EXPERIMENTAL AND NUMERICAL STUDIES OF LAMINATED GLASS SUBJECT TO HYPERVELOCITY IMPACT

Zhang Wei, Ha Yue, Guan Gongshun, Pang Baojun

Hypervelocity Impact Research Center, Harbin Institute of Technology,
P. O. Box 3020, Science Park, No.2 Yikuang Street, Nan'gang District,Harbin 150080, P. R. China
Email: zhdawei@hit.edu.cn

ABSTRACT

Windows as an earth orbiting spacecraft's most critical component would be also susceptible to hazards of the meteoroids and space debris. Glasses integrated into such systems must be designed to maximize the safety of the crew and instruments for the duration of the spacecraft's flight. Hypervelocity impact on glass materials produces features not observed on ductile targets. Low toughness and high yield strength produce a range of fracture morphologies including cracking, spallation and shatter at the target front and back surface around the initial impact site. The aim of this paper is to study the damage characteristic sizes (densely cracked zone diameter, spallation diameter and depth etc.) of laminated glass under hypervelocity impacts with experimental tests and numerical simulation method.

1. INTRODUCTION

All spacecraft in low orbit are subject to hypervelocity impacts by meteoroids and space debris. Windows as an earth orbiting spacecraft's most critical component would be also susceptible to hazards of the meteoroids and space debris. Glasses integrated into such systems must be designed to maximize the safety of the crew and instruments for the duration of the spacecraft's flight. The behavior of hypervelocity impact damage in ductile materials has been extensively investigated. Hypervelocity impacts in glass and laminated glass (a typical brittle material) have undergone less investigation (Cour-Palais,1987; Schneider, 1990,1995; Alwes,1990; Schonberg,1991; Taylor,1997,1999). Hypervelocity impact on glass materials produces features not observed on ductile targets. In glass materials, during the later stages of a hypervelocity impact, low toughness and high yield strength produce a range of fracture morphologies including cracking, spallation and shatter at the target front and back surface around the initial impact site. It has become necessary to study the response of windows materials to hypervelocity projectile impact and to evaluate their degradation and damage as a result of such impacts. A summary of early work studying the damage of impacts in glass can be found (Cour-Palais,1987) and recent discussions of damage in glass materials are found (Burt, 2003;Davison, 2004). The basic construction of laminated glass involves pieces of glass together with polyvinyl butyral (PVB) interlayer. It is widely used in automotive and architectural glazing structures. The study of low-velocity impacts damage of laminated glass can be found （Flocker,1997）. The aim of this paper is to study the damage characteristic sizes (densely cracked zone diameter, spallation diameter and depth etc.) of laminated glass under hypervelocity impacts with experimental tests and numerical simulation method. The effect of spherical projectile diameters and impact velocities, laminated glass configurations etc. on damage characteristic sizes has been investigated experimentally and numerically.

2. HYPERVELOCITY IMPACT EXPERIMENTAL TESTING

2.1 Laminated Glass Configuration

The laminated glass investigated in this paper composed by various thickness soda-lime glass and 0.76mm thick PVB interlayer. The testing laminated glasses have the configuration patterns as shown in Fig.1, A type is 4 layers 5mm glass with 3 layers 0.76mm PVB; B type is 3 layers 12mm glass with 2 layers 0.76mm PVB; C type is composed by front and back 5mm glasses and interlayer 12mm glass with 2 layers 0.76mm PVB. In preparation for lamination, the glass plies were cut using a cutter to dimensions 260mmx 260mmxthickness. The PVB interlayer was kept refrigerated until required in order to ensure minimal degradation. Following stacking, the laminates were vacuum-sealed and consolidated for 1 hour in an autoclave. During the autoclave cycle, a pressure of 1MPa and a temperature of 140^{0}C was maintained. Once the panels had cooled sufficiently, they were removed from the vacuum bagging material and cleaned in preparation for testing.

2.2 Experimental Set-up

Hypervelocity impact tests were performed at Harbin Institute of Technology two stage light gas gun in the velocity range 1.5~5km/s at normal angles to the surface of the laminated glass. The spherical projectile is made

Proceedings of the Fourth European Conference on Space Debris, Darmstadt, Germany, 18-20 April 2005
(ESA SP-587, August 2005)

by 2017-T4 aluminum alloy with the diameters of 3.97mm and 6.35mm. The velocities were measured by magnetic induced coils system and lasers system. The laminated glasses were clamped in a square frame with rubber plate at the backside.

