FRAGMENT SIMULATING PROJECTILE PENETRATION INTO LAYERED TARGETS

Petr Pěchouček*, Stanislav Rolc†, Jaroslav Buchar‡

Fragment Simulating Projectile (FSP) experiments using high strength steel were conducted to assess ballistic efficiency of some layered structures. Materials of single structures have been considered as: steel, ceramics, concrete and some ductile materials. The 53.78 ± 0.26 *g projectiles, with 20 mm in diameter were fired at velocities closed to 1000 m/s. The results of predictive calculations and experimental data are reported. Comparisons with LS DYNA 3D calculations show good agreement with experiments. The numerical simulation can be used for a proposoal of an optimum arrangement of layered targets.*

Keywords: *penetration, finite element, fragment simulating projectile, layered targets*

1. Introduction

Structures and vehicles have increasingly either been designed to protect their occupants from penetration of fragments or their level of protection against a variety of attacks has been assessed. These fragments typically are metal and strike the structure at a high rate of speed,attempting to penetrate and perforate the cladding of the structure and enter the interior, they inflicting significant damage to the structure and its occupants. Civil and military ballistic protection systems often consist of layered plates with or without spacing. The idea of using layered plates instead of a monolithic one in order to increase the ballistic perforation resistance is not new, and the effect of using targets made up of several thinner plates has been investigated in the literature for a long time. In [1] it has been found that layered plates in contact were superior to monolithic plates if the response changed from one being dominated by plate bending and shearing to one dominated by membrane stretching. The impact resistance of monolithic and multi-layered aluminium targets has been compared in [2]. In the tests both blunt and conical nosed projectiles were used. It was found that the ballistic resistance of adjusted targets of equal thickness was inferior to that of an equivalent single layer. It was also noted that spaced layers were less effective at impact loading thanlayers in contact. The ballistic resistance of layered steel plates struck by 7.62 mm standard bullets has been studied in [3]. First, single steel plates (1–8 mm thick) were tested and the effects of thickness and mechanical properties were studied. Second, layered targets both with and without spacing were considered, and the effects of number, thickness and arrangement of layered plates were explored. They found that single steel plates are more effective than layered targets of equal total thickness, and that the resistence of layered targets increases as the number of plates decreases and the thickness of the back plate increases.

* Ing. P. Pěchouček, Prototypa-ZM, s.r.o.
† doc. Ing. S. Rolc, CSc., VOP-026 Sternberk, s.p., Division VTUO Brno
‡ prof. Ing. J. Buchar, DrSc., SVS FEM Ltd., Brno

The model sof the ballistics efficiency of the layered structures has been developed in [3–5]. In some next studies, the protection performance of double-layered metal shields against projectile impact was studied in a pure numerice approach using ABAQUS/Explicit [6, 7]. Four types of projectiles at different weight and nose shape were considered, representing various fragments generated from improvised explosive devises (IEDs). These numerical simulations revealed advantageous behaviour using double-layered targets struck by blunt projectiles compared with monolithic plates of equal weight in ballistic protection.

In the present study, the ballistic perforation resistance of layered targets made from ARMOX 500 steel, ceramics Al_2O_3 and concrete struck by 53.78 ± 0.26 gram fragment simulating projectiles (FSP), with 20 mm in diameter at velocities closed to 1000 m/s. Projectiles were investigated both experimentally and numerically. The numerical simulation has been performed using LS DYNA 3D finite element code. In order to use this code a proper material models must be choosen.

2. Experimental procedure

2.1. Targets

The following layered structures have been considered:

