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Estimation of the Effectiveness of Reactive Armours with Nitrocellulose and Cellulose Composites in Jet Dispersion *)

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Abstract: Monolithic nitrocellulose and cellulose (NC-C) composites solidified with starch were used in a model reactive armour with steel plates. The acceleration ability of the gaseous reaction products of composites was examined by the use of X-ray technique. The effectiveness of the reactive armour containing NC-C composites in weakening the ability of jet penetration was assessed experimentally on the basis of the size of holes in the steel plates and effects of the impact of jet particles on a steel plate located under the armour. It has been shown that the size of the holes in the driven plate increases and the degree of penetration of the "witness" plate is reduced with the decrease of the angle of jet impact.
The modified Gurney model was applied to simulate the process of driving steel plates in the reactive armor with a layer of NC-C composite. The model was verified by using the results of X-ray recording of plates driven by the reaction products. The effectiveness of reactive armors with NC-C composites in weakening the penetration ability of shaped charge jets was evaluated in a manner based on the results of theoretical modeling

Keywords: nitrocellulose-cellulose composites, reactive armour

1 Introduction

In earlier papers [1, 2], monolithic nitrocellulose-cellulose composites, obtained by cross-linking of nitrocellulose-cellulose mixtures with HDI/DBTL in methylene

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chloride, were incorporated into a model reactive armour. An X-ray technique was used to examine the influence of the cellulose content on the accelerating ability of the gaseous reaction products of the composites. The modified Gurney model [2] was used to simulate the process of driving steel plates in the reactive armour after jet impact. Analysis of the X-ray images and calculated profiles of the plates show that the velocities of the driven plates are much lower than in the case of explosive reactive armour. Consequently the shielding effectiveness against shaped charge jet impact should be also much lower.

In work [3], NC-C composites solidified by starch were used in a model reactive armour with steel plates. The acceleration ability of the gaseous reaction products of composites was examined by the use of X-ray technique. In the present work, the effectiveness of the reactive armour containing NC-C composites in weakening the ability of jet penetration was assessed experimentally on the basis of the size of holes in the steel plates and effects of the impact of jet particles on a steel plate located under the armour. The modified Gurney model was applied to simulate the process of driving steel plates in the reactive armour with a layer of NC-C composite. The model was verified by using the results of X-ray recording of plates driven by the reaction products. It has been shown that the model is useful in determination of space-time characteristics of the reactive armour, in which NC-C composites were applied as an energetic material. The effectiveness of reactive armours with NC-C composites in weakening the penetration ability of shaped charge jets was evaluated basing on the results of theoretical modelling. Recommendations and restrictions have been formulated, which should be taken into account in constructing reactive armours containing NC-C composites.

2 Experimental

2.1 Materials

The composites were prepared using commercial grade nitrocellulose (13.13% N) and pure powdery cellulose (Whatman, CF 11). Starch was used for solidifying the polymers. The nitrocellulose and cellulose composites were prepared in a two-stage process. First nitrocellulose and cellulose were mixed in a water suspension. After separation and drying (under reduced pressure), the mixtures were wetted with a solution of starch in water. The resulting paste-like material was placed in a container or directly in the armour element. Finally the mixtures were dried at a temperature of ca. 65 °C. The composition of the composites tested are presented in Table 1. Average density of the composites was 0.34 g/cm^3.

Table 1. Composition of NCC*x*+S composites (*x* – percentage of cellulose in the mixture of NC+S)

Composite	Nitrocellulose, [%]	Cellulose, [%]	Starch, [%]
NCC10+S	80	10	10
NCC20+S	70	20	10
NCC30+S	60	30	10

The impact sensitivity of the composites was determined using a BAM apparatus with a 5 kg hammer, the friction sensitivity was measured using a Julius-Peters machine (IPTS-METALCHEM, Poland). The friction and impact sensitivity of pure nitrocellulose was found to be 170 N and <1 J, respectively. The values are the minimum force of friction and impact energy, respectively, at which at least one reaction was recorded in six consecutive trials. These figures change after solidifying pure nitrocelullose with starch. Increasing concentration of starch in the formulations resulted in a substantial decrease in their sensitivity – from 2.5 J for the composition containing 10% of starch to 4.0 J in the case of the composition with 50% of starch. The addition of cellulose to the formulation of nitrocellulose and starch also reduces its sensitivity. Increasing concentration of cellulose in the composite with 10% of starch from 10% to 20% decreases the sensitivity from 3.8 J to 4.6 J.