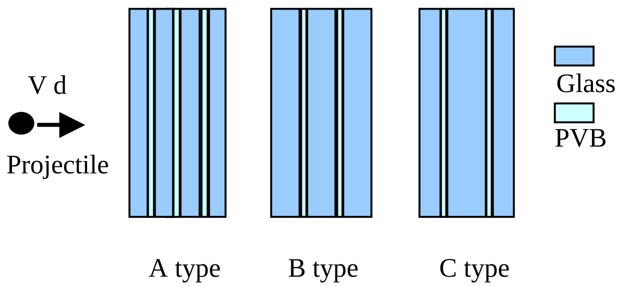


Figure.1 Laminated glass configuration patterns and experimental setup

2.3 Experimental Results and Analysis

The damage morphologies of the laminated glass impacted by sphere projectile is shown in Fig. 2, D_P is the diameter of central pit, D_{FS} is mean diameter of front face spallation zone, D_{FC} is mean diameter of densely cracked zone in front face, P is depth of front face penetration, D_C is radial crack diameter of laminated glass, D_{RC} is mean diameter of densely cracked zone in rear face, D_{RS} is mean diameter of rear face spallation zone, T_C is depth of rear face spallation. The representative experimental conditions and results of the hypervelocity impact test are presented in Tab.1. Fig.3 and Fig.4 give the damage morphologies of laminated glasses after testing at about 1km/s to 5km/s. From the results of Tab.1 and Fig.3, we can see that all laminated glasses impacted by sphere projectile have radial crack, a central impact zone is produced by the penetration projectile. Within this region, projectile and laminated glass materials are fragmented and ejected. This central crater region is surrounded by a zone of highly shocked, fine fragmented material. A regularly shaped spallation zone, where material is removed from the surface, extends further out into the laminated glass. The spallation zone itself goes over into a zone in which in most cases a nearly regular pattern of radial and concentric cracks is observed. These spallation and crack zones are caused by compression and release waves propagation into the glasses. From Tab.1 and Fig.3 to Fig5, we can also see that as impact velocity increase the damage characteristic sizes also increase. The PVB interlayer has a considerable enhancement of the protection effective.

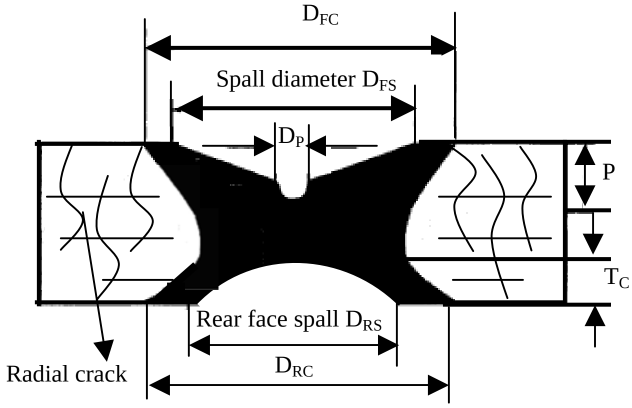
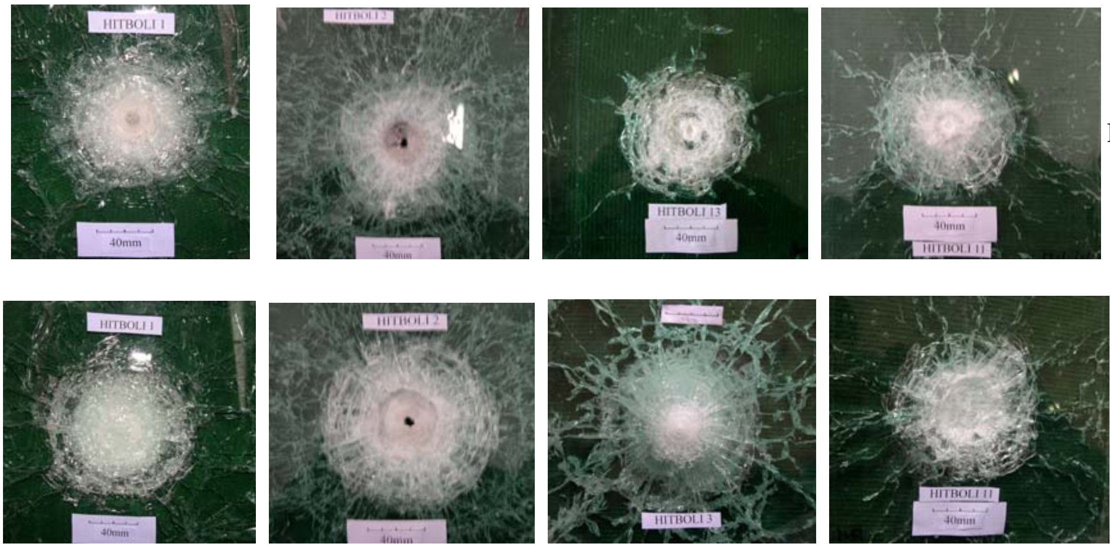


