have the measuring base of 200 mm. The linear – elastic dynamometer is statically and dynamically calibrated. The maximum value of the impact force $F_{\max}$ is depending on the square root of the quotient of kinetic energy E_k and the reduced mass of the device M_r

$$F_{\max} \sim (E_k/M_r)^{0.5}, \quad \text{N} \tag{1}$$

The turn angle of ballistic pendulum φ depends on the momentum I at $\varphi < 10^\circ$

$$\varphi = \frac{I}{M_r \cdot (g \cdot a)^{0.5}} \tag{2}$$

where: g – acceleration of gravity, a – radius of rotation.

The inlet and outlet velocities of the bullet penetrating the target and the momentum transferred to the dynamometer are used to determine the energy absorbed by the shield. The oscillogram of the impact force $F(t)$ of the target registered by the dynamometer is shown in Fig. 1, $F_{\max} = 161$ kN [3].

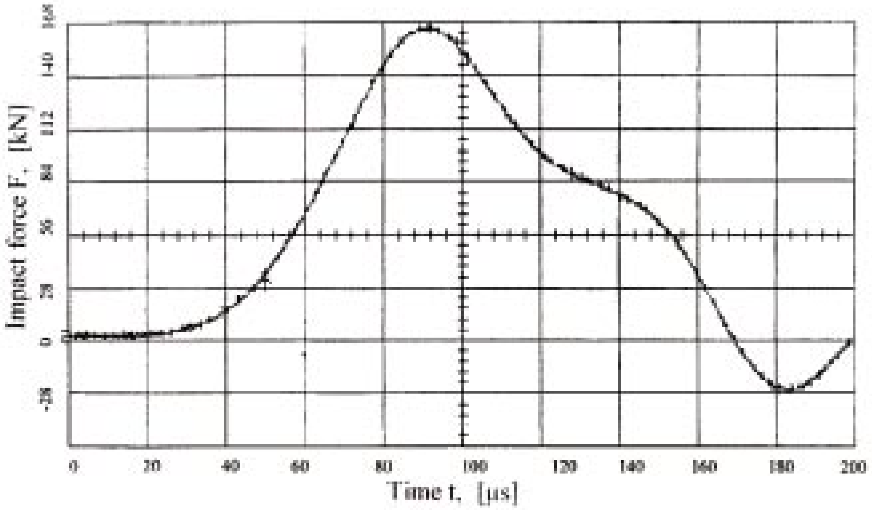

Fig. 1. The oscillogram of impact force $F(t)$ of the target registered by the dynamometer. 7.62 mm AP bullet with impact velocity V_p = 840 ms^{-1} is fired at the target of 50 mm diameter [3]

3. Experimental verification of ballistic resistance of the constructional shields

3.1. The momentum and energy conservation

The bullet of mass m_p and impact velocity V_p evokes ballistic erosion of the shield and the bullet, and causes that their residual masses m_{rt} and m_{rp} escape with residual velocity V_r on the line of fire.

The author introduces the following equations of momentum and energy conservation laws

$$m_p \cdot V_p = (m_{rp} + m_{rt}) \cdot V_r + I, \quad \text{kgms}^{-1} \tag{3}$$

$$\frac{m_p V_p^2}{2} = \frac{m_{BL} V_{BL}^2}{2} + \frac{(m_{rp} + m_{rt})^2 V_r^2}{2m_p}, \quad \text{kgm}^2\text{s}^{-2} \tag{4}$$

Then, in accordance with equations (3, 4) the energy absorbed by the shield takes the form

$$E_{abs} = \frac{m_p V_{BL[Z]}^2}{2} = I \cdot V_p - \frac{I^2}{2m_p}, \quad \text{kgm}^2\text{s}^{-2} \tag{5}$$

where: $m_{rt} + m_{rp} = m_p = m_{BL}$.

3.2. Analysis of firing parameters

In the following analysis, one uses the concept of proper energy absorbed by the shield, defined by the relationship

$$V_{BL[R]}^2 = V_p^2 - V_r^2, \quad \mathrm{m^2 s^{-2}} \tag{6}$$

according to Recht's and Ipson's method [6, 10], and

$$V_{BL[Z]}^2 = \frac{2 \cdot I}{m_p} \cdot \left(V_p - \frac{I}{2m_p} \right), \quad \mathrm{m^2 s^{-2}} \tag{7}$$

according to author's method,
where: I – the momentum of force is transferred to the dynamometer of ballistic pendulum

$$I = \int_0^{T_m} F(t) \cdot dt, \quad \mathrm{Ns} \tag{8}$$

where:
$F(t)$ – the impact force registered by the dynamometer of ballistic pendelum (Fig. 1),
T_m – the time at maximum impact force $F_{\max}$, and the impact force

$$F(t) = F_{\max.} \cdot \sin\left(\frac{\pi \cdot t}{2 \cdot T_m} \right), \quad \mathrm{N} \tag{9}$$

