1995

NASA/ASEE SUMMER FACULTY FELLOWSHIP PROGRAM

MARSHALL SPACE FLIGHT CENTER
THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

PRESSURE WALL HOLE SIZE AND MAXIMUM TIP-TO-TIP CRACK LENGTH FOLLOWING ORBITAL DEBRIS PENETRATION

Prepared By:	William P. Schonberg, PhD, PE

[redacted]

Academic Rank:	Professor
Institution and Department:	The University of Alabama in Huntsville Civil & Environmental Engineering Dept.
NASA/MSFC Laboratory:	Structures and Dynamics
Division:	Structural Design
Branch:	Structural Development
NASA/MSFC Colleague:	Joel Williamsen, PhD

PRESSURE WALL HOLE SIZE AND MAXIMUM TIP-TO-TIP CRACK LENGTH FOLLOWING ORBITAL DEBRIS PENETRATION

William P. Schonberg
Civil & Environmental Engineering Department
University of Alabama in Huntsville

Abstract

The threat of damage from high speed meteoroid and orbital debris particle impacts has become a significant design consideration in the development and construction of long duration earth-orbiting spacecraft. Historically, significant amounts of resources have been devoted to developing shielding for such structures as a means of reducing the penetration potential of high speed on-orbit impacts. These efforts have typically focused on simply whether or not the inner (or 'pressure') walls of candidate multi-wall structural systems would be perforated. Only recently the nature and extent of pressure wall penetration damage have begun to be explored. This report presents the results of a study whose objective was to characterize the hole formation and cracking phenomena associated with the penetration of the multi-wall systems being considered for the International Space Station Alpha (ISSA).

INTRODUCTION

All long-duration spacecraft in low-earth-orbit are subject to high speed impacts by meteoroids and pieces of orbital debris. The threat of damage from such high speed impacts has become a significant design consideration in the development and construction of long duration earth-orbiting spacecraft. Historically, significant amounts of resources have been devoted to developing shielding for such structures as a means of reducing the penetration potential of high speed on-orbit impacts (see, e.g. [1-5]). These efforts have typically focused on simply whether or not the inner (or 'pressure') walls of candidate multi-wall structural systems would be perforated. Numerous studies have concluded that the level of protection afforded a spacecraft by a multi-wall structure significantly exceeds the level provided by an equal weight single wall of the same material. However, the nature and extent of pressure wall damage in the event of a penetration have only recently begun to be explored [6].

In addition to a hole, the pressure wall of a dual-wall structure impacted by a high speed particle can also experience cracking and petalling ([3,5,7]). If such cracking were to occur on-orbit, it is possible that unstable crack growth could develop and possibly lead to an unzipping of the impacted module [8]. Thus, it is imperative to be able to characterize the cracking phenomena associated with the penetration of the dual-wall systems being considered for the International Space Station Alpha (ISSA). While pressure wall cracking and petalling have been observed in several previous laboratory studies of multi-wall structures under high speed impact, a systematic characterization of cracking phenomena in the various ISSA module wall systems has yet to be performed.

This report presents the results of a study whose objective was to develop empirical models of effective hole size and maximum tip-to-tip crack length for the various multi-wall systems being developed for the ISSA. The significance of the work performed is that these models can be incorporated directly into a survivability analysis (see, e.g. [9,10]) to determine whether or not module unzipping would occur under a specific set of impact conditions. The likelihood of module unzipping over a structure's lifetime based on the environment to which it is exposed can also be determined in such an analysis. In addition, the prediction of effective hole size can be used as part of a survivability analysis to determine the time available for module evacuation prior to the onset of incapacitation due to air loss.

