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# Damage Analysis for Hypervelocity Impact Experiments on Spaceship Windows Glass

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**Abstract.** The hypervelocity impact characteristics in fused silica glass, which is used for the outermost pane of the windshield as the critical part of the thermal protection system of spacecraft, were studied by 37 impact experiments with different millimeter diameter projectiles up to the velocity of 7 km/s launched by two stage light-gas-gun facility. The empirical damage equations were obtained from experiment data by the least square method and they were compared with NASA damage equations.

## 1 Introduction

As one of the important parts of the spaceship, windows are at the risk of impact from micrometeoroid and orbital debris in the space. Fused silica glass, which is used for the outermost pane of the window as the critical part of the thermal protection system of spaceship, has low coefficient of thermal expansion and exceptional optical quality. Some experiments had been conducted to obtain hypervelocity impact characteristics of fused silica glass [1-5]. The ratio of diameter to depth of the impact crater is 13 to 15, and the surface spall is 40 to 45 projectile diameters, which are in sharp contrast to the impact damage in a brittle aluminium target [1]. Ernst-Mach-Institut (EMI) had established a damage characteristics curve for viewport glass in the Russian Space Station MIR for spherical Al projectiles having masses roughly between about 3mg and 60mg, impact velocities ranging between 4km/s and 9.1km/s [2]. The NASA Johnson Space Centre Hypervelocity Impact Technology Facility (HITF) had modified the damage equations for the Orbiter vehicle windows glass by conducting the twenty-five tests using 0.4mm diameter Al projectile with impact velocities varying from 7km/s to 2.5km/s [3].

As a typical brittle material, fused silica glass has shown great difference from the ductile material. Generally there was a central pit in the front side of sample and a large area of spallation zone around central pit under hypervelocity impact. A lot of radial crack spread out of spallation zone. The rear side of sample had spallation zone, having been totally removed from sample, which was different from the front one, the spallation zone having been only partly detached and removed.

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# 2 Impact testing

## 2.1 Test articles and test matrix

In Beijing Institute of Spacecraft Environment Engineering (BISEE), hypervelocity impact characteristics in fused silica glass were studied by 37 impact experiments with different millimetre diameter projectiles up to the velocity of 7 km/s launched by two stage light-gas-gun facility. There were two sizes of samples, 5cm and 10cm in diameter separately, but their thickness is the same as 1.2cm, used in experiments. The Al spheres projectiles were used with dimensions of 0.15cm, 0.2cm, 0.25 cm and 0.3cm in diameter, which impact velocities were varied from 2.80km/s to 7.44km/s.

## 2.2 Damage characteristics

Table 1 has given all 37 test results. The results show that the sample would be perforated if the projectile is 0.25cm in diameter, under impact velocity 3.95km/s, as shown in Figure 1. Although the sample would not be perforated under impact velocity 3.72km/s (as shown in Figure 2), it had been in condition of critical perforation. So impact velocity 3.72km/s and projectile diameter 0.25cm had been regarded as one point of ballistic curve for our silica glass. EMI had also obtained that impact velocity 4.0km/s and the same projectile diameter were at ballistic curve for 1.4cm-thick glass [2].

**Fig. 1.** Critical perforation of fused silica glass (Test #31, projectile diameter 0.25cm, impact velocity 3.72km/s).

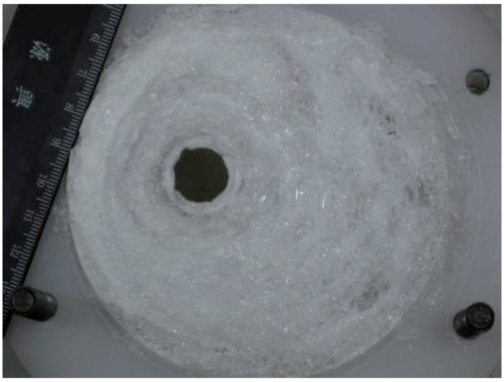

**Fig. 2.** Perforation of fused silica glass (Test #32, projectile diameter 0.25cm, impact velocity 3.95km/s).

## 2.3 Results

The impact characteristics of fused silica glass were analyzed by Olympus STM6 measuring microscope. The measured test data are listed in Table 1.

