Response of Spacecraft Window Materials to Hypervelocity Projectile Impact

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All large spacecraft are susceptible to impacts by meteoroids and pieces of orbiting space debris. These impacts occur at extremely high speeds and can damage flight critical systems, which can in turn lead to catastrophic failure of the spacecraft. In order to successfully design a spacecraft for a mission into the meteoroid and space debris environment, it is necessary to be able to characterize the response of a variety of structural materials under such high-speed impact loadings. This paper presents the results of an investigation of the response of window materials to hypervelocity projectile impact. Window impact damage is characterized according to the nature and extent of surface and internal damage. Analysis of the test data indicates that for single-pane specimens the extent of the damage to the test specimens can be written as functions of the impact parameters of the original projectile and the geometric and material properties of the projectile/window system. These functions can be used to perform parameter-sensitivity studies and to evaluate hypothetical design applications and configurations.

Introduction

ALL spacecraft with a mission duration of more than a few days are susceptible to impacts by meteoroids and pieces of orbiting space debris. These impacts occur at extremely high speeds and can damage the flight critical systems of a spacecraft, which can in turn lead to catastrophic failure of the spacecraft. To date, 26 impact craters have been found on Space Shuttle Orbiter windows.[1] Although it is not precisely known how many of these are due to orbital debris impacts, the susceptibility of spacecraft windows to debris impacts is clearly evident. Therefore, the design of a spacecraft for a long-duration mission must take into account the possibility of such high-speed impacts and their effects on the spacecraft structure and on all of its exposed subsystem components.

In order to successfully design a spacecraft for a mission into the meteoroid and space debris environment, it is necessary to be able to characterize the response of a variety of structural materials under high-speed impact loadings. Response characteristics of metals and composites under hypervelocity projectile impact have been analyzed over the last few decades (see, for example, Refs. 2–10). With the installation of windows for viewing, as well as scientific purposes in a variety of spacecraft such as the Space Shuttle Orbiters and Space Station Freedom, it has become necessary to study the response of window materials to hypervelocity projectile impact and to evaluate their degradation as a result of such impacts. Unfortunately, information on the hypervelocity impact response of window materials is relatively scarce.[11–13]

This paper summarizes the results of an investigation into the response of window materials under hypervelocity projectile impact loadings. Two window materials of different hardness were considered in this study: Lexgard and glass. Several layers of Lexgard were glued together to form the single-panel Lexgard window test specimens. The glass window test specimens consisted of three panes separated by small distances. The impact damage to the Lexgard specimens is characterized according to the extent of surface damage, the extent of internal delamination, and the area of rear-side spall damage. The impact damage in the glass specimens is characterized according to the nature of the damage to each pane in the glass window system. A statistical analysis of the Lexgard impact test data indicates that the extent of the damage to the Lexgard specimens can be written as functions of the impact parameters of the original projectile and the geometric and material properties of the projectile/Lexgard window system. These empirical response functions can be used to perform parameter sensitivity studies and to evaluate hypothetical design applications and configurations.

Hypervelocity Impact Testing of Window Materials

The high-speed impact testing of the window materials was performed at the Space Debris Simulation Facility of the Materials and Processes Laboratory at the NASA Marshall Space Flight Center.[14] The conditions of the impact tests were chosen to simulate space debris impact of lightweight space structures as closely as possible, and still remain within the realm of experimental feasibility. Kessler et al.[15] state that the average mass density for pieces of orbital debris less than 10 mm in diameter is approximately the same as that of aluminum. Although it is anticipated that the shape of the impacting projectile will affect impact damage formation and propagation to some extent, spherical projectiles were used in the test program to maintain repeatability and consistency. Thus, the testing was conducted with solid spherical 1100 aluminum projectiles with diameters ranging from 3.175 to 9.525 mm. The velocities of the impacting projectiles ranged from 5.4 to 7.5 km/s.