EXPERIMENTAL SET-UP AND DATA

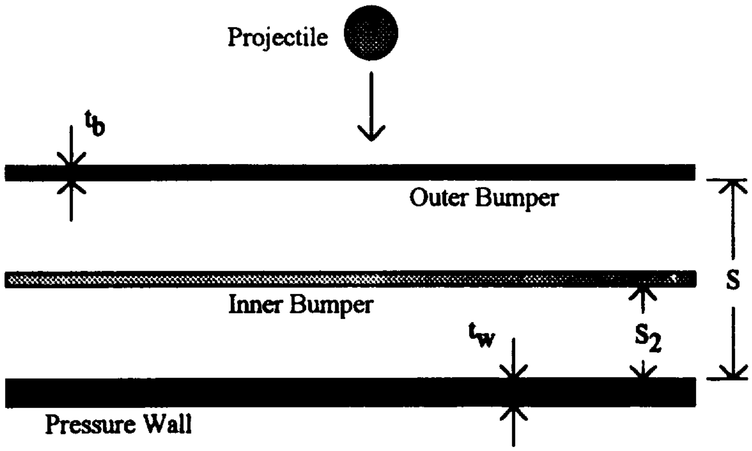

Figure 1. Hypervelocity Impact of a Multi-Wall Structure

Figure 1 shows the normal impact of a multi-wall structure impacted by a spherical projectile. In such a system, the outer and inner bumpers protect the pressure wall against perforation by causing the disintegration of the impacting projectile and the creation of a debris cloud which imparts a significantly lower impulse per unit area to the pressure wall. Table 1 contains the geometric and material parameters for the systems tested considered in this study. As noted in Table 1, 2/3-scale versions of the actual wall systems were occasionally used to allow the modeling of such systems under the impact of projectiles that are considerably larger than those which could be tested. In addition, the types of inner bumper specified in Table 1 are defined as follows.

Type A1,A2....aluminum 6061-T6 panel (A1 ... 0.125 in. thick, A2 ... 0.050 in. thick; used in 2/3 scale testing of two ESA module wall systems)
Type B............20 layers of MLI (areal density = 0.033 gm/cm^3)
Type C1..........6 layers of Nextel AF62 cloth backed with 6 layers of Kevlar 710 cloth (areal density = 0.80 gm/cm^3)
Type C2..........5 layers of Nextel AF62 cloth backed with 5 layers of Kevlar 710 cloth (areal density = 0.66 gm/cm^3)
Type C3..........4 layers of Nextel AF62 cloth backed with 4 layers of Kevlar 710 cloth (areal density = 0.53 gm/cm^3; used in 2/3 scale testing of configuration with a Type C1 inner bumper)

We note that in Table 1, for those tests conducted at 2/3 scale, the dimensions given in Table 1 are the test specimen dimensions; actual wall system dimensions can be obtained by multiplying the values given for the 2/3 scale tests by 3/2. The conditions of impact were chosen to simulate orbital debris impact of light-weight long-duration space structures as closely as possible and still remain within the realm of experimental feasibility. Kessler, et al. [11] state that the average density for orbital debris particles smaller than 1 cm in diameter is approx. 2.8 gm/cm^3, which is similar to that of aluminum. Therefore, aluminum 1100-0 was used as the projectile material in all of the tests.

Table 1. System Configuration Parameters

WALL TYPE	SCALE	OUTER BUMPER MAT'L	t_b (in)	INNER BUMPER TYPE	S (in)	S_2 (in)	PRESSURE WALL MAT'L	t_w (in)
US NODE	F	6061-T6	0.050	B	4.5	2.25	2219-T87	0.160
US LAB CYLINDER	F	6061-T6	0.050	B	4.5	2.25	2219-T87	0.188
ESA LAB CYLINDER	2/3	6061-T6	0.063	A1	3.4	1.0	2219-T87	0.080
ESA ENDCONE	2/3	6061-T6	0.063	A2	4.65	0.65	2219-T87	0.063
US NODE ENDCONE	2/3	6061-T6	0.032	B	5.81	4.81	2219-T87	0.150
US LAB ENDCONE	2/3	6061-T6	0.050	B	5.81	4.81	2219-T87	0.125
ENHANCED US LAB CYLINDER	2/3	6061-T6	0.050	C3	3.0	1.5	2219-T87	0.125
ENHANCED JEM CYLINDER	2/3	6061-T6	0.032	C3	3.0	1.5	2219-T87	0.080
JEM CYLINDER	F	6061-T6	0.050	B	4.5	2.25	2219-T87	0.125
FGB CYLINDER	F	5456-0	0.080	C2	4.0	2.0	5456-0	0.063
SERVICE CYLINDER	F	5456-0	0.040	B	2.0	0.0	5456-0	0.063
RESEARCH MODULE	F	6061-T6	0.040	B	2.2	0.0	5456-0	0.125
ENHANCED RESEARCH MODULE	F	6061-T6	0.040	C1	2.2	1.1	5456-0	0.125