**Table 1.** Hypervelocity impact test result of fused silica glass.

| NO. | Projectile Diameter (cm) | Projectile Mass (g) | Velocity (km/s) | Crater Depth (cm) | Spallation Diameter (cm) | Results | | Sample Size in Diameter(cm) |
|---|---|---|---|---|---|---|---|---|
| | | | | | | Front Surface | Back Surface | |
| 1 | 0.100 | 0.0014 | 2.99 | 0.235 | 2.850 | Crater | No Damage | 10 |
| 2 | 0.100 | 0.0014 | 3.72 | / | / | Crater | No Damage | 10 |
| 3 | 0.101 | 0.0015 | 3.94 | 0.190 | 2.368 | Crater | No Damage | 10 |
| 4 | 0.102 | 0.0015 | 4.72 | 0.216 | 2.746 | Crater | No Damage | 10 |
| 5 | 0.100 | 0.0015 | 5.06 | 0.181 | 1.156 | Crater | No Damage | 5 |
| 6 | 0.100 | 0.0015 | 5.79 | 0.187 | 2.824 | Crater | No Damage | 5 |
| 7 | 0.100 | 0.0015 | 5.93 | 0.190 | 3.004 | Crater | No Damage | 10 |
| 8 | 0.100 | 0.0015 | 6.43 | 0.200 | 3.112 | Crater | No Damage | 5 |
| 9 | 0.100 | 0.0015 | 6.50 | 0.217 | 3.082 | Crater | No Damage | 5 |
| 10 | 0.100 | 0.0015 | 7.06 | 0.187 | 2.872 | Crater | No Damage | 5 |
| 11 | 0.152 | 0.0051 | 3.28 | 0.387 | 1.456 | Crater | No Damage | 10 |
| 12 | 0.150 | 0.0049 | 3.71 | 0.207 | 1.916 | Crater | Damage | 10 |
| 13 | 0.151 | 0.0051 | 4.02 | 0.283 | 2.185 | Crater | No Damage | 10 |
| 14 | 0.151 | 0.0049 | 4.85 | 0.306 | 3.774 | Crater | No Damage | 10 |
| 15 | 0.150 | 0.0050 | 4.95 | 0.295 | 3.229 | Crater | Damage | 10 |
| 16 | 0.152 | 0.0050 | 5.18 | 0.346 | 3.578 | Crater | No Damage | 10 |
| 17 | 0.152 | 0.0051 | 6.02 | 0.222 | 4.620 | Crater | No Damage | 10 |
| 18 | 0.151 | 0.0050 | 6.56 | 0.301 | 3.915 | Crater | Damage | 10 |
| 19 | 0.151 | 0.0052 | 7.30 | 0.215 | 5.321 | Crater | Damage | 10 |
| 20 | 0.201 | 0.0125 | 3.18 | 0.232 | 3.091 | Crater | No Damage | 10 |
| 21 | 0.200 | 0.0125 | 3.26 | 0.354 | 5.630 | Crater | Damage | 10 |
| 22 | 0.201 | 0.0124 | 4.02 | 0.380 | 5.216 | Crater | No Damage | 10 |
| 23 | 0.200 | 0.0126 | 4.23 | 0.424 | 5.050 | Crater | Damage | 10 |
| 24 | 0.201 | 0.0125 | 4.87 | 0.392 | 5.076 | Crater | Damage | 10 |
| 25 | 0.200 | 0.0124 | 5.46 | 0.386 | 5.437 | Crater | Damage | 10 |
| 26 | 0.201 | 0.0126 | 6.34 | 0.596 | 5.424 | Crater | Damage | 10 |
| 27 | 0.201 | 0.0124 | 6.50 | 0.634 | 4.737 | Crater | Damage | 10 |
| 28 | 0.200 | 0.0124 | 7.44 | 0.309 | 5.280 | Crater | Damage | 10 |
| 29 | 0.251 | 0.0237 | 3.07 | 0.566 | 5.510 | Crater | Damage | 10 |
| 30 | 0.250 | 0.0234 | 3.58 | / | / | Crater | Damage | 10 |
| 31 | 0.250 | 0.0234 | 3.72 | 0.600 | 5.481 | Critical Perforation | | 10 |
| 32 | 0.250 | 0.0233 | 3.95 | / | / | Perforation | | 10 |
| 33 | 0.252 | 0.0235 | 4.74 | / | / | Perforation | | 10 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 34 | 0.300 | 0.0391 | 2.80 | / | / | Perforation | 5 |
| 35 | 0.300 | 0.0391 | 5.02 | / | | Perforation | 5 |
| 36 | 0.300 | 0.0391 | 5.23 | / | / | Perforation | 5 |
| 37 | 0.300 | 0.0391 | 6.43 | / | / | | 5 |

