ANALYSIS OF EXPERIMENTAL AND NUMERICAL INVESTIGATIONS WITH RIGID PROJECTILES IMPACTING GLASS TARGETS OF DIFFERING PHYSICAL QUALITY

H. Senf, H. Rothenhäusler, W. Pavel, H.-J. Raatschen, R. Schwarz

JOURNAL DE PHYSIQUE
Colloque C3, Supplément au n°9, Tome 49, septembre 1988

ANALYSIS OF EXPERIMENTAL AND NUMERICAL INVESTIGATIONS WITH RIGID PROJECTILES IMPACTING GLASS TARGETS OF DIFFERING PHYSICAL QUALITY

H. SENF, H. ROTHENHÄUSLER, W. PAVEL*, H.-J. RAATSCHEN* and R. SCHWARZ*

Fraunhofer-Institut für Kurzzeitdynamik, Ernst-Mach-Institut, Abteilung für Ballistik (EMI-AFB), D-7858 Weil-am-Rhein, F.R.G.
**Industrieanlagen-Betriebsgesellschaft mbH, Einsteinstr. 20, D-8012 Ottobrunn, F.R.G.*

Résumé - La réponse de cibles en verres differents à l'impact des projectiles en carbide de tungstène a été étudiée avec des moyens expérimentaux et numériques. Dans la plupart des cas les projectiles ont perforé les cibles sans dommage importants pour les projectiles. Pour cette raison les recherches ont été concentrées sur l'analyse du comportement balistique du verre, en considérant les propriétés matérielles des cibles. Les verres utilisés différaient en densité, résistance et vitesse du son. Les résultats des recherches expérimentales et numériques démonstrèrent que les propriétés mécaniques des matériaux de verre standard n'ont aucune influence significative sur leur résistance balistique. C'était l'épaisseur des cibles en verre qui était déterminante pour leur résistance protective.

Abstract - Experimental and numerical simulations were performed to study the response of different glass targets to impact loading by tungsten carbide projectiles. In most cases the projectiles perforated the targets without significant damage to the projectile. Therefore the investigation concentrated on taking into account the material properties of the targets to analyse the ballistic behavior of glass. Accordingly, the glasses used as target material had very different densities, strengths and speed of sound. The results from experimental and numerical investigations showed that the mechanical properties exhibited by standard glass materials have no significant influence on the ballistic resistance. It was the thickness of the glass targets which in general determined its protective strength.

INTRODUCTION

Glass materials are of actual interest for ballistic protection. However, for high dynamic loading the mechanical behavior of glass is not well understood. Therefore, in this dynamic range experiments are performed which are supported by numerical simulations. Homogeneous and layered glass targets of circular shape and 150 mm diameter with thicknesses varying from 10 mm to 250 mm are centrally impacted by tungsten carbide projectiles (L = 41 mm, D = 13 mm, m = 68.9 g). A radial confinement (20 mm steel, Figure 1) of the glass proves to be without influence on the results. In most cases the projectiles perforate the target without significant damage to the projectile. This

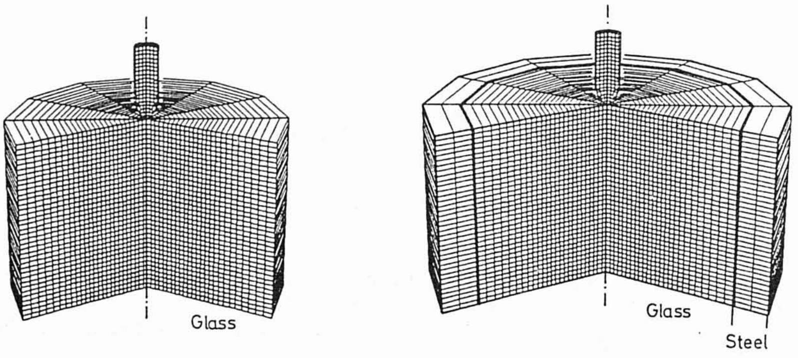


Fig. 1 - Structural plots of projectile and of targets without and with a confining steel case.

quasi-rigid behavior of the projectile allows to restrict the investigation to considering only the target material. Therefore, glasses with different mechanical properties are investigated. The densities vary from 2.5 to 5.18 g/cm³, the speeds of sound have values from 3595 to 6051 m/s, and the VICKERS hardness is in the range of 407 to 710. The ballistic resistance of the glass targets is characterized by the normalized residual velocity of the projectile behind the target.