Figure.2 Hypervelocity impact damage morphology characteristic sizes of laminated glass

Table 1 Experimental results of laminated glass impact by sphere projectile

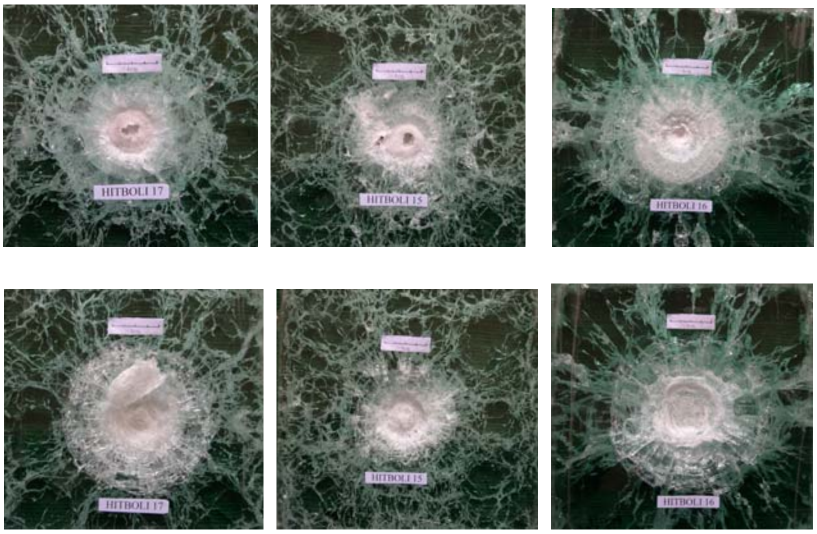
No.	Projectile diameter /mm	Impact velocity /km/s	Configuration patterns	D_C/mm	Damage in front face			Damage in rear face		
					D_{FS}/mm	D_{FC}/mm	P/mm	D_{RS}/mm	D_{RC}/mm	T_C/mm
Boli1	3.97	4.24	C	260	57	70	7	76	91	5
Boli2	3.97	2.90	A	260	52	69	perforation	64	77	perforation
Boli3	3.97	3.9	B	260	54	116	9.8	No spall	86	N0 spall
Boli5	3.97	4.0	B	260	84	116	7.6	No spall	120	--
Boli7	6.35	4.03	B	260	88	132	9.8	116	155	11.5
Boli8	6.35	4.03	C*No PVB	260	Totally disintegrated					
Boli9	6.35	4.10	A*No PVB	260	52	260	perforation	67	260	perforation
Boli11	3.97	2.77	A	260	49	70	5.1	65	78	4.5
Boli12	3.97	2.90	C	260	50	60	5.4	64	80	6.1
Boli13	3.97	3.01	B	260	56	102	6.2	No spallation		
Boli14	3.97	1.40	A	260	33	48	3.6	43	60	8.6
Boli15	6.35	2.74	A	260	75	110	14	100	120	9.5
Boli16	6.35	2.71	B	260	52	132	11.3	152	165	11.2
Boli17	6.35	2.67	C	260	70	80	8.0	88	114	10.1
Boli18	6.35	4.17	A	260	95	120	perforation	115	136	perforation
Boli19	6.35	4.17	C	260	90	111	perforation	120	145	perforation
Boli20	6.35	5.0	A	260	100	124.0	perforation	120.0	140	perforation