The model armour consisted of two square (120×120 mm) steel plates separated by a layer of NCC*x*+S composite of thickness *h*. The upper and lower cover plates were 4 and 8 mm thickness, respectively. Square rods (10×*h* mm) made of Plexiglas were used as a lateral enclosure of the NCC*x*+S layer. The diagnostic shaped charge was placed above the upper steel plate at a distance of 70 mm. The shaped charges were made of 21.5 g pressed, phlegmatized HMX and included 14 g sintered copper liners with a cone-shape angle of 60^o and base diameter of 32 mm. The estimated jet velocity was 5750 m/s. The jet reached the upper armour plate within ca. 20 μs after firing the shaped charge.

2.2 Reaction to cumulated jet impact

The displacements and shapes of the plates at different time delays were recorded by the use of X-ray flash photography (SCANDIFLASH). The photographs were recorded 100 and 200 μs after the firing of the shaped charge. Figure 1 shows exemplary pictures of the reactive armour containing composition NCC20+S recorded at 200 μs after firing the shaped charge.

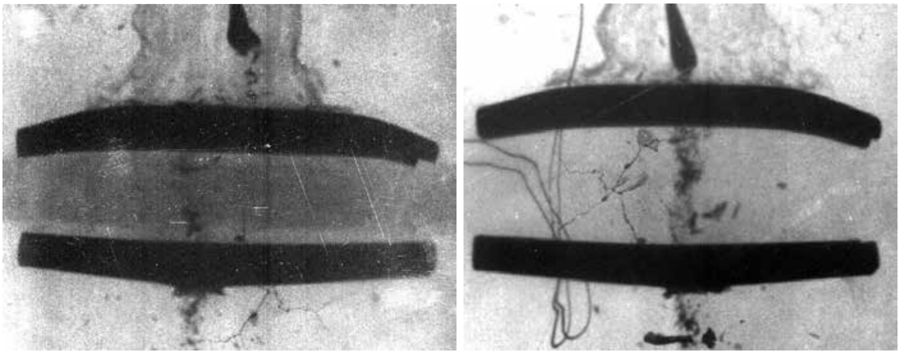

Figure 1. X-ray photographs of armour plates driven by explosion of NCC20+S composite (h = 18 mm, τ = 200 μs, with and without Plexiglas rod).

In order to compare the positions of the steel plates and to estimate their velocity, profiles of the plates were scanned using the Sigma Scan graphics program [4]. The mean velocity of the upper plate of the armour containing a layer of NCC20+S composite, within a recorded time interval of 100-200 μs, was found to be u_1 = 290, 380 and 420 m/s for h = 9, 18 and 27 mm, respectively. Due to the small initial variation of the model reactive armour from the horizontal position and relatively small displacement of the lower plates, their velocities were not determined. The steel plates in the armour without the Plexiglas rod were moved at greater distances than in the case of the reactive system with rod. The mean velocity of the upper plate of the armour containing the 18 mm layer of NCC20+S composite and not containing the rod was estimated to be u_1 = 400 m/s. The plate profiles were also used to verify the theoretical Gurney model.

The plates were more deformed when more energetic material was used as the armour intermediate layer, but they were never fragmented. This fact and the comparatively low initial velocities of the plates indicate that the tested NC-C compositions explode or deflagrate under the experimental conditions.

