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THE DEVELOPMENT OF THE GLASS LAMINATES RESISTANT TO THE SMALL ARMS FIRE

J. Buchar[1], S. Rolc[2], J.Voldrich[3], M. Lazar[4] and M. Starek[5]

[1]*Mendel University of Agriculture and Forestry, Zemedelska 1, 613 00 Brno, Czech Republic*
[2]*Military Research Institute, Rybkova 2, 602 00 Brno, Czech Republic*
[3]*University of the West Bohemia, 306 14 Plzen, Czech Republic*
[4]*Military Technical and Testing Institute, 905 24 Slovak Republic*
[5]*SVS – FEM, Ltd., Cechynska 25, 602 00 Brno, Czech republic*

The paper deals with the use of ballistic experiments and numerical analysis to the development of some glass laminates which should exhibit protective efficiency against projectiles fired from the small arms. The mechanical propertries of single layers have been evaluated by the use of different methods of the high strain rates testing, namely ba the use of the Hopkinson Split Pressure Bar Test. The ballistic experiments have been used for the evaluation of some parameters of the failure criteria. The next numerical simulation performed by the LS DYNA 3D finite element code led to some results on the ballistic efficiency of the glass laminated targets.

INTRODUCTION

Glass material have generally poor mechanical properties compared with crystalline ceramics and these materials exhibit much more lower ballistic performance against to projectiles. This is a consequence of the amorphous structure of glass. In order to improve ballistic resistance the glass laminates are designed. The development of such layered armours may be cost effectively only if we use of some appropriate numerical simulation [1]. The use of numerical code than need the very good knowledge of the material properties of single layers at strain rates corresponding to those during the ballistic impact. Even if there are many papers dealing with the determination of the glass properties under the conditions mentioned above [2–4] owing to a great scatter of these data it is necessary to perform measurement of these properties for every proposed material.

In the given paper we have focused on the laminated glass where layers of glass changed with the layers of different polymeric materials. The numerical simulation has been used for the prediction of the ballistic performance of these targets against three kinds of small arms projectiles.

EXPERIMENTS

For the investigation we have used three different projectiles which are shown in Figs.1a–c.

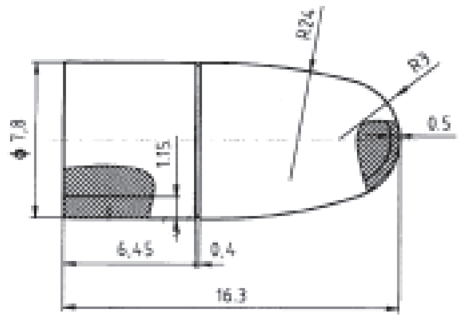

Figure 1a: Projectile A. Core Fe covered by red brass (dimensions in mm).

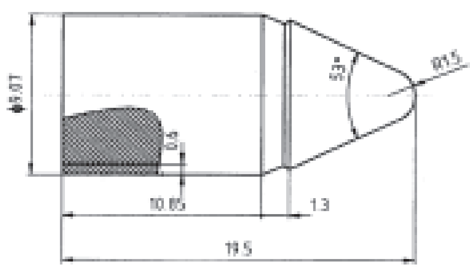

Figure 1b: Projectile B. Core Pb covered by red brass (dimensions in mm).

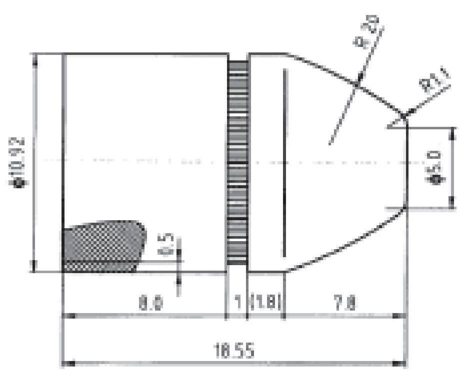

Figure 1c: Projectile C. Core Pb covered by brass (70:30) (dimensions in mm).

The configuration of the glass laminates is described in Table 1.

Table 1: The configuration of the glass laminates. (PVB, PUR,PET and PC denote different polymeric materials)

TARGET	ORDER OF THE LAYER FROM THE IMPACTED FACE	MATERIAL	THICKNESS (mm)
I	1	GLASS	6
	2	PVB	0.76
	3	GLASS	8
	4	PVB	0.76
	5	GLASS	8
	6	PVB	3
	7	GLASS	5
II	1	GLASS	5
	2	PVB	0.76
	3	GLASS	3
	4	PVB	0.76
	5	GLASS	9.5
	6	PVB	0.76
	7	PUR	0.60
	8	PVB	0.76
	9	PET	0.25
III	1	GLASS	5
	2	PVB	0.76
	3	GLASS	5
	4	PVB	0.76
	5	GLASS	5
	6	PUR	1.20
	7	PC	4
IV	1	GLASS	4
	2	PVB	0.76
	3	GLASS	4
	4	PVB	0.76
	5	GLASS	8
	6	PVB	0.76
	7	GLASS	8
	8	PVB	0.76
	9	GLASS	6