Front face

Rear face

Boli1 Boli2 Boli113 Boli11

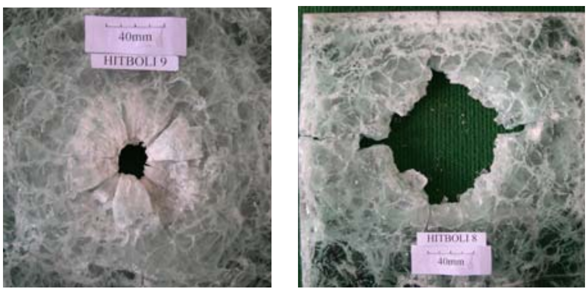


Front face

Rear face

Boli17 Boli15 Boli16

Figure.3 Damage morphologies of laminated glasses after testing



Boli9 Boli8

Figure.4 Damage of laminated glass without PVB

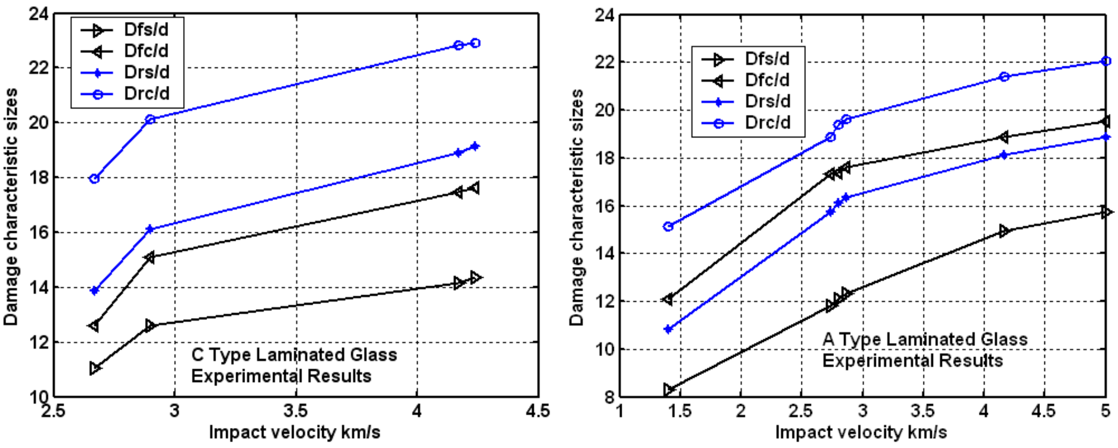


Fig.5 Experimental results of effect of impact velocity on damage characteristic sizes

3. HYPERVELOCITY IMPACT NUMERICAL SIMULATION

3.1 Material Models

In order to investigate the impact processes on laminated glass and to evaluate the damage characteristic sizes at experimental test regime velocities and beyond the experimental regime, the numerical simulations of projectile hypervelocity impact on laminated glass at normal have been carried out using the SPH (smoothed particle hydrodynamics) technique of AUTODYN-2D hydro-codes in this paper. The glass material model applied Johnson-Holmquist strength and failure model, the equation of state is a simple polynomial. The Johnson-Holmquist model is applicable to brittle materials subjected to large strains, high strain rates and high pressures and gives the yield strength as a function of pressure. The strength model incorporates the experimental observation that a brittle material has some compressive strength but no tensile or spall strength after fracture, and includes strain rate and bulking effects. The yield strength is also a function of damage, the residual strength in fractured material, dilation and strain rate effects. The strength model does not include thermal softening. Dilation occurs because brittle materials fail by cracking, leading to free surfaces and increase in volume. The Johnson-Holmquist mode dimensionless constants are shown in Tab.2. In addition to the equation of state and strength models for the glass, we assumed that the material would fail (with the possibility of re-healing on recompression) when the pressure fell below a nominal minimum value of P_{min}=-0.1Gpa. The PVB is a visco-elastic polymer, therefore the material model applied a linear visco-elastic-plastic model. The PVB material model parameters are presented in Tab.3.

Table.2 Glass material model data

Parameter	Value	Parameter	Value
A	0.93	M	0.4
N	0.77	Fs	0.5
HEL (GPa)	5.95	T(MPa)	-35
G (GPa)	30.4	C	0.003
B	0.35	D1	0.053
D2	0.85	Beta	1.0
ρ(g/cm^3)	2.49	A1	4.54E7
A2	-1.38E8	A3	2.9E8
Poisson's ratio ν	0.225	E	68.5GPa
Sound velocity	5.2km/s		

Table.3 PVB material model data

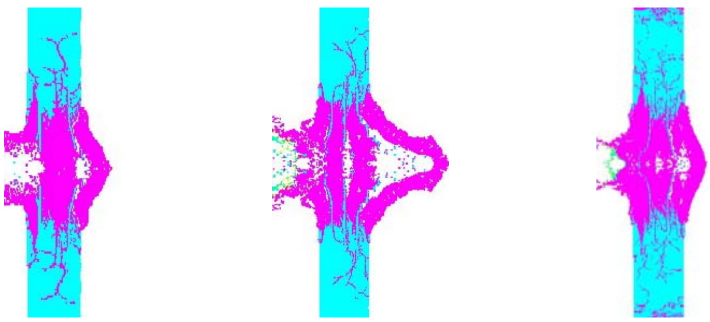
Parameter	Value
Initial density)	1.1 g/cm^3
Young's modulus E	689.5KPa
Poisson's ratio ν	0.5
Yield strength Y	32.1MPa
Hardening modulus E_t	1.0MPa
Bulk modulus K	2.0GPa
Shear modulus G	1.0GPa
Hydro limit	-32MPa