In order to determine which of these process is more probable, the velocity of propagation of the chemical reaction's wave in a layered charge was measured. A layer of NCC20+S composite with a thickness of 9 or 18 mm was placed between steel plates both with a thickness of 4 mm and 250 mm square side. Holes were drilled along the diagonal of a one of plate, into which four short-circuit sensors were inserted, in order to measure the wave velocity in the composite layer. The distance between adjacent sensors was 40 mm, and the point of jet impact on the plate was situated at a distance of about 60 mm from the first sensor.

The following wave velocities were measured in successive pairs of adjacent sensors: 1880, 1920 and 1950 m/s for the 9 mm layer and 2150, 2250 and 2330 m/s for the 18 mm layer. In both the cases the velocity slightly increases. This fact and the high values of the average velocity (1920 and 2240 m/s, respectively) indicate that there is an explosion process. For this reason, the NCC20+S composition cannot be treated as a non-explosive material. However, the low density of the composition makes the explosion pressure low which does not cause fragmentation of accelerated plates, but it is sufficient to drive them relatively fast.

2.3 Effectiveness of the reactive armour

The effectiveness of the model reactive armour in weakening the penetration ability of jets was assessed experimentally on the basis of the size and shape of holes in the upper steel plates. If the hole is larger and more elongated, the efficiency of the armour is greater. Shaped charge jets hit the armour at various incidence angles. Exemplary of the images of the upper and lower steel plates after the jet impact on the model armour containing the layer of NCC20+S composite of a 18 mm thickness are shown in Figure 2.

Figure 2. Upper and lower steel plates after hitting by the cumulated jet at an angle of 30° (NCC20+S composite, h = 18 mm).

Average values of maximum length a and the width b of the holes in the upper plates from two tests are summarized in Table 2. The table shows also the calculated values of the area of the ellipse surface that approximates the area of the hole. As could be expected, in the case of angles 60° and 30°, the surface area of holes is much greater than after hitting by the jet perpendicular to the surface of the armour (2 and 3.3 times, respectively). This means that the velocity of the steel plate with a thickness of 4 mm is sufficient to “consume” a part of the cumulative jet striking at a small angle. This is confirmed by the fact that the total area of the holes in the plate of 8 mm thickness is reduced with decreasing of the angle of impact. Table 2 also shows that the armour with the composite layer of a thickness of 18 mm is more effective in the destruction of the 4 mm plate than that with the layer of 9 mm (1.7 and 1.3 times for the angles of 30° and 60°, respectively).

Table 2. Average parameters of holes in upper plates of the model reactive armour with NCC20+S composite for various angles of the cumulative jet

Thickness of NCC20+S composite	Angle, α	*a*, [mm]	*b*, [mm]	*S*, [mm^2]
9 mm	90°	9	8	57
	60°	16	9	114
	30°	20	12	188
18 mm	90°	9	9	64
	60°	26	10	204
	30°	28	12	264

In order to record the effects of jet particles passing through the reactive armour, a steel plate with dimensions 500×500×1.5 mm (a witness plate) was placed under the tested system. The distance from the witness plate to the bottom surface of the armour was approximately 800 mm. Photos of witness plates from the tests performed for reactive armours containing NCC20+S composite of various thickness are shown in Figures 3 and 4.

From the analysis of all photos it follows that the size of the main hole in the witness plate decreases when the impact angle is getting smaller. The hole is also reduced if the thickness of the composite increases. Reducing area of the hole is accompanied by smaller number of debris hitting the plate. Their ability to penetrate the steel plate is limited.

Figure 3. Witness plates hit by particles of jets striking the reactive armour at 60° and 30° (NCC20+S composite of a thickness of 9 mm).

Figure 4. Witness plates hit by particles of jets striking the reactive armour at 60° and 30° (NCC20+S composite of a thickness of 18 mm).

3 Modelling

3.1 Model description

The modified Gurney model was used to simulate the process of driving steel plates in a reactive armour after jet impact. It is assumed in the Gurney model that detonation of a given explosive releases a fixed amount of energy which is converted into the kinetic energy of the driven inert material and the detonation product gases. It is also assumed that the gaseous products have uniform density and a linear, one-dimensional, velocity profile in the spatial coordinates of the system. Based on this assumption, it is possible to obtain, from the laws of conservation of energy and momentum, simple formulae for the terminal velocity of driven bodies. Jones, Kennedy and Bertholf [5] applied the Gurney model to describe the process of acceleration of bodies and they obtained the solution of the differential equations in the closed form.