EXPERIMENT

The kinematics of the perforation process is observed by multiple spark flash and x-ray cinematography. The investigations are in general performed at a striking velocity as close as possible to 1060 m/s. In some special cases the impact velocity is varied between 800 and 1250 m/s.

NUMERICAL SIMULATION

The penetration and perforation mechanism is analyzed by numerical simulation using the 2D/3D LAGRANGE code DYSMAS/L. The material behavior of glass is described by a continuum model. Dilatatoric stresses are calculated by the equation of state for glass and the deviatoric stresses are determined by the HENCKY flow rule in rate type formulation with the DRUCKER-PRAGER yield condition. The material parameters are the YOUNG's modulus, POISSON ratio, density, technical cohesion and angle of interior friction. The material failure is initiated by equivalent strain criterions under tension and compression. Because of the quasi-rigid behavior of the projectile, observed in the experiments, the projectile is described with linear elastic properties [1].

TYPES OF GLASS TARGETS

Glasses used for impact loading are float glass, several optical glasses manufactured by SCHOTT Company, and ZERODUR a SCHOTT glass ceramic. The chemical properties of the different types of glasses are listed in the following Table 1. For our purposes the classification of the glasses according to their chemical composition is of relevance. The SiO_2-glasses which contain PbO are called flint glasses, SiO_2-glasses without PbO are called crown glasses. The phosphate crown glasses PK do not contain P_2O_5, they are borosilicate glasses [2]. ZERODUR is a glass ceramic with an extremely small thermal expansion

Table 1: Composition of glass target material [3]

Types	SiO_2	B_2O_3	Na_2O	K_2O	Al_2O_3	CaO	BaO	ZnO	La_2O_3	ZrO_2	TiO_2	PbO
Float	70		15*		1	12**						
SF6	25		≤ 1	≤ 1								70
SF14	30		≤ 1	≤ 1	≤ 5						≤ 5	60
F6	40		≤ 5	≤ 5			≤ 5					45
SKN18	30	15			≤ 1	≤ 5	45	≤ 5	≤ 5	≤ 1	≤ 1	
K5	65	≤ 5	≤ 5	15		≤ 5		8			≤ 1	≤ 1
PK3	65	15	8	8			≤ 5				≤ 1	

* (Na_2O + K_2O); ** (CaO + MgO)

coefficient and contains a glass and a crystal phase which consists of high quartz solid solution crystals [4,5]. The physical properties of these glasses are shown in Table 2.

Table 2: Physical properties [6,7]

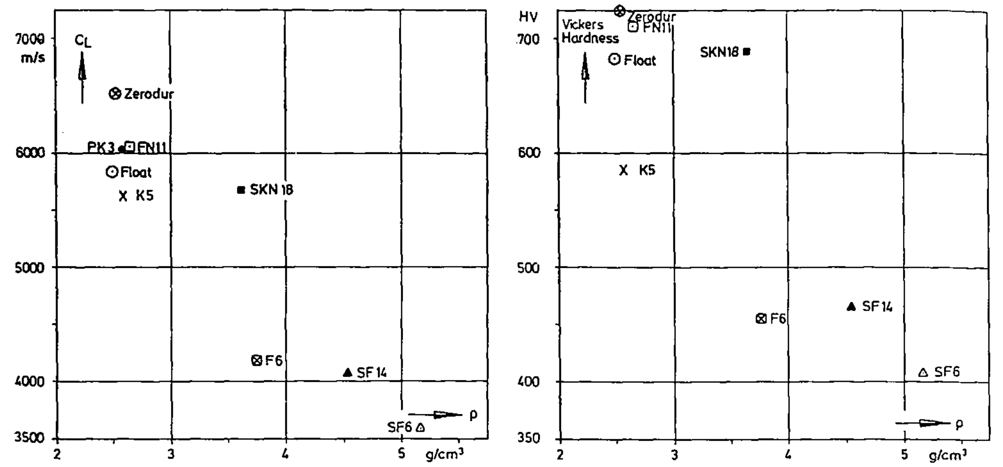
Types	Density [g/cm³]	E-Modul [10³N/mm²]	Poisson Ratio	HV	Wavespeed [m/s]
Float	2.5	-	-	680	5860
SF6	5.18	56	.248	407	3595
SF14	4.54	65	.235	465	4091
F6	3.76	57	.231	455	4196
SKN18	3.64	88	.296	689	5673
FN11	2.66	84	.23	710	6051
K5	2.59	71	.227	584	5624
PK3	2.59	84	.207	680	6030
Zerodur	2.53	91	.24	750	6511

In addition, important features of optical glass in contrast to float glass specimens are homogeneity, optical and mechanical isotropic behavior and absence of bubbles, striae and strain. The mechanical parameters of importance for our study are density, velocity of sound, and hardness (Figs. 2 and 3). The glasses we selected for our investigations in such a way that specimen with nearly corresponding values for two of their parameters and large difference in the third parameter are available.