A total of 21 single-pane Lexgard specimens and five triple-pane glass specimens were used to study and evaluate the hypervelocity impact response of window materials. The test specimens represent typical window configurations used in space structures. The Lexgard specimens were made from several 23 × 23-cm Lexgard sheets of varying thicknesses glued together (Figs. 1a and 1b). The glass specimens consisted of three 15 × 15-cm panes separated by varying standoff distances (Fig. 2). In the glass specimens, the outer and inner panes were made from annealed soda-lime and tempered Herculite II glass, respectively, while some middle panes were made from soda-lime glass and others from Herculite II glass.

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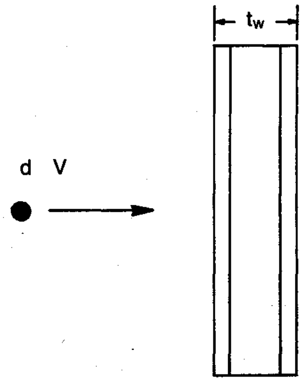

Fig. 1a Thin Lexgard window test specimen configuration.

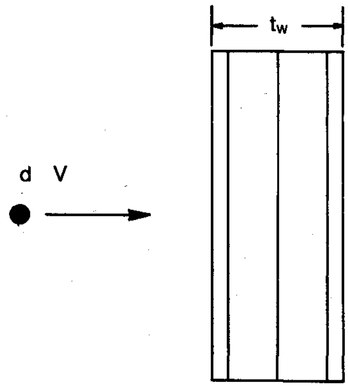

Fig. 1b Thick Lexgard window test specimen configuration.

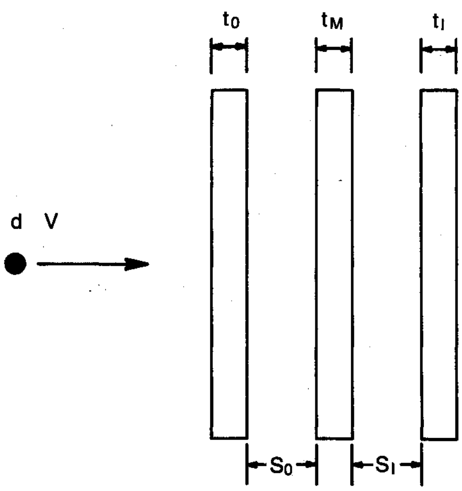

Fig. 2 Triple-pane glass window test specimen configuration.

The mechanical properties of the window materials are given in Table 1; test parameters and configuration geometries for each window type are given in Tables 2–4. The results of the hypervelocity impact test firings are given in Table 5 for the Lexgard specimens and in Table 7 for the glass specimens. Column entries of "——" in Table 5 indicate that penetration and/or spall of the Lexgard specimen did not occur. Table 6 contains a summary of the differences between experimental response characteristics and the response characteristics predicted using empirical equations derived from the experimental data. Photographs of damaged Lexgard test specimens are shown in Figs. 3–6 for various projectile diameters, impact speeds, and specimen thicknesses; a damaged triple-pane glass test specimen is shown in Fig. 7. Detailed analyses of the damaged test specimens revealed many interesting features and response characteristics of window materials under hypervelocity projectile impact loadings.

Table 1 Mechanical properties of window materials

	Lexgard	Soda-lime glass	Herculite II
E ($\times 10^9$ N/m^2)	2.47	70.4	75.9
ν	——	0.22	0.21
ρ, kg/m^3	1150	2410	2464

Table 2 Lexgard impact test parameters

Test no.	V, km/s	θ	d, mm	t_w, mm
123-1	5.40	0	3.175	19.05
123-2	5.80	0	3.175	19.05
123-3	6.40	0	3.175	19.05
124-1	6.30	0	4.750	19.05
124-2	5.86	0	4.750	10.05
124-3	5.50	0	4.750	19.05
124-4	4.66	0	4.750	19.05
125A	5.27	0	6.350	19.05
125B	3.78	0	6.350	19.05
125C	3.23	0	6.350	19.05
126A	7.24	0	4.750	31.75
126B	7.46	0	4.750	31.75
127A	7.16	0	6.350	31.75
127B	7.41	0	6.350	31.75
129A	6.86	0	7.620	31.75
129B	6.45	0	7.620	31.75
129C	6.00	0	7.620	31.75
171A	6.60	45	9.525	31.75
172A	6.65	65	9.525	31.75
173A	6.91	45	7.950	19.05
174A	6.94	65	7.950	19.05