Following the authors of work [5], the Gurney approach was applied in this work to estimate the variations in velocity of the metal plates adjacent to the charge of the energetic material, in the so-called “sandwich” system (Figure 5). If we apply the ideal gas equation to describe the physical properties of the gaseous charge, then the formula for the velocity of the metal plate *M* has the form:

$$V_M^2 = \frac{2E}{B}\left\{1 - \left[\left(\frac{x_M}{x_{M0}}\right)(A+1) - A\right]^{-BC(\gamma-1)/M(A+1)}\right\} \tag{1}$$

where: $A = \dfrac{2\dfrac{M}{C}+1}{2\dfrac{N}{C}+1}$, $B \equiv \dfrac{N}{C}A^2 + \dfrac{M}{C} + \dfrac{1}{3}\dfrac{1+A^3}{1+A}$, γ is a constant adiabatic exponent, E denotes the Gurney energy of the energetic material, x_M and x_{M0} are the Eulerian position coordinates of the plate M at the time t and at the initial time t_0, respectively.

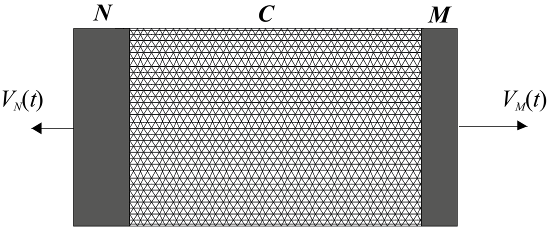

Figure 5. A scheme of the plane system for driving plates: N, M and C − respectively the mass of the plates and gaseous charge per unit area.

Relation (1) was derived in [5]. However, taking into account the definition:

$$\frac{dx_M}{dt} \equiv V_M \tag{2}$$

the time-dependence of a position of the plate M can be also derived from the relation:

$$t = \int_{x_{M0}}^{x_M} \frac{1}{V_M(x_M)}\,dx_M \tag{3}$$

by calculating the integral in a numerical way.

Formulae (1) and (3) were derived on the assumption that the transformation of the explosive into the gaseous products occurs instantaneously in the whole volume of the charge. In the case of a detonation running at high velocity this is a reasonable assumption. However, when a lower velocity of explosion takes place in the energetic material, the time of the explosion of the charge may have a significant influence on the acceleration process and profiles of the driven plates. We have assumed that the model described above can be applied independently to the transverse slices (rings) of the steel plates and a slab of energetic material. The chemical transformation and the movement of the plates in subsequent sections of the system begins with a delay associated with the arrival of the explosion wave. However, it is necessary to note that the assumption of planar symmetry in subsequent sections of the system is a coarse approximation, because in real armour the wave propagation at low velocity causes deflection of the steel plates. Thus, the modified model requires experimental verification.

3.2 Verification of the model

The proposed model was used to simulate the acceleration of steel plates by the explosion products of the NCC*x*+S composites described in Table 1. The characteristics of the composite components used for the thermochemical calculations are presented in Table 3. Due to the lack of thermodynamic data for starch, in calculations they were replaced by the data for cellulose.

The thermochemical calculations were performed using the CHEETAH code [6] with a set of parameters of the BKW equation given in [7] (BKWS). It was assumed that cellulose and starch are chemically inert during the explosion of the composite section, because of the negative oxygen balance (approx. -30%) of the nitrocellulose. Initially, the adiabatic exponent γ for the explosion products was determined for each composite. On the basis of the calculated velocity of the standard copper tube, driven by the detonation products of a given composition, the Gurney energy E was estimated. Next, it was assumed that this energy is equal to the Gurney energy corresponding to the explosion of the real composite. The parameters obtained and the calculated detonation velocity for the tested composites are given in Table 4.