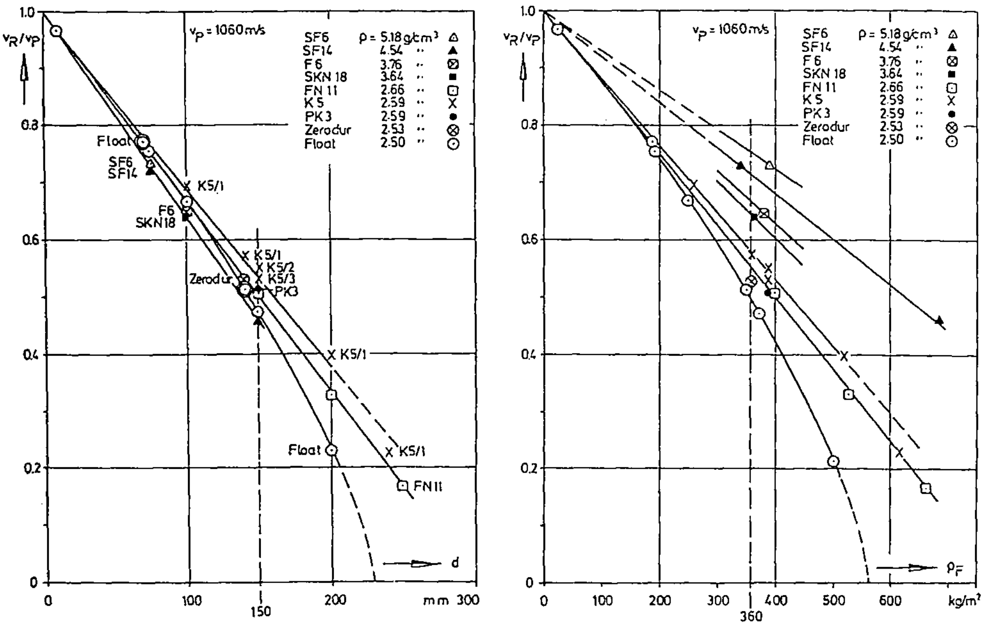
RESULTS

In Figure 4 the ratio of residual to impact velocity is plotted versus target thickness d. The residual velocity decreases nearly linearly with increasing glass thickness. The densities of the several glass types vary between 2.5 and 5.18 g/cm³, and the hardnesses, longitudinal wave velocities, and the other physical properties are very different (Table 2). Nevertheless, all results scatter in a small domain only.

Some targets are layered and pasted (all float glass targets and the one K5/3 target consist of 10 mm plates). The experimental points



Figs. 2 and 3 - Longitudinal wave velocity c_L and Vickers hardness HV of float and SCHOTT glasses versus the material density ρ

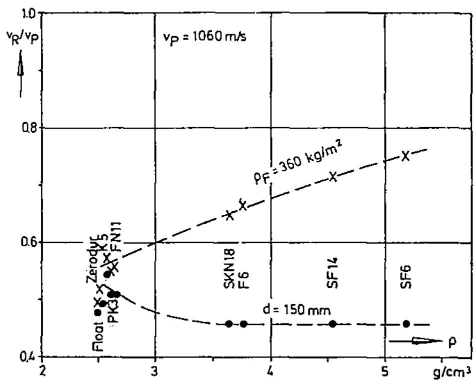


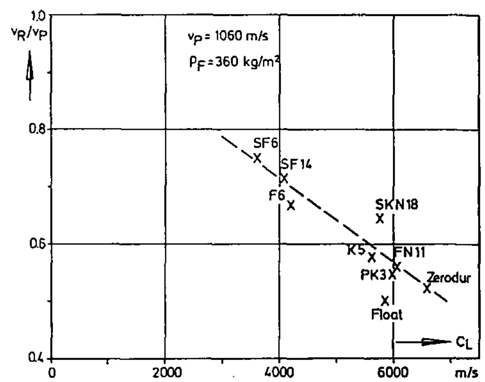
Figs. 4 and 5 - Ratio of residual velocity to impact velocity versus the thickness d and areal density ρ_F of the target material