Then, the momentum transferred to the dynamometer can be expressed as

$$I = \frac{2 \cdot F_{\max.} \cdot T_m}{\pi}, \quad \mathrm{Ns} \tag{10}$$

The mass coefficient α^2 is defined as

$$\alpha^2 = \frac{V_p^2 - V_{BL[Z]}^2}{V_r^2} \tag{11}$$

and the average mass coefficient α_s^2 is determined as

$$\alpha_s^2 = \frac{1}{n} \cdot \sum_{k=1}^{n} \alpha_k^2 \tag{12}$$

The average effectiveness coefficient β_s of energy absorbed by the shield V_{BL}^2 is calculated as

$$\beta_s = \frac{V^2_{BLs} - V^2_{BL[Z]s}}{V^2_{BL[Z]s}} \tag{13}$$

where:

$$V^2_{BLs} = \frac{1}{n} \cdot \sum_{k=1}^{n} V^2_{BLk}, \tag{14}$$

$$V^2_{BL[Z]s} = \frac{1}{n} \cdot \sum_{k=1}^{n} V^2_{BL[Z]k} \tag{15}$$

3.3. Experimental verification of the method

Experimental verification of the developed method was done by means of tests on a test stand at the Naval University of Gdynia [2], [3], [7]. The results of firing 7.62 mm ŁPS bullets at multi – layered shields [2] are shown in Fig. 2 and Fig. 3.

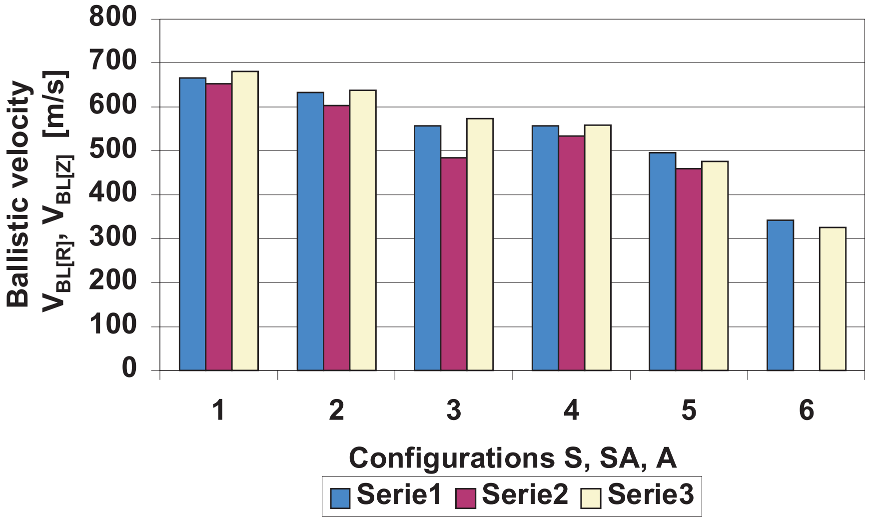

Fig. 2. Ballistic velocities $V_{BL[R]}$ (1, 3, 5) and $V_{BL[Z]}$ (2, 4, 6) of multi – layer steel (1, 2), steel – aluminium alloy (3, 4) and aluminium alloy (5, 6) shields with air gaps of 0, 6, 12 mm thick (S1, S2, S3) against 7.62 mm ŁPS bullets

Fig. 2 shows ballistic velocities $V_{BL[R]}$ (1, 3, 5) and $V_{BL[Z]}$ (2, 4, 6) of multi – layer steel, steel – aluminium alloy and aluminium alloy shields with air gaps 0, 6, 12 mm thick (S1,S2,S3) against 7.62mm ŁPS bullets. The graphs in Fig. 3 illustrate mass coefficients α_s^2 (1, 3, 5) and effectiveness coefficients β_s (2, 4, 6) of multi – layer steel, steel – aluminium alloy and aluminium alloy shields with air gaps 0, 6, 12 mm thick (S1, S2, S3) against 7.62mm ŁPS bullets. The ballistic velocities $V_{BL[R]}$ and $V_{BL[Z]}$ of multi – layer steel (1,2), steel – aluminium alloy (3,4) shields are approximately equal, however they are quite different for aluminium alloy (5,6) shields with air gaps 0, 6, 12 mm thick (S1, S2, S3). It can be seen in the graph of Fig. 2. Determination of the proper energy $V^2_{BL[R]}$ according to Recht's and Ipson's method is limited to steel and steel – aluminium alloy shields. The proper energy $V^2_{BL[Z]}$ absorbed by aluminium alloy shields should be determined according to the experimentally veryfied method by the author.