Table 3 Glass impact test parameters

Test no.	V, km/s	d, mm	t_o, mm	t_m, mm	t_i, mm	S_o, mm	S_i, mm
18-1	6.50	3.175	6.4	16.0	16.0	12.7	12.7
18-2	6.33	3.175	6.4	16.0	16.0	12.7	12.7
18-3	6.50	3.175	16.0	16.0	16.0	50.8	12.7
18-4	6.63	3.175	16.0	16.0	16.0	50.8	12.7
15-5	6.50	3.175	6.4	16.0	16.0	12.7	12.7

Table 4 Glass window pane materials

Test no.	Outer pane	Middle pane	Inner pane
18-1	Soda lime	Herculite II	Herculite II
18-2	Soda lime	Laminated Herculite II	Herculite II
18-3	Soda lime	Soda lime	Herculite II
18-4	Soda lime	Laminated Soda lime	Herculite II
18-5	Laminated Soda lime	Laminated Soda lime	Herculite II

Hypervelocity Impact Response of Lexgard

Qualitative Damage Analysis

Two different window constructions were used to evaluate the response of Lexgard windows to hypervelocity projectile impact. One consisted of a 12.7-mm layer of Lexgard sandwiched in between two 3.175-mm Lexgard layers for a total specimen thickness t_w = 19.05 mm (Fig. 1a). The other contained an additional interior 12.7-mm layer for a total specimen thickness t_w = 31.75 mm (Fig. 1b). In each test, a projectile of diameter d and velocity V impacted a Lexgard window specimen along a trajectory perpendicular to the plane of the window (Figs. 1a and 1b). The projectile shattered upon impact and set off a series of shock waves that created an internal area of damage. This internal damage area was typically a circular area of delamination between the Lexgard layers (Figs. 3–6). The window specimens ceased to be transparent near the

Table 5 Hypervelocity impact test results for Lexgard panels

Test no.	D, mm	A_d, cm^2	A_s, cm^2
123-1	—	24.45	2.787
123-2	—	20.26	1.510
123-3	—	33.48	0.806
124-1	7.493	64.71	—
124-2	6.299	63.29	—
124-3	5.791	49.81	—
124-4	—	59.10	1.026
125A	10.414	113.42	—
125B	6.756	60.32	—
125C	—	51.81	—
126A	—	135.03	—
126B	—	109.42	—
127A	—	182.06	—
127B	—	188.39	—
129A	6.629	230.84	—
129B	—	159.61	—
129C	—	186.32	—
171A	—	387.93	—
172A	—	230.52	—
173A	45.7×53.3	153.29	—
174A	31.750	167.55	—

Table 6 Regression analysis of Lexgard damage data error summary

Regression function	$\%\epsilon_{avg}$	σ, %	R^2
D/d	0.038	3.045	0.971
A_s/A_p	10.658	62.233	0.827
A_d/A_p	1.280	16.402	0.804

Table 7 Hypervelocity impact test results for glass systems

Test no.	Outer pane	Middle pane	Inner pane	Penetrated?
18-1	Shattered; ≃100 fragments 0.1–2.5 cm	Shattered	No damage	No
18-2	Shattered; ≃100 fragments 0.1–3.2 cm	Cracked No penetration	No damage	No
18-3	Shattered; 19 fragments 3.5–7.5 cm	Minor pitting	No damage	No
18-4	Shattered; 6 fragments 3.5–5.1 cm	Minor pitting	No damage	No
18-5	3.25-mm hole; 4.3-cm diam spall on both surfaces; No disintegration	Cracked No penetration	No damage	No

internal damage area. In some instances, rear-surface spall, as well as front and rear-surface petalling (Figs. 3b, 4b, 5b, and 6b), resulted from shock-wave interaction at the interface between a thin surface layer and a thick interior layer. Occasionally, penetration of the window specimen occurred as well (Fig. 4a). In these cases, the material surrounding the hole was melted and torn through the thickness of the specimen.