Table 3. Characteristics of the composite components

Component	Chemical formula	Density [g/cm^3]	Enthalpy of formation [kJ/mol]
nitrocellulose	$C_6H_{7.29}N_{2.71}O_{10.41}$	1.45	-682
cellulose	$C_6H_{10}O_5$	0.90	-962

Table 4. Explosion parameters for compositions NCC*x*+S

Composite	Adiabatic exponent γ	Guerney energy E [J/g]	Detonation velocity D [m/s]
NCC10+S	2.16	1028	2901
NCC20+S	2.18	842	2536
NCC30+S	2.18	635	2164

The data corresponding to the armour with steel plates driven by the products from NCC*x*+S composites were used in the calculations. It was assumed that the model plate has an area equal to the contact surface of the real plate with a layer of energetic material, and its mass is identical to the actual total mass of the plate.

Exemplary results of modeling for the composites NCC*x*+S are shown in Figure 6. The calculated profiles of the outer surface of plates are compared with the profiles obtained from X-rays measurements.

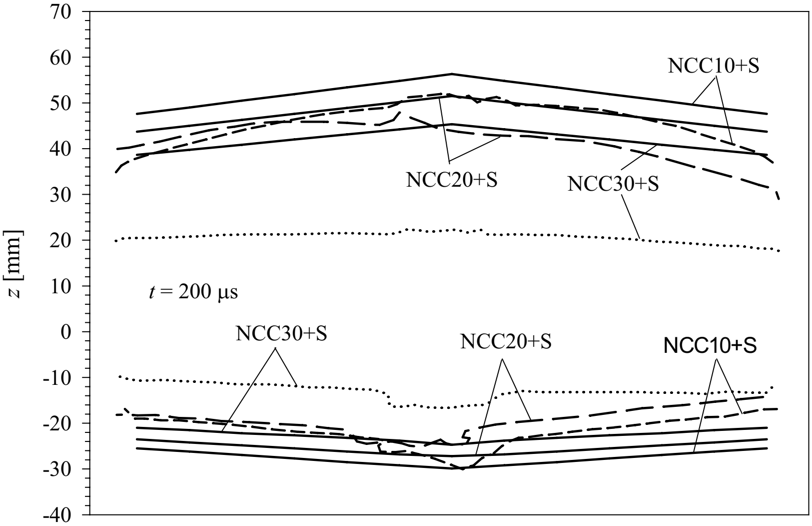

Figure 6. Comparison of the profiles of the external surfaces of plates obtained by modeling (solid line) and X-rays measurements (after time $\tau = 200$ μs) for the composites NCC*x*+S of 9 mm thickness.

The model does not take into account the flow of explosion gases through the holes in the plates, caused by penetration of the steel by the cumulative jet, and the lateral expansion of the gases. The steady transformation of NCC*x*+S composites was also assumed. Thus, significant differences in the shape and displacements of the calculated and experimental profiles of the plates in the middle and outer parts of the system are observed.

The results of calculations for the NCC20+S composite layer of varying thickness are shown in Figure 7 as the dependences of plate *M* of 4 mm thickness on the driving distance. The relationship of this distance with time is also shown. The locations of the center parts of the plates, read from the X-rays photographs taken after 80 and 180 μs after the moment of impact, are also shown in Figure 7.