marked by K5/1 indicate that these experiments are performed using homogeneous glass blocks. If the glass blocks are laterally cased by very thick steel rings (wall thickness 20 mm) then the points are marked by concentric circles (float glass) or by K5/2. All other experiments are performed using homogeneous blocks. From these test series can be derived that a glass block with 150 mm diameter has about the same strong eigenstrength as a cased block or a semi-infinite target and that the ballistic resistance is not significantly influenced by the type of structure (homogeneous and/or laminated). These statements are verified by numerical simulation.

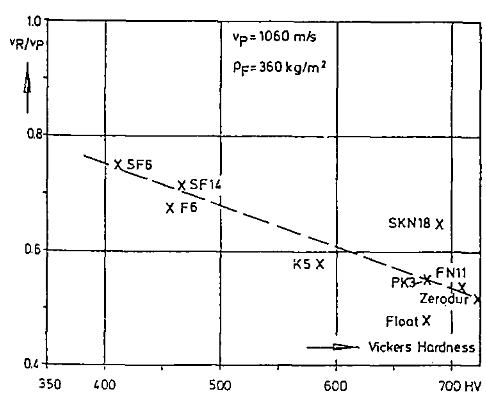
Plotting normalized residual velocities versus areal density the results spread out (Fig. 5). Now it can be seen that targets with low densities present a better ballistic resistance. In order to analyze the dependence on density, in Figure 6 the foregoing results are depicted for an areal density of ρ_F = 360 kg/m² and a target thickness of d = 150 mm (marked by crosses and by dark dots), respectively. These special values are chosen as representatives for cases where the projectile perforates the target without failure.

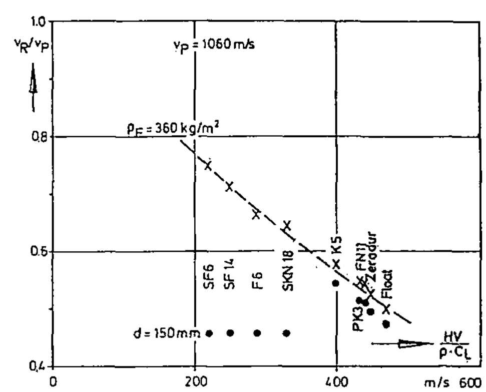
Figure 6 shows that for these values at densities greater than 3.5 g/cm³ the ballistic resistance is independent of density. Hence, target thickness is the important ballistic parameter. Therefore, if minimum protective mass is important a glass of low density is to be preferred as long as densities above 2.5 g/cm³ are used. Below, resistance may decrease with density. The residual velocity is plotted versus speed of sound (Fig. 7) and hardness (Fig. 8). Though the measurement of hardness presents many difficulties and data depend





Figs. 6 and 7 - Normalized residual velocity versus material density of the targets and longitudinal wave velocity (x: constant areal density; •: constant plate thickness).





Figs. 8 and 9 - Normalized residual velocity versus Vickers hardness and versus the ratio of Vickers hardness, density and wave velocity (x: constant areal density and •: constant plate thickness).

largely on the measuring technique applied it is possible to use them to characterize the resistance behavior of the material against mechanical loading.

The results indicate that the ballistic resistance increases with increasing speed of sound and increasing hardness. This leads to Figure 9 where residual velocity is plotted versus the ratio of hardness to mechanical impedance. If hardness values are given as strength values, i.e., in N/mm², this ratio obtains the dimension of velocity. For constant areal density all results can be fitted by a curve. This Figure enables the design engineer to choose the best type of glass when areal density is given. On the other hand, Figure 9 shows that glass targets of a given thickness have the same resistance if the value of $HV/\rho c_L$ is less than 350 m/s. In further test series the residual velocity was determined as function of impact velocity (Fig. 10). All targets had same areal densities that means different thicknesses. Within this velocity range between 800 m/s and 1250 m/s the residual velocity increases nearly linearly with impact velocity and behaves similar to metallic materials.