1) Arrangament S1: frontal layer: steel ARMOX 440 (20 mm) – Air gap (50 mm) – steel ARMOX 440 (20 mm),
2) Arrangament S2: frontal layer: steel ARMOX 500 (8.2 mm) – Air gap (50 mm) – steel ARMOX 500 (8.2 mm),
3) Arrangament S3: frontal layer: Concrete VUSTAH1 (40 mm) – Concrete VUSTAH1 (40 mm) – Concrete VUSTAH1 (40 mm) – Air gap (30 mm) – ARMOX 500 (6 mm),
4) Arrangament S4: frontal layer: BASE 1 Armour – ceramic composite, 9.3 mm Al_2O_3, total thickness 20.12 mm – Air gap (50 mm) – steel ARMOX 500 (6 mm),
5) Arrangament S5: Armour BASE 2 (ceramic composite, ceramics Al_2O_3 total thickness 20 mm),
6) Arrangament S6: Protective tin (0.5 mm) – Concrete VUSTAH1 (40 mm) – Concrete ZPSV1 (40 mm),
7) Arrangament S7: Protective tin (0.5 mm) – Concrete VUSTAH1 (40 mm) – Concrete ZPSV2 (40 mm),
8) Arrangament S8: Protective tin (0.5 mm) – Concrete ZPSV1 (40 mm) – Concrete ZPSV1 (40 mm) – Concrete ZPSV2 (40 mm).

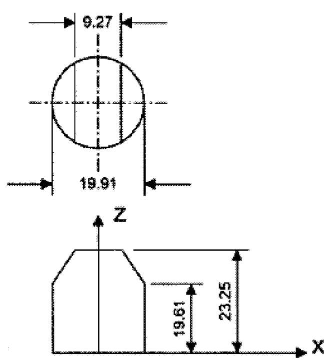

Fig.1: Fragment simulating projectile (FSP)

2.2. Ballistics device

The used fragment simulating projectile is shown in Fig. 1.

FSP projectiles have been launched from the equipment shown in the Fig. 2.

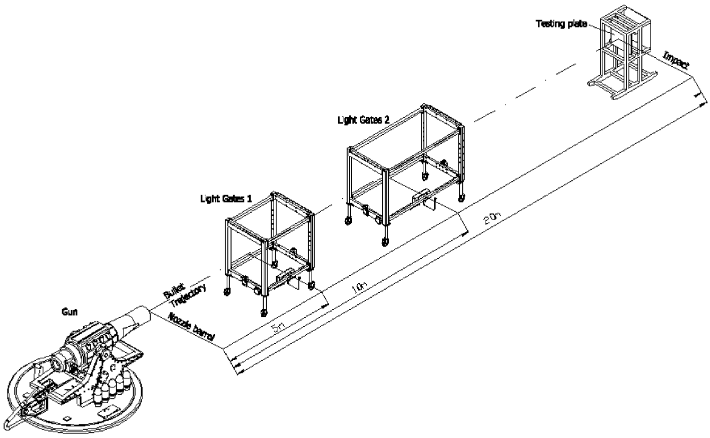

Fig.2: Schematic of the experimental device

View on the experimental device is shown in the photo in the Fig. 3.

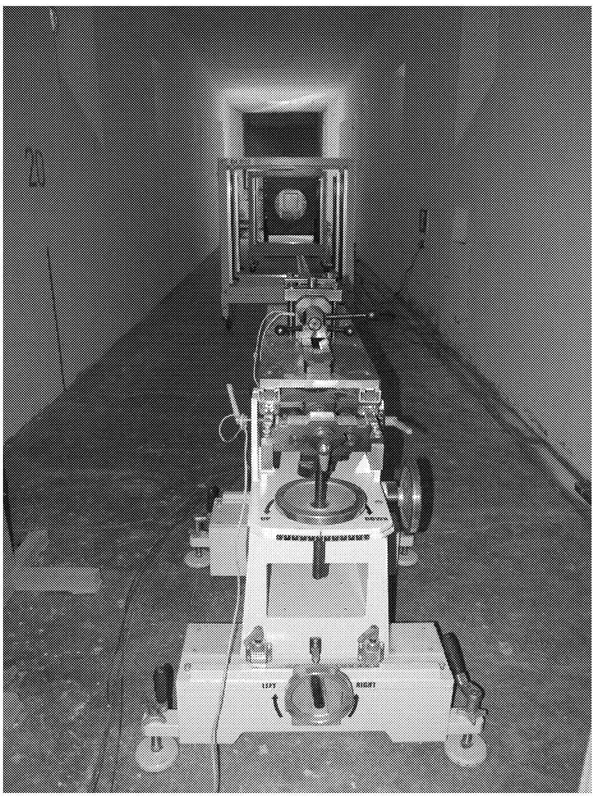

Fig.3: Photo of the experimental device (a more detail description can be found on www.prototypa.cz/pdf/FSP-20.pdf)