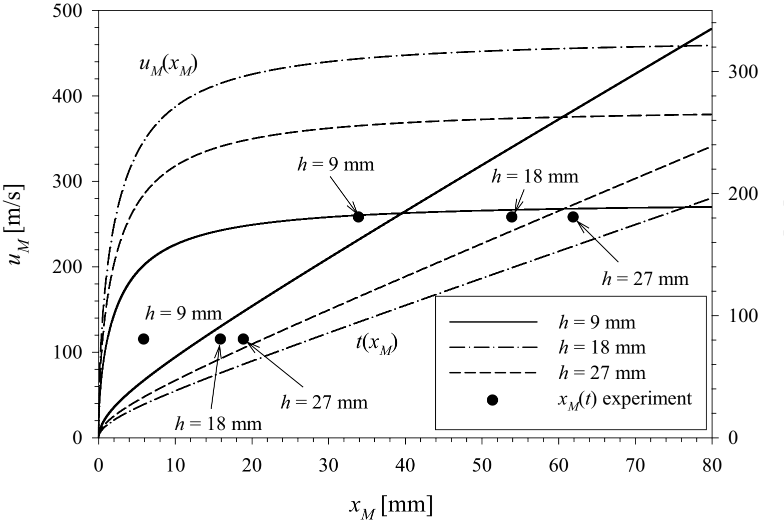

Figure 7. Dependence of the velocities of the thicker steel plates on distance and the relationship between the distance and the time for the composite NCC20+S of various thickness.

The maximum calculated velocity of plate with mass M is 270, 380 and 460 m/s for the composite layer thickness of 9, 18 and 27 mm, respectively. The mean experimental velocity of the upper plate was found to be 290, 380 and 420 m/s, respectively. Relatively high average experimental velocity of the plate M obtained for the thickness of 9 mm is due to the small plate displacement determined from the X-ray image taken at time τ = 100 μs. Such displacement may be caused by a relatively high error in reading the profile of the deformed plate.

More results of calculations are given in works [2] and [3]. From their comparison with the experimental data it follows that the proposed modified Gurney model allows us to determine the approximate time-space characteristics for the reactive armor, in which nitrocellulose and cellulose composites are used. The model can be applied to assess the effectiveness of reactive armors with those composites in weakening the penetrating efficiency of cumulative jets.

3.3 Stopping power of ERA sandwiches

Held [8] investigated the dependence of the stopping power of ERA symmetric sandwiches on explosive layer thickness. The latter can be clearly related to the velocity of armour steel plates. The explosive layer thickness was varied from 0.25 to 5 mm. The thickness of mild steel plates was H = 1 mm. The tests were performed with a medium calibre shaped charge of 96 mm diameter. The velocity of a cumulative jet tip was 8300 m/s. The jet hit the ERA sandwich at an angle 30°. Mild steel witness blocks were used to determine the reduction effect of ERA. The penetration depth of the block without the explosive in ERA was $P_0 = 500$ mm. This depth in the system with an explosive layer was marked as P_{res}. Held also associated the thickness of explosive with the steel plates' velocity u. Finally, the experimental data were approximated by the relation:

$$\frac{P_{res}}{P_0} = 0{,}375\,u^{-1{,}678} \tag{4}$$

In similar manner Held approximated the results of experiments reported in [9] for the ERA with steel plates of 3 mm thickness. Small shaped charges with 30 mm diameter were used. In this case the relation between P_0 (120 mm) and P_{res} had the form:

$$\frac{P_{res}}{P_0} = 0{,}135\,u^{-2} \tag{5}$$

A simple theoretical model of the interaction of a shaped charge jet with a reactive armour cassette are presented in paper [10]. The formula for the stopping efficiency of shaped charge jests was derived from the geometric relationships. This efficiency was defined as the ratio of the mass of steel plate penetrated by the jet per unit time to the jet mass reaching the plate at this time. The proposed model of reaction of the reactive cassette on jet impact enabled the author of paper [10] to estimate the relative penetration of the steel block in the presence of the cassette which plates were driven up to the velocity u_1 on the basis of the penetration specified for the same layout for the velocity u_2:

$$\frac{P_{res-1}}{P_0} = \frac{P_{res-2}}{P_0}\,\frac{\dfrac{V_j}{u_1}\sin\alpha - 1}{\dfrac{V_j}{u_2}\sin\alpha - 1} \tag{6}$$

where V_j is the jet velocity and α is the angle between the direction of the jet and the surface of the ERA. This formula was applied to the systems studied by Held [8]. Comparison of the relative penetration obtained from empirical Held's formulae and by using the Equation (6) is shown in Figure 8. The discussion of both model is given in work [10].