A summary of the damage to each of the Lexgard specimens can be found in Table 5, where D is the diameter of the hole in the specimen if penetration occurred, A_d is the area of the internal damage region, and A_s is the area of rear-surface spall if spall occurred. Penetration functions for normal impact of both specimen types are shown in Fig. 8 based on the penetration data in Table 5; a spall function for the normal impact of the thin Lexgard panels is shown in Fig. 9. These curves can be used to determine if penetration or rear-surface spall will occur as a result of a particular high-velocity impact. It is noted that the curves in Figs. 8 and 9 are simply lines of demarcation between areas of penetration and no penetration and spall and no spall for the parameters indicated.

Although rear-surface spall occurred frequently in the impact of the thin Lexgard specimens, it is interesting to note

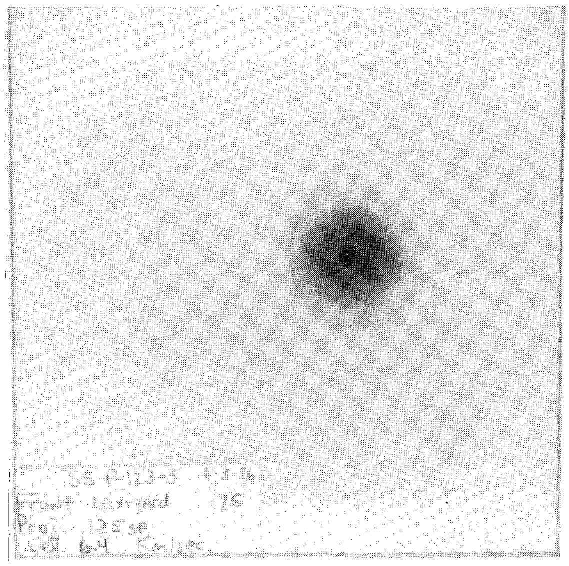

Fig. 3a Damaged thin Lexgard window, front view, test no. 123-3 (small projectile diameter, high impact velocity).

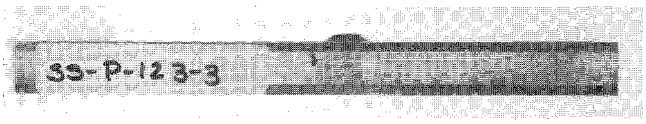

Fig. 3b Damaged thin Lexgard window, side view, test no. 123-3 (small projectile diameter, high impact velocity).

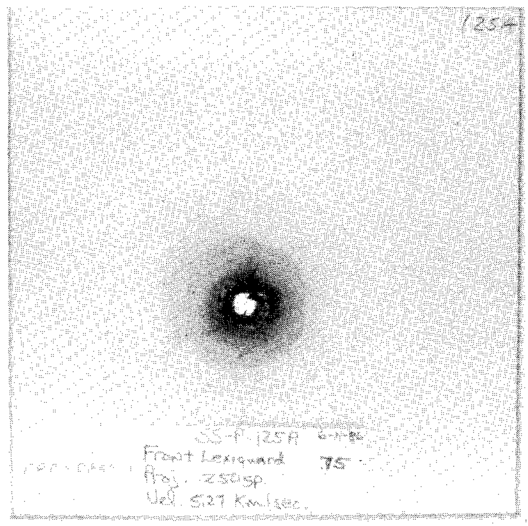

Fig. 4a Penetrated thin Lexgard window, front view, test no. 125A (large projectile diameter, high impact velocity).