From Table 1, we can obtain the ballistic limit curve of fused silica, as shown in Figure 3.

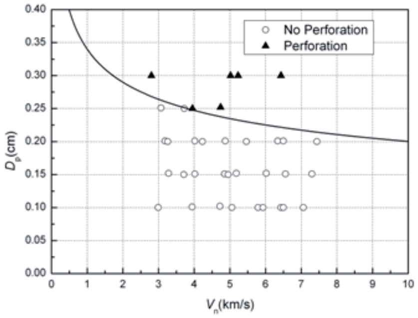

**Fig. 3.** The ballistic limit curve of fused silica

# 3 Discussions

## 3.1 Damage equations

The empirical damage equations were obtained from experiment data by the least square method. The relation between central pit depth and impact velocity was shown as equation (1) and the one between the front side spallation zone diameter and impact velocity was shown as equation (2).

$$P_{\mathrm{f}} = 0.96 d_{\mathrm{p}}^{1.26} V_{\mathrm{n}}^{0.67} \tag{1}$$

$$D_{\mathrm{fs}} = 9.83 d_{\mathrm{p}}^{1.03} V_{\mathrm{n}}^{0.57} \tag{2}$$

Where $P_{\mathrm{f}}$ is the crater depth (cm), $D_{\mathrm{fs}}$ is the front surface spall diameter (cm), $d_{\mathrm{p}}$ is the projectile diameter (cm), $V_{\mathrm{n}}$ is the normal component of the projectile velocity (km/s),.

These empirical damage equations were compared with NASA damage equations [3],

$$P_{\mathrm{f,\,NASA}} = 0.266 \rho_{\mathrm{p}}^{0.595} d_{\mathrm{p}}^{1.06} V^{0.995} (\cos\theta)^{0.496} \tag{3}$$

$$D_{\mathrm{fs,\,NASA}} = 9.656 \rho_{\mathrm{p}}^{0.373} d_{\mathrm{p}}^{1.183} V^{0.915} (\cos\theta)^{0.545} \tag{4}$$

Where $\rho_{\mathrm{p}}$ is the projectile density (g/cm$^3$), $V$ is the projectile velocity (km/s), and $\theta$ is the projectile impact angle.

A comparison of the predicted impact crater depths using both equations to the measured test data is given in Figure 4. A similar comparison of the predicted front surface spall diameter using both equations to the measured test data is given in Figure 5.