3.2 Numerical Simulation Results and Analysis

Numerical simulations with three configuration patterns and different impact velocities over a wide range have been performed and partly compared with the experimental results. The numerical simulation conditions and results are given in the Tab.4. Plots of numerical simulation result are shown by Fig.6 to Fig.8. From Tab.1 Tab.4 Fig.3 Fig.5 and Fig.6 to Fig.8, by compared the results of the experimental and numerical, it shows that the numerical results are in good agreement with the experimental results.

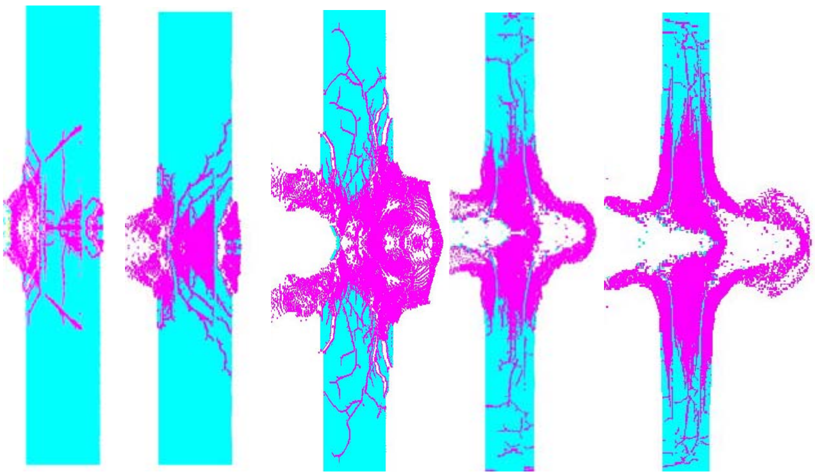
Table 4 Numerical simulation results of laminated glass impact by sphere projectile

No.	Projectile diameter /mm	Impact velocity /km/s	Configuration patterns	D_C/mm	Damage in front face			Damage in rear face		
					D_{FS}/mm	D_{FC}/mm	P/mm	D_{RS}/mm	D_{RC}/mm	T_C/mm
Boli1	3.97	4.24	C	260	50	86	6.91	52	74	4.5
Boli2	3.97	2.90	A	260	50	66	perforation	55	76	perforation
Boli7	6.35	4.0	B	260	62	92	3.55	85	113	13.3
Boli12	3.97	2.9	C	260	40	75	9.7	40	68	6.5
Boli13	3.97	3.0	C	260	41	80	4.21	45	71	4.5l
Boli15	6.35	2.74	A	260	46	90	3.45	68	112	11.2
Boli23	3.97	8.0	C	260	70	106	perforation	76	96	perforation
Boli24	3.97	1.0	C	42	26.4	40	4.44	10	12.8	4.5
Boli25	3.97	15	C	260	85	118	perforation	110	142	perforation
Boli26	3.97	2.0	A	70	28	50	4.46	40	70	9.4
Boli27	3.97	8.	A	260	60	88	9.0	80	100	3.2
Boli28	3.97	15	A	260	68	105	perforation	95	117	perforation
Boli31	3.97	2.0	C	82	34	60	4.7	30	40	4.5
Boli32	3.97	15.0	B	260	72	110	10	90	134	12
Boli33	3.97	2.0	B	65	36	58	1.90	No spall	24	-
Boli34	3.97	8.0	B	260	64	90	5.90	84	120	7.10



Boli1 Boli2 Boli15

Figure.6 Numerical simulation results of laminated glasses



1.0km/s 2.0km/s 2.9km/s 8km/s 15km/s

Figure.7 Numerical simulation results of C type laminated glasses at different impact velocities