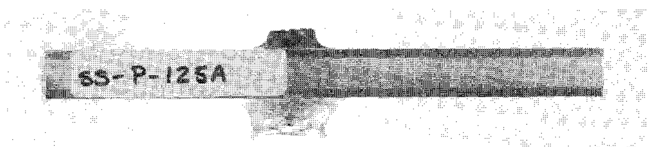

Fig. 4b Penetrated thin Lexgard window, side view, test no. 125A (large projectile diameter, high impact velocity).

that rear-surface spall did not occur in any of the thick specimens. Impact of the thick specimens resulted in either rear-surface petalling without spall or in a "ballooning" of the rear surface, also without spall. Additionally, the rear surface remained undamaged when a thick Lexgard specimen was impacted by the smaller projectiles (Fig. 5b); impact by the larger projectiles resulted in significant delamination between the two thick interior layers and petalling of the front and rear

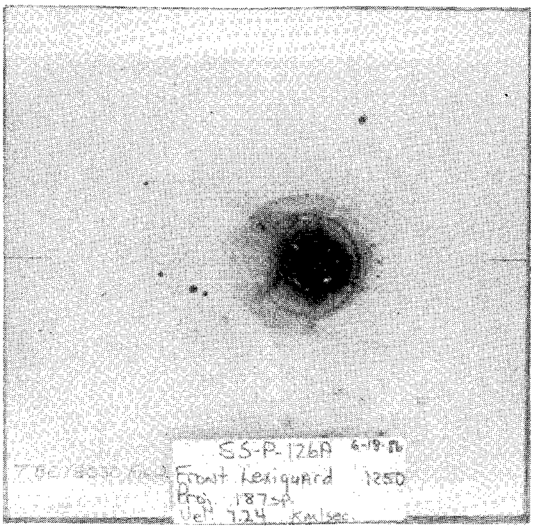

Fig. 5a Damaged thick Lexgard window, front view, test no. 126A (small projectile diameter, high impact velocity).

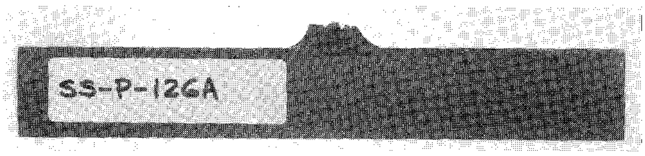

Fig. 5b Damaged thick Lexgard window, side view, test no. 126A (small projectile diameter, high impact velocity).

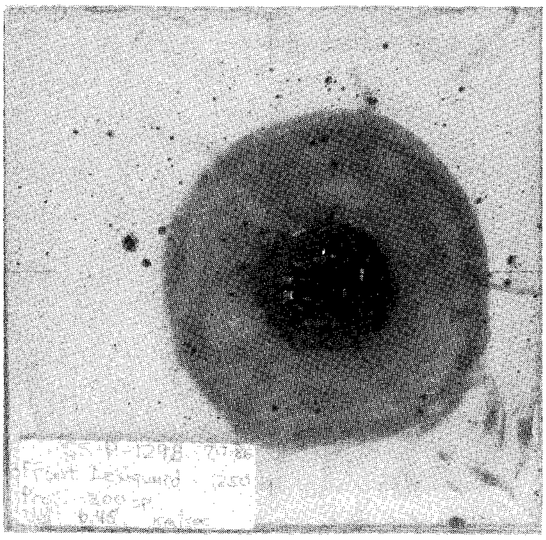

Fig. 6a Damaged thick Lexgard window, front view, test no. 129B (large projectile diameter, high impact velocity).

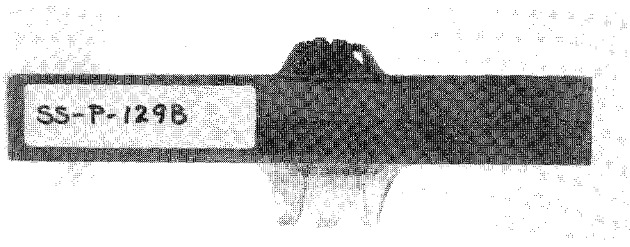

Fig. 6b Damaged thick lexgard window, side view, test no. 129B (large projectile diameter, high impact velocity).