3. Experimental results

The aim of the ballistics experiments consisted in the evaluation of the level of ballistic protection. This level is definied by the standard STANAG 4569, AEP-55. The level is given by the FSP striking velocity and the distance of the FSP launching when the target remains stil non – perforated. Corresponding values of both quantities are given in Table 1. Experimental results are than given in the Table 2. In this table the next meaning quantity – area density – is also given. It can be see that the best solution of the ballistic protection consists in the use of Armour BASE 2. The performed experiments show that there is a great variety of possible arrangement of layered targets. The experimental verification of all possible solutions is very difficult to perform. In order to obtain some reasonable insight the numericaal simulation of ballistic experiment sis needed.

Level of the protection	Distance (m)	20 mm FSP striking velocity V_s ($m\,s^{-1}$)
5	25	960
4	25	960
3	60	770
2	80	630
1	100	520

Tab.1: Levels of the ballistic efficiency according to the standard STANAG 4569, AEP-55

Target	Arrangement of the target	Thickness [mm]	Area density [kg/m^2]	Level of the protection STANAG 4569
S1	frontal layer : steel ARMOX 440 (20 mm) – Air gap (50 mm) – steel ARMOX 440 (20 mm)	91	319	5
S2	frontal layer : steel ARMOX 500 (8.2 mm) – Air gap (50 mm) – steel ARMOX 500 (8.2 mm)	67	130	3
S3	frontal layer : Concrete VUSTAH1 (40 mm) – Concrete VUSTAH1 (40 mm) – Concrete VUSTAH1 (40 mm) – Air gap (30 mm) – ARMOX 500 (6 mm)	156	310	5
S4	frontal layer : BASE 1 Armour (ceramic composite, 9.3 mm Al_2O_3, total thickness 20.12 mm) – Air gap (50 mm) – steel ARMOX 500 (6 mm)	77	89	3
S5	Armour BASE2 (frontal layer of ceramics Al_2O_3 – 20 mm and 22 mm of ARMOX 500 steel)	42	113	5
S6	Protective tin (0.5 mm) – Concrete VUSTAH1 (40 mm) – Concrete ZPSV1 (40 mm)	81	184	3
S7	Protective tin (0.5 mm) – Concrete VUSTAH1 (40 mm) – Concrete ZPSV2 (40 mm)	81	185	3
S8	Protective tin (0.5 mm) – Concrete ZPSV1 (40 mm) – Concrete ZPSV1 (40 mm) – Concrete ZPSV2 (40 mm)	121	286	3

Tab.2: Experimental results

4. Numerical simulation

The numerical simulation has been performed using LS DYNA 3D finite element code. In order to use this code a proper material models must be choosen.