The mechanical properties of the material of the single layers as well as projectiles have been evaluated by the using of the Hopkinson Split Pressure Bar Test, by the Taylor test and by the plate impact test. As a result we have obtained:

Projectile A: density ρ = 7800 kg/m^3, Elastic properties: Young s modulus E = 2.1 10^5 MPa, Poisson ratio ν = 0.28. Elastic behaviour up to strain 0.002. Plastic behaviour: σ= (E/150).(ε-0.002). The strain rate behaviuor is described by the Cowper Symonds constitutive equation:

$$\sigma = \sigma_s(\varepsilon)\left\{1+\left(\frac{\frac{d\varepsilon}{dt}}{D}\right)^{\frac{1}{p}}\right\}$$

Where $\sigma_S(\varepsilon)$ is the dependence of the flow stress on the strain at the quasi static loading and D and p are material parameters describing the influence of the strain rate. D = 40 s^{-1}, p = 5.

Projectile B (Pb): density ρ = 11200 kg/m^3, Elastic properties: Young s modulus E = 1.6 10^4 MPa, Poisson ratio ν = 0.44. Elastic behaviour up to strain 0.002. Plastic behaviour: σ= (E/300).(ε-0.002). The strain rate behaviour is described by the Cowper Symonds constitutive equation, D = 40 s^{-1}, p = 0.8.

Glass: density ρ = 2500 kg/m^3, Elastic properties: Young s modulus E = 7.16 10^4 MPa, Poisson ratio ν = 0.227. Elastic behaviour up to strain 0.002. Strain behaviour for higher strain: σ= (0.98E).(ε-0.002). The strain rate behaviour is described by the Cowper Symonds constitutive equation, D = 1000 s^{-1}, p = 100.

PVB (rubber like material): density ρ = 1070 kg/m^3, Elastic properties: Young s modulus E = 2.6 10^3 MPa, Poisson ratio ν = 0.435. Elastic behaviour up to strain 0.1. Plastic behaviour: σ= (E/400).(ε-0.1). The strain rate behaviour is described by the Cowper Symonds constitutive equation, D = 80 s^{-1}, p = 6.7.

PC material: density ρ = 1200 kg/m^3, Elastic properties: Young s modulus E = 2.3 10^3 MPa, Poisson ratio ν = 0.38. Elastic behaviour up to strain 0.15. Plastic behaviour: σ= (E/100).(ε-0.15). The strain rate behaviour is described by the Cowper Symonds constitutive equation, D = 650 s^{-1}, p = 75.

PUR material (superelastic): density ρ = 1200 kg/m^3, Elastic properties: Young s modulus E = 49 MPa, Poisson ratio ν = 0.45. Elastic behaviour up to strain 0.2. Plastic behaviour: σ= (E/200).(ε-0.2). The strain rate behaviour is described by the Cowper Symonds constitutive equation, D = 360 s^{-1}, p = 43.

PET material: density ρ = 1390 kg/m^3, Elastic properties: Young s modulus E = 3.6 10^3 MPa, Poisson ratio ν = 0.37. Elastic behaviour up to strain 0.07. Plastic behaviour: σ= (E/100).(ε-0.07). The strain rate behaviour is described by the Cowper Symonds constitutive equation, D = 846 s^{-1}, p = 87.

In the next step we performed ballistic experiments with the target I (see Table 1) in order to find some reliable criteria of the material failure. From the experiments, see [5] for details, we found that the best criterion of the material failure is the criterion of the maximum principal strain. According to this criterion the failure of the materials occurs if

$$\varepsilon \geq \varepsilon_{\max}$$

Where ε is the maximum principal strain and ε_{max} is the principal strain at failure. From the experiments we have found that the principal strain at the failure did not depend on the kind of the projectile. The values of these strains are given in Table 2.

Table 2: Principal strains at failure (Values of the true strain are given).

Material	Glass	PVB	PET	PUR	PC	Fe	Pb
Strain (1)	0.022	0.5	0.023	1.09	0.742	1.5	2.5

NUMERICAL SIMULATION

In Fig. 2 the penetration of the projectile C into target I is shown. In this case the projectile has been stopped by the target. The last layer of the glass did not exhibit any damage, depth of the penetration was 24.28 mm, the total target thickness was 29.28 mm. The time dependence of the projectile velocity shown in Fig. 3 suggests that the projectile is reflected back.