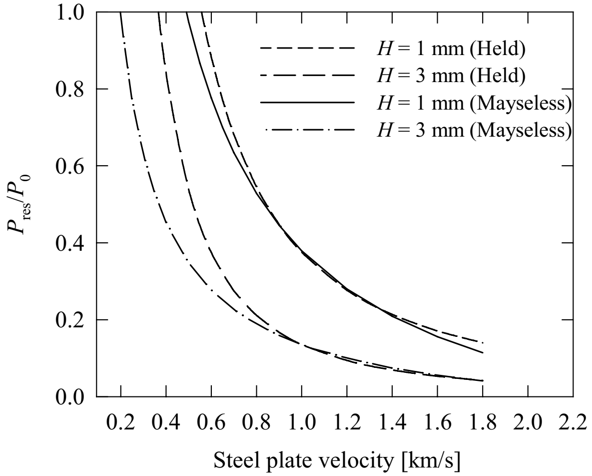

Figure 8. Comparison of the relative penetration calculated by empirical Held's formulae ([9]) and the theoretical Mayseless equation [10].

3.4 Theoretical effectiveness of the model reactive armour

In order to verify the effect of sandwiches with NC-C composites on the stopping efficiency of shaped charge jets described in [8], the velocity of steel plates of thickness of 1 and 3 mm in the model symmetrical reactive armour containing the NCC20+S composite layer with a thickness C = 10, 20, 30, 40 and 50 mm was calculated. For calculations, the modified Gurney model was used. The modelling results are shown in Figures 9 and 10.

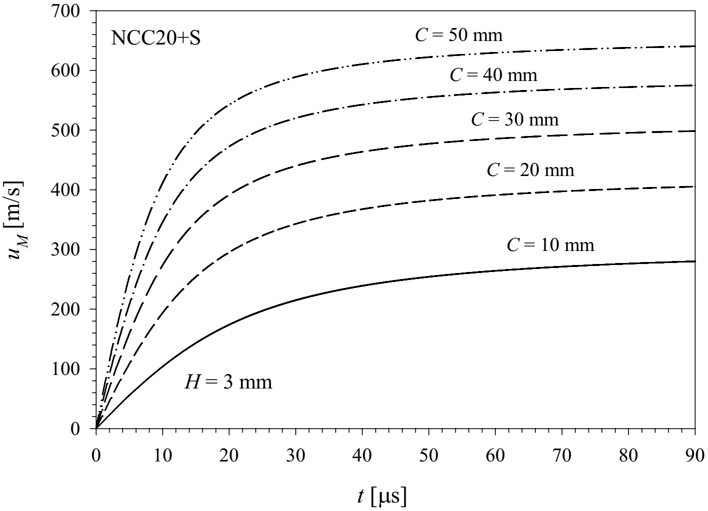

Figure 9. Time-dependence of velocity of steel plates of a thickness of 3 mm for a symmetrical reactive armour with the layer of NCC20+S composite.

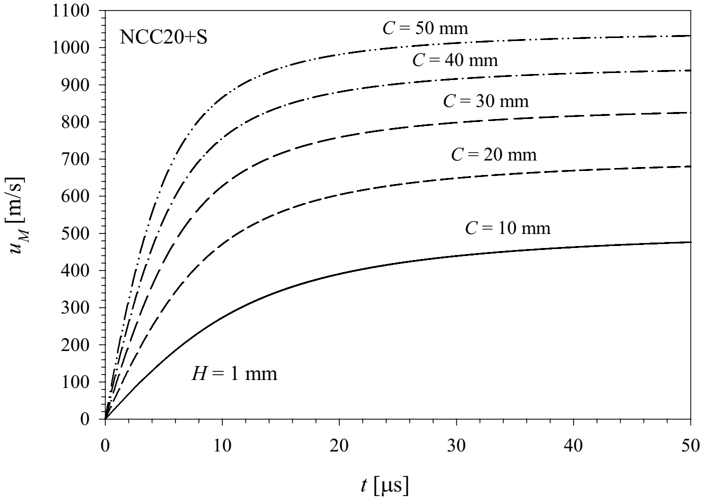

Figure 10. Time-dependence of velocity of steel plates of a thickness of 1 mm for a symmetrical reactive armour with the layer of NCC20+S composite.