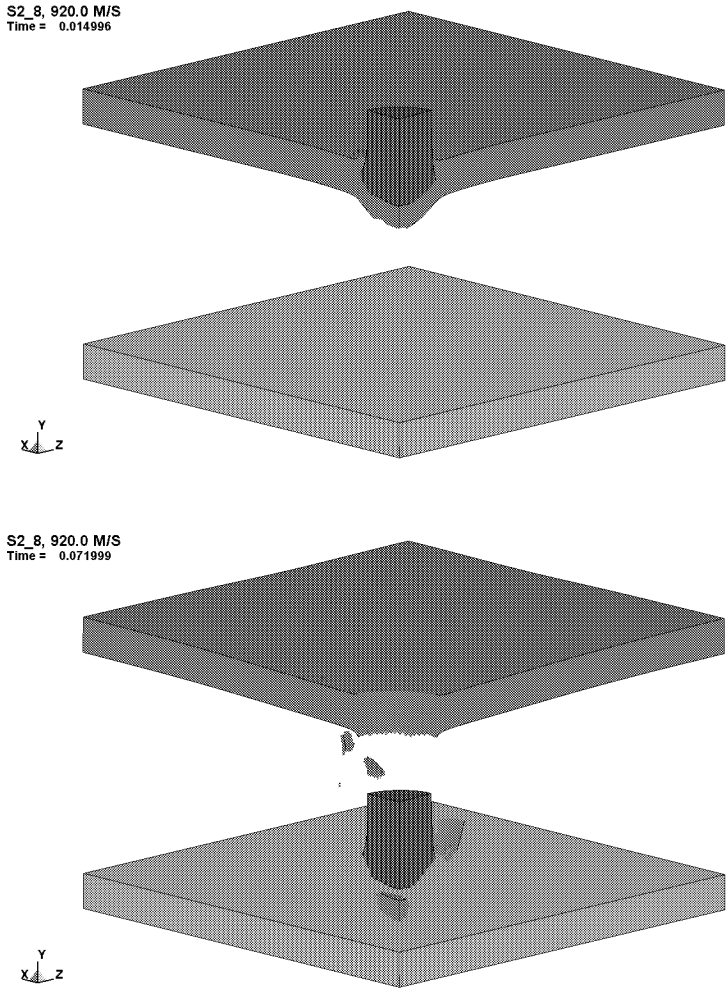

Fig.4: Penetration of the FSP projectile into layered target S2 at two different times (time is given in seconds); shoot No. 8 – projectile striking velocity was 920 m/s

4.1. Material model

For the steel, the Johnson-Cook constitutive model was used.

$$\sigma = (A + B\,\varepsilon^n)\,(1 + C\,\ln\dot{\varepsilon})\,(1 - T^{*m}) \ .$$

The meaning of single parameters of this equation can be found e.g. in [8]. The values of these parameters are:

– Fragments: $A = 1650\,\mathrm{MPa}$, $B = 807\,\mathrm{MPa}$, $C = 0.008$, $n = 0.1$, $m = 1.0$.
– Steel ARMOX 500: $A = 1470\,\mathrm{MPa}$, $B = 702\,\mathrm{MPa}$, $C = 0.00549$, $n = 0.199$, $m = 0.811$.

The fracture strain is given as [9]

$$\varepsilon_\mathrm{f} = D_1 + D_2\,\exp(D_3\,\sigma^*)\,(1 - \dot{\varepsilon}_\mathrm{eq})^{D_4}\,(1 + D_5\,T^*)$$

where $D_1, \dots, D_5$ are material constants determined from material tests, and σ^* is the stress triaxiality ratio [10]. The following values of these constants have been determined:

$D_1 = 1.4$, $D_2 = 0.08$, $D_3 = 0.04$, $D_4 = 0$, $D_5 = 0$. Fracture occurs when damage of a material element equals unity, since no coupling between the damage and the constitutive relation is considered in this study.

The properties of the concrete have been described in terms of the Johnson-Holmquist model [11]: $A = 0.75$, $B = 1.34$, $C = 0.029$, $N = 0.53$, $S_{\mathrm{max}} = 7.0$, $f_{\mathrm{c}} = 87.6\,\mathrm{MPa}$, $f_{\mathrm{t}} = 17.86\,\mathrm{MPa}$, $P_{\mathrm{crush}} = 40\,\mathrm{MPa}$, $\mu_{\mathrm{crush}} = f_{\mathrm{c}}\,(1-2\,\nu)/E$, $P_{\mathrm{lock}} = 800\,\mathrm{MPa}$, $\mu_{\mathrm{crush}} = 0.1$, $D_1 = 0.04$, $D_2 = 1.0$, $K_1 = 8500\,\mathrm{MPa}$, $K_2 = -17100\,\mathrm{MPa}$, $K_3 = 20800\,\mathrm{MPa}$.

Very similar model has been used for the description of the properties of ceramics. The corresponding values of the constants of this model are given in our previous work [12].