Results from two test programs were used to develop empirical predictor equations for effective pressure wall hole diameter and maximum tip-to-tip crack length. The first test program was conducted at

NASA/MSFC. In this test program, 0.313, 0.375, and 0.438 in. diameter aluminum spheres were fired at multi-wall test specimens at a nominal velocity of 6.5 and at obliquities of 0, 45, and 65 degrees. A total of 126 shots were completed as part of this test program. The second test program was conducted at the White Sands Test Facility. In this test program, 0.375, 0.5, 0.625, and 0.688 in. diameter aluminum projectiles were fired at selected multi-wall test specimens at a nominal velocity of 6.5 and at obliquities of 0, 45, and 65 degrees. At total of 23 shots were completed as part of this test program.

EMPIRICAL PREDICTOR EQUATIONS

The empirical predictor equations for pressure wall hole diameter and maximum tip-to-tip crack length were all in the following format:

$$X = A\cos^{B}\theta\left[1-e^{-C\left(d_p/d_{BL}-1\right)}\right] \tag{1}$$

where we can write, for example, $X=D_h$ for hole diameter and $X=L_{tt}$ for maximum tip-to-tip crack length, respectively. In equation (1), d_p and θ_p are the diameter and obliquity of the impacting projectile while d_{BL} is the ballistic limit diameter at 6.5 km/s for the particular system under consideration under a θ_p-degree impact. Ballistic limit diameters for the various systems considered in this study were obtained using the equations given in References [12,13].

The form given by equation (1) was chosen for the two reasons. First, the quantity X, is zero when the projectile diameter equals the ballistic limit diameter. Second, the form of equation (1) represents the phenomenology expected to occur as the projectile diameter is increased beyond the ballistic limit diameter. The values of the constants A B, and C were obtained for each system considered using a simplex curve fitting algorithm; resultant values, as well as the correlation coefficients for each equation, are given in Table 2. As can be seen in this Table, the high correlation coefficients indicate a rather good fit to the experimental data. It is noted that since the left-hand-side of equation (1) is not non-dimensional, the units of D_h and L_{tt} as predicted by the constants in Table 2 will be the same as the constant A in those tables.

Table 2. Empirical Equation Information: Pressure Wall Hole Diameter

WALL	A	B	C	R^2

Table 3. Empirical Equation Information: Maximum Tip-to-Tip Crack Length

WALL TYPE	A (in)	B (—)	C (—)	R^2
US NODE	3.476	1.603	4.933	0.87
US LAB CYLINDER	3.869	1.041	2.772	0.81
ESA LAB CYLINDER	13.325	1.771	3.349	0.97
ESA ENDCONE	10.779	1.655	7.031	0.96
US NODE ENDCONE	3.847	0.973	4.293	0.96
US LAB ENDCONE	13.609	3.67	1.908	0.99
ENHANCED US LAB CYLINDER	10.219	0.226	178.09	0.91
ENHANCED JEM CYLINDER	14.554	0.177	80.797	0.89
JEM CYLINDER	8.021	4.007	4.287	0.99
FGB CYLINDER	46.813	1.920	0.197	0.99
SERVICE CYLINDER (Center)	10.714	1.448	0.110	0.98
SERVICE CYLINDER (On-rib)	36.996	0.945	0.0248	0.87
RESEARCH MODULE	1.926	0.498	9.518	0.79
ENHANCED RES. MODULE	7.612	0.565	6.308	0.99

COMMENTS AND OBSERVATIONS

The empirical equations obtained through the curve fitting exercise were plotted against empirical data for an impact velocity of 6.5 km/s; the projectile diameter was varied between one and five times the ballistic limit diameter. A review of these plots revealed some interesting information regarding the nature of the penetration phenomena that take place in each of the multi-wall systems considered.