The relative jet penetration was estimated for the calculated maximum velocity of plates by using Held and Meyseless relations. The calculation results for armour plates having a thickness of 3 mm and a jet generated by the shaped charge with a diameter of 30 mm are shown in Table 5, and in Table 6 for plates with a thickness of 1 mm and the charge of 96 mm diameter.

Table 5. Calculated relative jet penetration after breaking the model reactive armour composed from NCC20+S composite and steel plates of 3 mm thickness

Thickness of NCC20+S composite [mm]	Maximum velocity of plates [m/s]	P_{res}/P_0 (Held)	P_{res}/P_0 (Mayseless)
10	298	1.0	0.63
20	418	0.77	0.43
30	508	0.52	0.34
40	582	0.40	0.28
50	646	0.32	0.25

Table 6. Calculated relative jet penetration after breaking the model reactive armour composed from NCC20+S composite and steel plates of 1 mm thickness

Thickness of NCC20+S composite [mm]	Maximum velocity of plates [m/s]	P_{res}/P_0 (Held)	P_{res}/P_0 (Mayseless)
10	508	1.0	0.96
20	702	0.68	0.63
30	840	0.50	0.49
40	950	0.41	0.41
50	1040	0.35	0.36

During the analysis of the data in Tables 5 and 6 the fact should be taken into account that the velocity adopted in evaluation of the jet effectiveness in penetration of a steel block was calculated by the Gurney model. As previously shown, this model gives the displacement of plates slightly larger than that obtained from the experiment, and thus the velocity of the plates is also overestimated. Furthermore, the model was verified only for the composite layers of thickness of 10, 20 and 30 mm. With the greater thickness of the layer, lateral expansion of the explosion products can have a significant impact on the velocity of plates, which reduces their acceleration ability. This expansion is not included in the Gurney model. Nevertheless, the data in Tables 5 and 6 show that it is possible to build a reactive armour with nitrocellulose and cellulose composite, for example NCC20+S, reducing penetration of the jet by at least half ($P_{res}/P_0 = 0.5$).

The detailed analysis of the graphs shown in Figures 9 and 10 indicates that the plates of 3 mm thickness can reach the velocity equal to 0.8 maximum velocity after 40, 28, 22, 19 and 17 s respectively for the thickness of the composite layer 10, 20, 30, 40 and 50 mm. In the case of plates with thickness of 1 mm, these times are respectively 22, 15, 12, 10 and 9 s. These times should also be taken into account in assessing the effectiveness of the reactive armour for weakening of the particular cumulative jet with known parameters such as velocity of jet tip, jet thickness and particle velocity gradient in the jet. They cannot be greater than the duration of reactive armour penetration by a jet, because then the effectiveness of plates in reducing the penetration ability of the jet will be less than that estimated by using the Gurney model and Held or Mayseless relations.

4 Conclusions

The effectiveness in jet dispersion of the model reactive armour with a nitrocellulose and cellulose composite layer was estimated experimentally and theoretically. It was estimated experimentally that the area of the hole in 4 mm thick steel plate is increasing from 2 to 4 times for the angle of jet of 60° or 30° degrees in comparison with perpendicular hitting of the model armour. The effectiveness of the armour in jet dispersion was confirmed by the number and quantity of holes in the witness plate.

It was also shown theoretically that it is possible to build the reactive armour with NC-C composition, providing a 50% reduction in the steel penetration by a shaped charge jet. Moreover, the time required to accelerate the steel plates was estimated for the model reactive armour of different thickness of NC-C composite layer. It changes from 17 to 40 μs and from 9 to 22 μs for 3 mm and 1 mm thickness plates, respectively. These times should be taken into account in assessing the effectiveness of the reactive armour for weakening of a jet. They cannot be greater than the duration of reactive armour penetration by the jet, because then the effectiveness of plates in reducing the penetration ability of the jet will be less than that estimated theoretically.

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