4.2. Numerical simulation

In the Figure 4 an example of the fragment simulating projectile penetration into target (Arrangament S2) is shown. Even if these results show e.g. origin of projectile erosion which is also observed the main results represents the value of the projectile residual velocity and/or

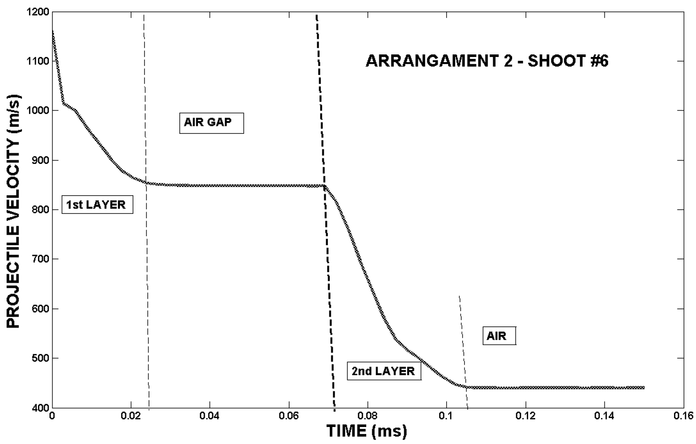

Fig.5: Example of the projectile velocity during its penetration into layered target S2

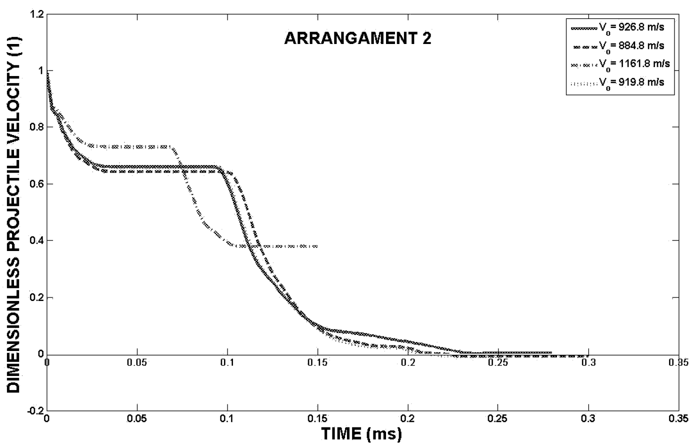

Fig.6: The influence of the projectile striking velocity on its penetration velocity

projectile penetration depth, respectively. Both these quantities are easily measurable. The dependence of the projectile velocity though the target is shown in the Fig. 5. The velocity in single layers gradualy decreases. The computations have been made for different velocities of the projectile. The influence of its striking velocity is displayed in the Figure 6. It is evident that for the velocities about 900 m/s the change in the projectile velocity exhibits a small effect on qualitative features of the penetration velocity vs. time dependence.

The computation has been focused on the determination of the ballistic limit. Results are given in the Table 3 together with experimental values of the FSP striking velocity. It can be see that the computed ballistic limit lies slightly above experimental data. The difference is relatively very small. It means the results of the numerical simulation can be used for the evaluation of the ballistic efficiency of the tested targets. The used material models probably well describe the material behavior of targets components. These models can be used for the numerical simulation of different targets behavior under ballistic attacks.

Target	Shoot #	Striking velocity V_s ($\mathrm{m\,s^{-1}}$)	Target	Ballistic limit – computed ($\mathrm{m\,s^{-1}}$)
S1	1	953.8	NO	
S1	2	898.9	NO	
S1	3	916.1	NO	
S1	4	934.4	NO	1210
S1	5	1167.0	NO	
S1	6	1152.0	NO	
S2	1	927.0	YES	
S2	2	900.9	NO	
S2	3	900.9	NO	930
S2	4	886.1	NO	
S2	5	885.0	NO	
S2	6	1162.0	YES	
S2	7	925.9	NO	
S2	8	920.3	NO	
S2	9	925.7	YES	
S3	1	925.9	NO	980
S3	2	861.9	NO	
S4	1	929.7	YES	
S4	2	744.8	NO	
S4	3	644.3	NO	
S4	4	834.5	NO	860
S4	5	841.4	NO	
S5	1	1049.0	NO	
S5	2	1158.0	NO	1280
S6	1	701.4	NO	780
S7	1	666.5	NO	
S7	2	800.0	NO	830
S8	1	763.0	NO	820
S8	2	827.5	NO	