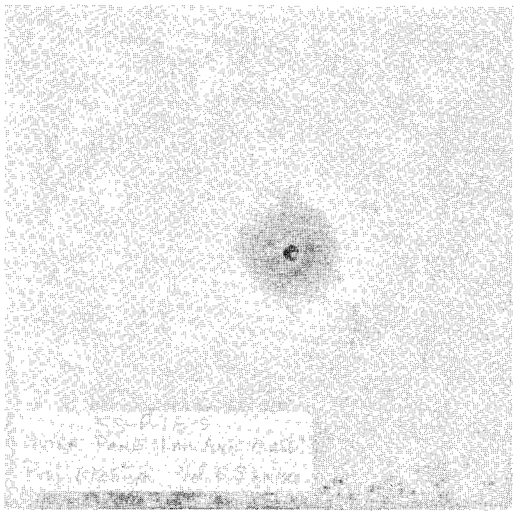

Fig. 7a Triple-pane glass window system, outer pane, test no. 18-5.

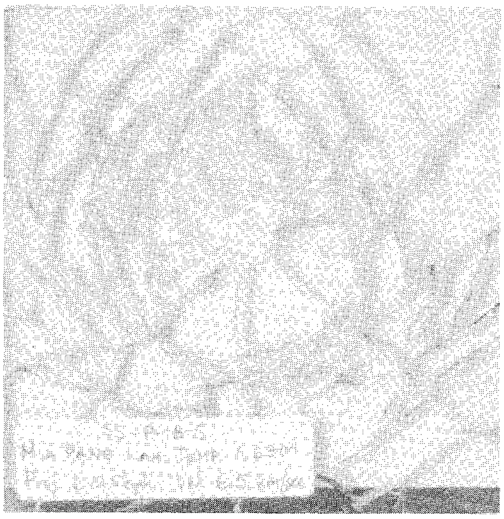

Fig. 7b Triple-pane glass window system, middle pane, test no. 18-5.

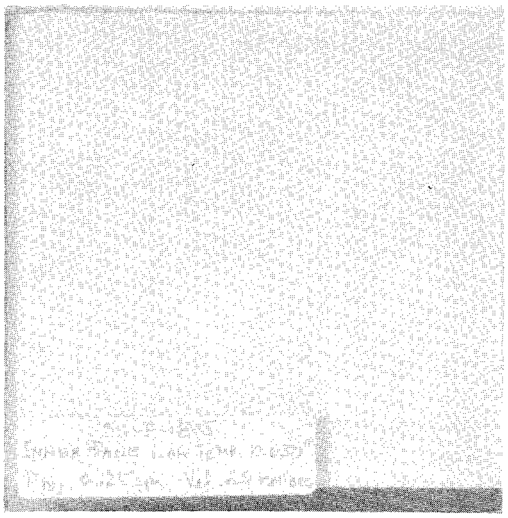

Fig. 7c Triple-pane glass window system, inner pane, test no. 18-5.

surfaces (Fig. 6b). Oblique impacts were observed to pentrate the thin specimens but not the thick specimens. At trajectory obliquities of 45 and 65 deg, the thin specimens were penetrated by 7.95-mm projectiles. However, the thick specimens were not penetrated at either trajectory obliquity, even though the projectile diameter was increased to 9.525 mm. Significant front- and rear-surface petalling and large areas of internal delamination were also observed in Lexgard specimens impacted by large obliquely incident projectiles.

Regression Analysis of Damage Data

A standard multiple linear regression analysis of the data in Table 5 was performed to obtain equations for hole diameter in the event of a penetration, internal damage area, and rear-surface spall area if spall occurs as functions of geometric, material, and impact parameters:

Hole diameter:

$$D/d = 1.043(V/C)^{1.389}(t_w/d)^{-1.201}, \qquad \theta = 0 \text{ deg} \qquad (1)$$

Rear-spall area:

$$A_s/A_p = 0.000505(V/C)^{6.909}(t_w/d)^{0.946}, \qquad \theta = 0 \text{ deg} \qquad (2)$$