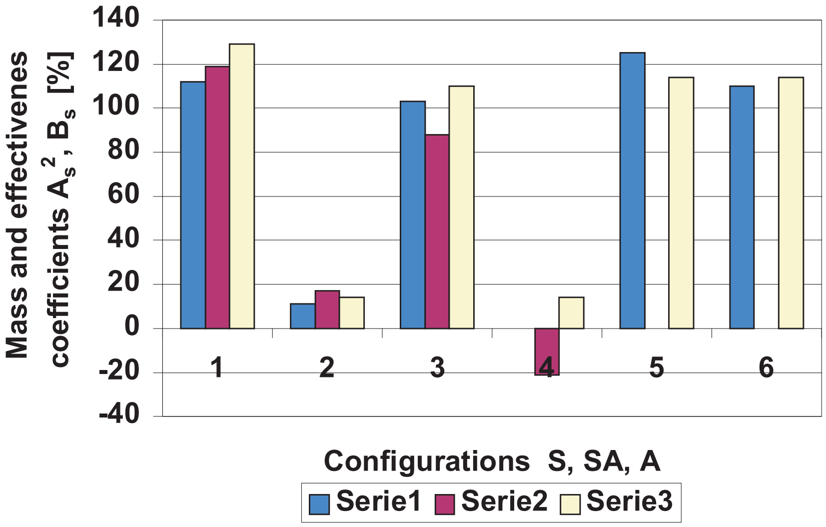

Fig. 3. Mass coefficients α_s^2 (1, 3, 5) and effectiveness coefficients β_s (2, 4, 6) of multi – layer steel (1, 2), steel – aluminium alloy (3, 4) and aluminium alloy (5, 6) shields with air gaps 0, 6, 12 mm thick (S1, S2, S3) against 7.62 mm ŁPS bullets

The method of modelling energy absorbed by homogeneous plates $V^2_{BL[R]}$ and the design of the multi – layered ballistic shields with air gaps was veryfied experimentally [8], [9].

4. Conclusions

1. The criterion of the energy absorbed by the shield $m_p V^2_{BL}/2$ was introduced to elaborate the results of firing results of homogeneous plates and multi – layered constructional shields in order to determine ballistic thickness h_{BL} and ballistic velocity V_{BL} against 7.62 mm ŁPS bullets.

2. The experimental tests were performed on an unified test stand to investigate ballistic resistance of materials in field conditions. The test stand was developed at the Naval University of Gdynia.
3. The ballistic energy absorbed by the shield $m_p \cdot V^2_{BL[}/2$ was subject to further analysis as $V^2_{BL[R]}$ according to Recht's and Ipson's method, while the proper absorbed energy $V^2_{BL[Z]}$ was analysed according to author's method.
4. The ballistic velocities $V_{BL[R]}$ and $V_{BL[Z]}$ against 7.62mm ŁPS bullets of steel and steel – aluminium alloy shields with air gaps 0, 6, 12 mm thick were approximately equal, however, they were significantly different for aluminium alloy multi – layered shields.
5. These properties were also confirmed by the average mass coefficients α^2_s and average effectiveness coefficients β_s of tested methods.

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Modelowanie i weryfikacja doświadczalna energii absorbowanej przez osłony konstrukcyjne pod ostrzałem

Streszczenie

W prezentowanej pracy wprowadzono kryterium energii balistycznej absorbowanej przez osłonę $m_p V_{BL}^2/2$ dla oceny wyników ostrzału płyt jednorodnych i wielowarstwowych osłon konstrukcyjnych. Wprowadzone kryterium V_{BL}^2 sformułowano w zależności od grubości balistycznej h_{BL} i prędkości balistycznej V_{BL} zwłaszcza pod ostrzałem pociskami 7.62 mm ŁPS.

Eksperymentalne testy realizowano na zunifikowanym stanowisku do badania odporności balistycznej materiałów w warunkach polowych; opracowanym i opatentowanym w Akademii Marynarki Wojennej w Gdyni.

Zasadę budowy stanowiska oparto o konstrukcję wahadła balistycznego wyposażonego w układy pomiarowe: siły uderzenia, prędkości pocisku na wlocie i resztkowej na wylocie z tarczy oraz kąta obrotu wahadła. Wszystkie przetworzone wielkości mierzone przenoszone są do oscyloskopu cyfrowego i komputera PC. Energię absorbowaną przez osłonę wprowadzono do dalszej analizy w postaci energii właściwej $V_{BL[R]}^2$ zgodnie z metodą Rechta i Ipsona oraz $V_{BL[Z]}^2$ zgodnie z metodą autora. Weryfikacja powyżej opracowanych zależności następowała na bazie wyników prób wykonanych w AMW na prezentowanym stanowisku. Prędkości balistyczne $V_{BL[R]}$ i $V_{BL[Z]}$ osłon stalowych i stalowo-aluminiowych z międzywarstwą powietrzną o grubości 0, 6, 12 mm są prawie równe, natomiast różnią się znacznie dla wielowarstwowych osłon aluminiowych zgodnie z wynikami ostrzału pociskami 7.62 mm ŁPS. Potwierdzają to również współczynniki masowe α_s^2 i współczynniki efektywności β_s.