Most notably, the nature of the inner bumper had a profound effect on the damage sustained by the pressure wall. Systems such as the LAB Cylinder and the JEM Cylinder sustained significantly larger holes when the MLI inner bumper in the baseline configuration was replaced by a Nextel/Kevlar inner bumper to yield the "enhanced" configuration. Thus, whereas the use of Nextel/Kevlar inner bumpers can increase the ballistic limit of such systems [14], this benefit must be balanced in any survivability analysis with possible increases in crew vulnerability due to increased leak rates following module wall perforation. It was also observed that the mounting of the Nextel/Kevlar inner bumper may have had an effect on the effective hole diameters and the maximum tip-to-tip crack lengths. Additional tests are planned at NASA/MSFC to quantify this effect.

ACKNOWLEDGMENTS

The author is grateful for the support provided by the NASA/ASEE Summer Faculty Fellowship Program and the NASA/MSFC Structural Developments Branch. The author would also like to acknowledge the work of Angela Nolen, Melanie McCain, and Mary Hovater (EH15) in performing the high speed impact tests at NASA/MSFC that made this study possible. Finally, the author is grateful to Joel Williamsen (ED52) for his many helpful suggestions during the course of this investigation.

REFERENCES

1. Maiden, C.J., Gehring, J.W., and McMillan, A.R., Investigation of Fundamental Mechanism of Damage to Thin Targets by Hypervelocity Projectiles, GM-DRL-TR-63-225, Santa Barbara, California, 1963.

2. McMillan, A.R., Experimental Investigation of Simulated Meteoroid Damage to Various Spacecraft Structures, NASA-CR-915, Washington, D.C., 1965.

3. Burch, G.T., Multi-plate Damage Study, AFATL-TR-67-116, Eglin Air Force Base, Florida, 1967.

4. Lundeberg, J.F., Stern, P.H., and Bristow, J.R., Meteoroid Protection for Spacecraft Structures, NASA-TM-54201, Washington, D.C., 1965.

5. Schonberg, W.P., Bean, A.J., and Darzi, K., Hypervelocity Impact Physics, NASA-CR-4343, Washington, D.C., 1991.

6. Schonberg, W.P., Cracking Characteristics of a Habitable Module Pressure Wall Following Orbital Debris Penetration, Final Report, NASA/ASEE Summer Faculty Fellowship Program, Marshall Space Flight Center, Huntsville, Alabama, 1994.

7. Schonberg, W.P., "Aluminum 2219-T87 vs. 5456-H116: A Comparative Study of Pressure Wall Materials in Dual-Wall Structures Under Hypervelocity Impact", *Acta Astronautica*, Vol. 26, No. 11, 1992, pp. 799-812.

8. Common Module Shell Unzipping Due to Meteoroid/Orbital Debris Strikes, Space Station Freedom Program Office, Report No. GSS-40.05-RPT-6-001, Reston, Virginia, 1994.

9. Williamsen, J.E., Vulnerability of Manned Spacecraft to Crew Loss from Orbital Debris Penetration, NASA-TM-108452, Marshall Space Flight Center, Alabama, 1994.

10. Micrometeoroid and Orbital Debris Induced Catastrophic Failure Prediction Methods, Space Station Freedom Program Office, Report No. GSS-40.05-RPT-6-003, Reston, Virginia, 1994.

11. Kessler, D.J., Reynolds, R.C., and Anz-Meador, P.D., Orbital Debris Environment for Spacecraft Designed to Operate in Low Earth Orbit, NASA-TM-100471, Houston, Texas, 1988.

12. Christiansen, E.L., "Design and Performance Equations for Advanced Meteoroid and Debris Shields", *International Journal of Impact Engineering*, Vol. 14, pp. 145-156, 1992.

13. Christiansen, E.L., *Private Communication*, 1995.

14. Christiansen, E.L., Crews, J.L, Williamsen, J.E., Robinson, J.H., and Nolen, A.M., "Enhanced Meteoroid and Orbital Debris Shielding", *International Journal of Impact Engineering*, Vol. 17, 1995.