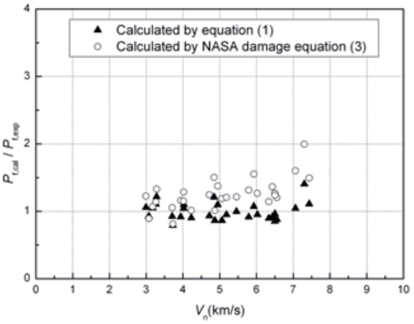

**Fig. 4.** The impact crater depths comparison between equation (1) and NASA damage equation (3).

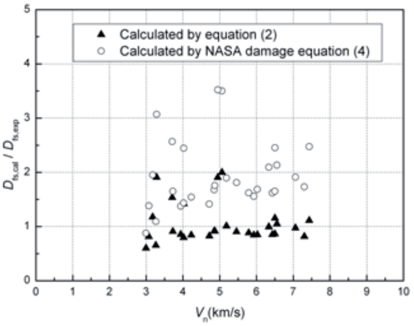

**Fig. 5.** The front surface spall diameters comparison between equation (2) and NASA damage equation (4).

From Figure 4 and Figure 5, two empirical equations obtained from our experiments had only a little difference from NASA equations considering the difference between samples. Because all impact angles of our experiments were 0º, it is necessary to supply several oblique impact data in the future test.

On the other hand, the comparison have been drawn between our damage equations and NASA damage equations using EMI test data [2], as shown in Figure 6 and Figure 7.

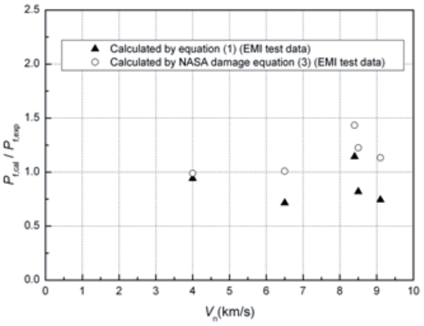

**Fig. 6.** Comparison between equation (1) and NASA damage equation (3) using EMI test data.

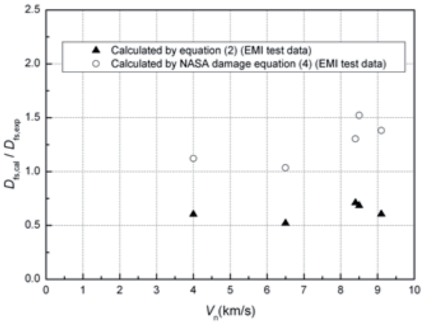

**Fig. 7.** Comparison between equation (2) and NASA damage equation (4) using EMI test data.

From Figure 6, equation (1) is generally suitable for EMI test data and NASA equation (3) is partly conservative.

## 3.2 Edge effect

Generally, small samples are desirable to conserve expensive target material. However, too small samples can result in larger edge effects that influence the extent of damage to them. Figure 8 shows impact test result for 5cm diameter sample.

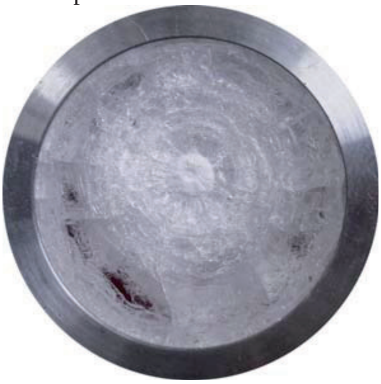

**Fig. 8.** Edge effect of impact test (Test #8, 5cm diameter target)

It is easy to be observed for edge effect damage when impacts are not centered on the target as illustrated in Figure 9. Generally, edge effect damage mainly appears on the back of target, which the damage location is symmetric with impact crater about the center of target. In Figure 9, the upper damage is done by edge effect and the lower one is the impact crater.

**Fig. 9.** Edge effect of impact test (Test #1, 10cm diameter target, not centered impact)

## 5 Conclusions

The impact damage equations have been obtained by 37 impact tests for fused silica glass and a comparison has been draw between our damage equations and NASA damage equations. From the comparison, our equations may be applied for design in engineering.

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