Damage area:

$$A_d/A_p = 39.04(V/C)^{1.390}\cos^{0.266}\theta(t_w/d)^{0.241} \qquad (3)$$

where $C = \sqrt{E/\rho}$ and $A_p = \pi d^2/4$. The average errors, standard deviations, and correlation coefficients for Eqs. (1–3) are given in Table 6. Based on the data in Table 6, it is evident that Eqs. (1–3) fit the experimental data fairly well. It is noted that Eqs. (1–3) are valid only for impacts of aluminum projectiles on Lexgard panels of similar layup and construction, and for impact velocities between 5.4 and 7.5 km/s. Additionally, Eqs. (1) and (2) are valid only for normal impacts while Eq. (3) may be used to calculate internal damage areas for normal and oblique impacts. Furthermore, before using Eqs. (1) and (2), Figs. 8 and 9 must be consulted to determine whether or not penetration or spall will occur as a result of a particular impact. If penetration or spall will indeed occur, then Eq. (1) may be used to estimate the diameter of the resulting hole and Eq. (2) may be used to calculate the anticipated area of rear-side spall.

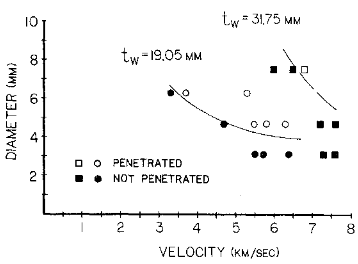

Fig. 8 Penetration functions for Lexgard windows.

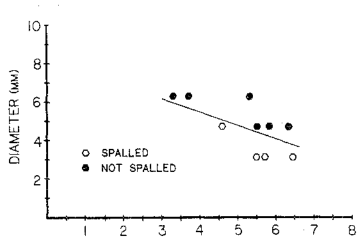

Fig. 9 Spall function for thin Lexgard windows.

Hypervelocity Impact of Glass Systems

Two different configurations were used to study the response of triple-pane glass windows to hypervelocity projectile impact. The essential differences between the two systems were the thickness of the outer panes and the standoff distance between the outer and middle panes (the "outer standoff distance"). In one triple-pane system, the outer-pane thickness was 6.4 mm and the outer standoff distance was 12.7 mm. In the other, the outer pane was 16 mm thick and the distance between the outer and middle pane was 50.8 mm. In both systems, the thicknesses of the middle and inner panes were 16 mm each and the spacing between the middle and inner panes was 12.7 mm.

A summary of the resulting damage to each pane in each test is presented in Table 7. For the purposes of this investigation, a glass window specimen was considered to be penetrated if the inner pane was cracked or shattered. A shattered pane is defined as a pane that disintegrates into smaller pieces upon impact. A cracked pane has numerous fractures, but remains intact after impact. Because of the relatively small number of tests performed, it would be impossible and inappropriate to perform a regression analysis of the glass system damage data presented in Table 7. However, a qualitative analysis of the damage revealed many interesting features and characteristics of multipane window systems under hypervelocity impact.

The hypervelocity impact response of the triple-pane glass specimens was significantly different from that of the Lexgard test specimens. The damage in the glass panes was much more extensive because of their brittleness and low tensile strength. This allowed the shock-related stresses to overwhelm the material strength for a longer period of time in the glass specimens than in the Lexgard test specimens.[12] In four of the glass tests, the outer pane was completely shattered and disintegrated. The thinner outer panes of tests 18-1 and 18-2 were shattered into hundreds of pieces ranging from approximately 0.1 to 3.0 cm in diameter; the thicker outer panes of tests 18-3 and 18-4 were shattered into several chunks ranging from about 3.5 to 7.5 cm in diameter. In the fifth test, the outer pane was laminated and, as such, did not disintegrate upon impact. However, it was penetrated and sustained relatively large areas of spallation on both the front and rear surfaces (Fig. 7a). The middle panes in the specimens with the thick outer panes and the larger outer standoff distance sustained no serious damage. The middle panes in the specimens with the thinner outer panes and the smaller outer standoff distance were either cracked or shattered. The cracked middle panes contained numerous overlapping radial and concentric ring fractures (Fig. 7b). As such, their appearance strongly resembled that of a thick glass block subjected to a hypervelocity projectile impact.[11] The inner panes sustained no damage regardless of the thickness of the outer pane (see, e.g., Fig. 7c).