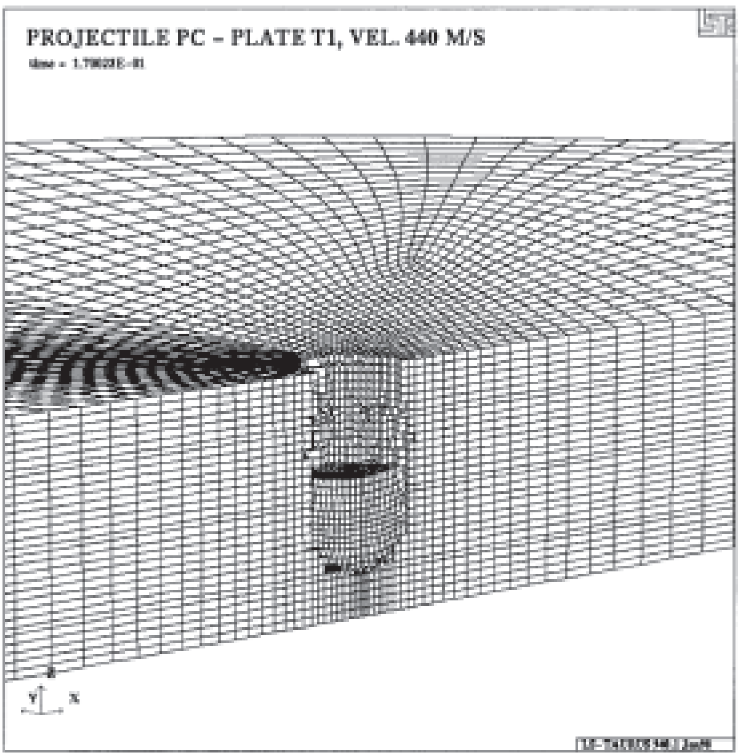

Figure 2: The penetration of the projectile C into target I.

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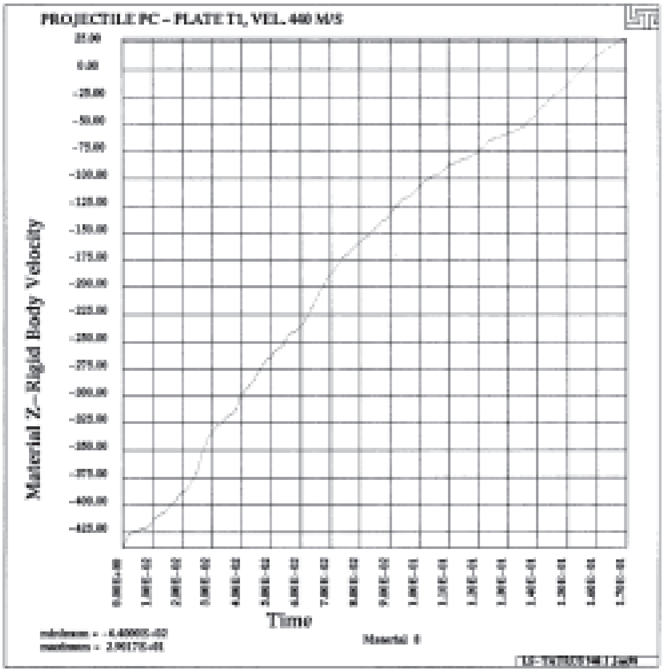

Figure 3: The dependence of the projectile velocity (in m/s) on the time (in ms).

The results of the numerical simulations, which were obtained using of the LS DYNA 3D finite element code are:

Target I – projectile C – impact velocity 440 m/s.
Number of nodes: 28 901
Number of elements: 26 064 (864 projectile)
Real time: 0.17 ms
CPU: 10 hours 11 minutes 36 seconds
Results: no perforation, depth of the penetration 24.28 mm.

Target II – projectile C – impact velocity 440 m/s.
Number of nodes: 40 250
Number of elements: 36 864 (864 projectile)
Real time: 0.1 ms
CPU: 2 hours 35 minutes 296 seconds
Results: perforation, residual projectile velocity is 252.34 m/s (experimentally found 231 m/s). The protective efficiency of the PET and PUR layers seems be negligible.

Target III – projectile C – impact velocity 440 m/s.
Number of nodes: 30 162
Number of elements: 27 264 (864 projectile)
Real time: 0.20 ms
CPU: 5 hours 11 minutes 1 seconds
Results: perforation, residual projectile velocity is 54.92 m/s

From the results presented in the given paper and collected in our report [5] one may conclude that the connection of material testing, limited number of the ballistic experiments and numerical simulation can lead to the effective development of the glass laminates which exhibit very good protective properties against to the small arms projectiles. The most of numerical results have been confirmed by the experiments. In the given paper we have modeled the projectiles without the cover. Our preliminary computational results show that this approach is too conservative. It means the ballistic performance of the targets considered in this paper may be better that that reported here. As a critical point seems be the model of the material failure. The next research of this problem seems be desirable.

ACKNOWLEDGEMENT

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