The response of two glass targets with extremely different densities (float: ρ = 2.5 g/cm³; SF6: 5.18 g/cm³) is investigated using numerical simulation. The material data of Table 1 are used. A good agreement with the experimental results (Fig. 11) is achieved [1]. Varying the technical cohesion from 10 MPa to 60 MPa results in 5 % difference in the residual velocity for a SF6-glass with 75 mm thickness (areal density ρ_F = 388.5 kg/m²). Calculations with an areal density of ρ_F = 518 kg/m² give the result that the residual velocity still decreases linear with the areal density at a thickness of 100 mm. In all calculations the angle of interior friction is 10°.

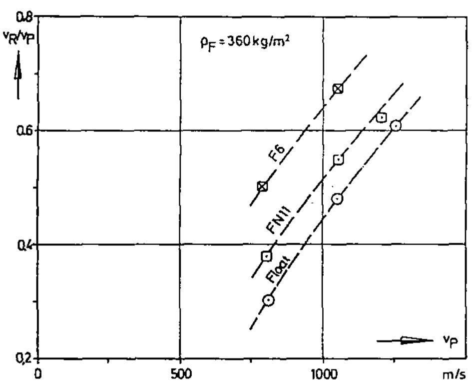


Fig. 10 - Normalized residual velocity versus impact velocity v_P

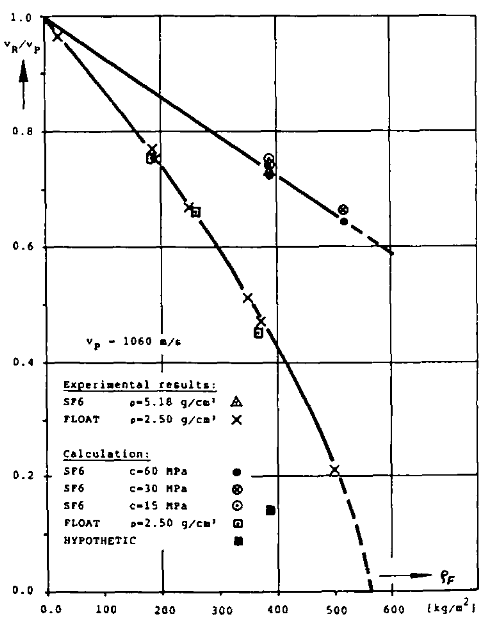


Fig. 11 - Normalized residual velocity versus areal density, comparison of experimental and numerical results.

Calculation and experiment show that the ballistic resistance of all investigated glasses is determined mainly by the thickness of the target. However, from numerical simulation it can be shown that this result cannot be generalized for all glasses. For example, if a hypothetical brittle material is assumed which combines the density of the SF6-glass with the technical cohesion (hardness) and the YOUNG's modulus of the FN11-glass. The calculated perforation process through a 75 mm target leads to the residual velocity of $v_R/v_P = 0.14$. This value differs largely from those of all investigated glasses of same thickness. It represents a resistance similar to ceramic materials.

CONCLUSION

The numerical results show that the penetration of glass targets can be calculated very well. Especially the numerical calculation of hypothetical glasses points out the direction of glass development due to ballistic applications. A simple relation between residual velocity and $HV/\rho c_L$ helps the designer to compare protective glasses of equivalent areal density. In general, it is important to note that for glasses of medium and high densities it was found that only the target thickness determines the ballistic resistance.

REFERENCES

[1] W. Pavel, H.-J. Raatschen, R. Schwarz, H. Senf, H. Rothenhäusler, "Experimental and Numerical Investigations of the Failure Behavior of Glass Targets under Impact Loading by Rigid Projectiles", Proceedings Tenth International Symposium on Ballistics San Diego, USA, October 1987

[2] T.S. Izumitani, "Optical Glass", American Institute of Physics, Translation Series, New York, 1986

[3] M. Clement, SCHOTT Glaswerke, private information, April 1988

[4] F. Bayer-Helms, H. Darnedde, G. Exner, "Längenstabilität bei Raumtemperatur von Proben der Glaskeramik 'Zerodur'", Metrologia 21, 1985, pp. 49-57

[5] O. Lindig, W. Pannhorst, "Thermal Expansion and Length Stability of Zerodur in Dependence on Temperature and Time", Applied Optics, Vol. 24, No. 20, 1985

[6] SCHOTT Katalog Optisches Glas, 1984

[7] Prospekt SCHOTT Glaswerke Mainz, "Zerodur Glaskeramik", 1982