A more detailed examination of the damage sustained by each pane in the triple-pane glass window systems revealed that the systems with laminated panes faired better overall than did those systems without laminated panes. For example, in test 18-2, the middle pane was laminated while in test 18-1 it was not. Accordingly, the middle pane in test 18-1 cracked in half while the middle pane in test 18-2 merely sustained some cracks on the front surface and was not penetrated. Furthermore, lamination of the outer pane in test 18-5 prevented its complete disintegration whereas the otherwise identical outer panes in tests 18-1 and 18-2 were completely shattered under similar impacts.

Finally, the observed failures of the outer glass panes were compared against the predictions of the window-penetration equations developed during the Apollo/Skylab era[13]:

$$p = 0.53\rho_p^{0.5}d_p^{1.06}V_p^{0.67} \qquad (4)$$

$$t_c = 0.14V_p^{1.28}p \qquad (5a)$$

$$t_s = 7p \tag{5b}$$

where ρ_p, d_p, V_p are the density (in g/cm^3), diameter (in cm), and velocity (in km/s) of the impacting projectile, respectively; p is the depth of penetration (in cm); t_c is the minimum thickness necessary to prevent through-cracks (in cm); and t_s is the minimum thickness required to prevent rear-side spallation (in cm). Using these equations and the parameters presented in Table 3, it was found that thicknesses on the order of 14 and 64 mm would be required to prevent through-cracks and rear-side spallation, respectively. Thus, it is not surprising that the thinner outer panes (in tests 18-1 and 18-2) broke apart into hundreds of pieces while the thicker panes in tests 18-3 and 18-4, which were fairly close to the thickness required for no through-cracking, broke apart into a relatively small number of pieces.

From these results, it can be concluded that both triple-pane glass window systems can withstand impacts of 3.175-mm-diam aluminum particles traveling at speeds of up to 6.6 km/s. If similar systems were used for spacecraft windows, it is unlikely that a pressure leak would occur due to an on-orbit impact of similar magnitude. If such an impact were to occur on a window system containing a thin outer pane placed at a small distance away from the middle pane, only the inner pane would be left to maintain the pressure seal. If the glass window system were to have a laminated thin outer pane or a thick outer pane placed at a relatively large distance from the middle pane, the middle pane would most likely remain undamaged and two window panes would be left to maintain the pressure seal. However, an on-orbit impact of a triple-pane glass window system with a thick outer pane would create large chunks of secondary debris that could subsequently be more damaging than the smaller secondary debris pieces created by the impact of a triple-pane window system with a thin outer pane. Lamination of both the outer and middle panes would reduce the potential for the creation of any glass-debris fragments. In any case, the window would be rendered useless for viewing and scientific purposes and the replacement of at least one pane of the window system would be necessary.

Conclusions

An investigation of the hypervelocity impact response of spacecraft window materials has revealed many interesting features and response characteristics. Multilayer Lexgard windows were found to sustain high levels of internal, penetration, and rear-side spall damage as a result of normal and oblique hypervelocity impacts. The tendency of the Lexgard window panels to spall as a result of a hypervelocity impact is an area of major concern. Because of the high speeds with which spall fragments can travel, impact-induced spall can be as deleterious to mission success and crew safety as an actual penetration. The lethality of the high-speed spall fragments must not be overlooked.

Triple-pane glass window systems were found to be rather resilient under hypervelocity projectile impact loadings and did not sustain any penetration or spall damage of the innermost window pane. Increasing the thickness of the outer pane served to reduce the number of fragments; increasing the outer standoff distance resulted in a significant decrease in the damage sustained by the middle window pane. Furthermore, it was found that laminating the outer and middle panes prevented them from disintegrating upon impact. This is a highly desirable quality because, in the event of an on-orbit impact, it must be ensured that the orbital environment does not become further contaminated by hundreds of glass debris fragments.

Based on the observations made during the course of this investigation, multipane glass systems appear to be the most promising for use as spacecraft windows. However, it is recommended that additional testing of laminated and unlaminated multipane glass window systems be performed using large diameter projectiles and at oblique angles. Such testing would result in a more complete understanding of the growth of impact damage in glass window systems and in more accurate prediction of the response of such systems in the event of an on-orbit impact.

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