Tab.3: Ballistic limits of the tested targets

5. Conclussions

Based on a large number of full-scale impact tests and corresponding numerical simulations using the explicit solver in LS DYNA, the ballistic perforation resistance of layered targets impacted by fragment simulating projectiles has been investigated. Within the limitations of the presented study, the following main conclusions can be drawn:

- The best protection properties exhibits the target S5 (frontal layer of ceramics Al_2O_3 – 20 mm and 22 mm of ARMOX 500 steel). This arrangement guarantees the ballistic resistence at level 5.
- The use of double layered ARMOX 440 steel plates spaced with 50 mm air gap (S1 target) leeds to the same level of ballistic protection but its thickness and area density are significantly higher than those for S5 target. The use of S1 target may be supported by its lower price and by some technological reasons.
- The S3 target which also guarantees the level 5 of the ballistic protection can be probably used namely for protection of stationary objets.
- The remaining targets given in the Table 2 exhibit ballistic protection at level 3. The optimum properties for ballistic protection of mobile objects exhibit targets S3 and S4. Targets S6–S8 can be considered as protection part of stationary objects.
- Good agreement is in general obtained between the numerical simulations and experiment results. Thus, finite element simulations using proper material models are able to capture the main physical behaviour during perforation of layered targets.

The last conclussion is probably the best contribution of the present paper because all results and conclusions in this study are based on a limited number of ballistic tests in the sub-ordnance velocity regime using projectiles at normal impact. However, from a design perspective the projectile always impacts the target with some obliquity and yaw. The influence of these effects can be effectively studied namely by the use of the numerical simulation of the ballistic tests.

Acknowledgement

The research has been supported by MPO ČR under project FT-TA4/011 Výzkum a vývoj technických prostředků pro zkoušení ochranných materiálů.

References

[1] Radin J., Goldsmith W: Normal projectile penetration and perforation of layered targets, International Journal of Impact Engineering 7 (1988) 229

[2] Teng X., Dey S., Børvik T., Wierzbicki T: Protection performance of double-layered metal shields against projectile impal, International Journal of Impact Engineering, 35 (2008) 870

[3] Ben-Dor G., Dubinsky A., Elperin T.: On the ballistic resistance of multi-layered targets with air gaps, International Journal of Solids and Structures 35 (1998), 3097

[4] Ben-Dor G., Dubinsky A., Elperin T.: Effect of air gaps on ballistic resistance of targets for conical impactors, Theoretical and Applied Fracture Mechanics 30 (1998) 243

[5] Ben-Dor G., Dubinsky A., Elperin T.: Effect of air gaps on the ballistic resistance of ductile shields perforated by non-conical impactors, Journal of Mechanics of Materials and Structures 1 (2006), 279

[6] Elek P., Jaramaz S., Mickovic D.: Modeling of perforation of plates and multi-layered metallic targets, International Journal of Solids and Structures 42 (2005), 1209

[7] Liang C.C., Yang M.F., Wu P.W., Teng T.L.: Resistant performance of perforation of multi-layered targets using an estimation procedure with marine application, Ocean Engineering 32 (2005) 441

[8] Johnson G.R., Cook W.H.: A constitutive model and data for metals subjected to large strains, high strain rates and high temperatures, In: Proceedings of the 7th International Symposium on Ballistics, Hague, 1983
[9] Johnson G.R., Cook W.H. Fracture characteristics of three metals subjected to various strains, strain rates, temperatures and pressures, Engng Fract Mech 21(1985) 31
[10] Borvik T., Hopperstad O.S., Berstad T., Langseth M.: A computational model of viscoplasticity and ductile damage for impact and penetration, European Journal of Mechanics, A/Solids 20 (2001) 685
[11] Johnson G.R., Holmquist T.J.: A computational model for brittle materials subjected to large strains, high strain rates and high pressures, in Shock-Wave and High-Strain-Rate Phenomena in Materials, ed. M.A. Meyers, L.E. Murr and K.P. Staudhammer, publ. New York: Marcel-Dekker, pp. 1075–1082
[12] Buchar J., Voldřich J.: Terminal Ballistics (in Czech), Academia Publ. Ho., Prague 2004

Received in editor's office: February 2, 2011
Approved for publishing: March 8, 2012