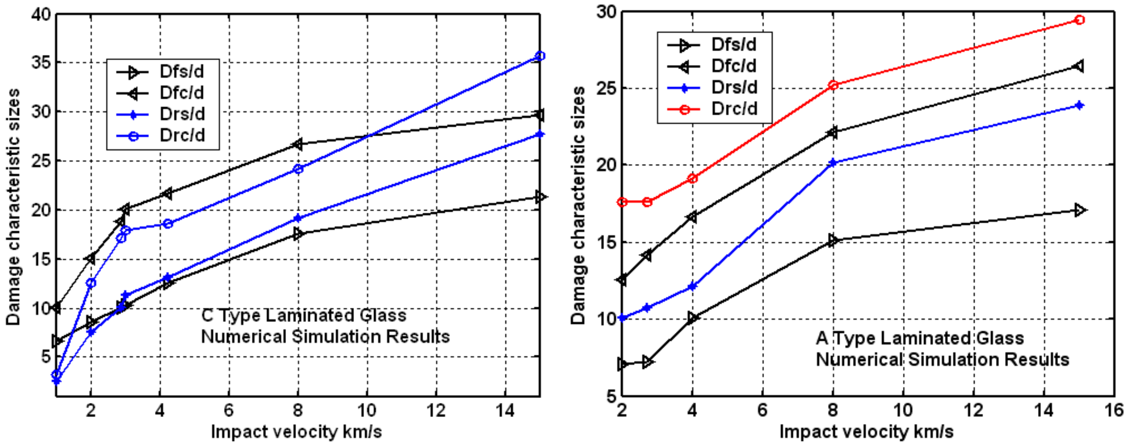


Fig.8 Numerical results of effect of impact velocity on damage characteristic sizes

4. CONCLUSION

The experimental and numerical results obtained form a database for evaluating the protection effectiveness of laminated glass against meteoroids and space debris impacts. It has been found that glass plies bound with plastic PVB interlayer leads to a considerable enhancement of the protection efficiency than glass plies put together without PVB at almost same areal density. For investigation of the hypervelocity impact resistance of laminated glass a test program has been carried out, and further tests should be performed on the influence of test parameters, such as projectile incident obliquities, experimental temperature, interlayer PVB thickness, Toughening process, glass size and number of glass plies, etc. in more detail. The numerical simulation results show in comparison with the experimental results that they are fairly consistent with the experiments. The effect of spherical projectile diameters and impact velocities, laminated glass configurations etc. on damage characteristic sizes has been investigated experimentally and numerically. From experimental and numerical studies, the conclusion can be obtained that as the projectile diameter and impact velocity increase the damage characteristic sizes increase.

5. REFERENCES

Cour-Palais B. J. Hypervelocity impacts in metals, glass and composites. *Int. J. Impact Eng.* **5**, 221–237, 1987.

Schneider E., Stilp A. J., et al, Meteoroid/debris simulation experiments on MIR viewport samples. *Int. J. Impact Eng* 17, 731-741,1995

Alwes D.，Columbus-viewport glass pane hypervelocity impact testing and analysis. *Int. J. Impact Eng.*, 10,1-22,1990

Schonberg W. P. Response of spacecraft window materials to hypervelocity projectile impact. *J. Spacecraft*, 28, 118-123,1991

Burchell, M. J. and I. D. S. Grey. Oblique hypervelocity impacts on thick glass targets. *Mater. Sci. Eng.***303**, 134–141, 2001

Taylor, E. A., Tsembelis K., et al. Hydrocode modeling of hypervelocity impact on brittle materials: Depth of penetration and conchoidal diameter. *Int. J. Impact Eng.* **23**, 895–904, 1999

Schneider E. and Stilp A. Micrometorite and space debris simulation for Columbus hull components. Int. J. Impact Eng. 10,499-509,1990

Burt R. R. and Christiansen E. L., An enhanced shutter to protect spacecraft windows from meteoroids and orbital debris. Int. J. Impact Eng. 29,135-152,2003

Davison D, Cour-Palais B., Quan X. Y. et al. Computer models of micrometeoroid impact on fused silica glass mirrors. *Int. J. Impact Eng.*, 26,487-496,2004

Taylor, E. A., Hayhurst C. J., et al. Hydrocode modeling of space debris hypervelocity impact on soda-lime glass using the Johnson-Holmquist brittle material model. *Second European Conference on Space Debris*, Darmstadt, Germany, 1997

Flocker F. W.,Dharani L. R., Stresses in laminated glass subject to low velocity impact, Engineering Structures, 19(10),851-856,1997

Holmquist T. J., Johnson G. R., High strain rate properties and constitutive modeling of glass, 15th Int. Symp. Ballistics. 21-24,1995

AUTODYN Theory Manual, Revision 4.3, Century Dynamics, Inc.,2004