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A DISCUSSION OF THE MODES OF FAILURE OF BUMPER-HULL STRUCTURES WITH APPLICATION TO THE METEOROID HAZARD

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16. Abstract

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Also, it is concluded that if the sheet-thickness ratios are selected according to both high- and low-speed results (observing the above thickness-ratio minimums), and the sheet spacing is selected according to low-speed results, the structure will perform satisfactorily for all probable impact conditions.

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SYMBOLS

d	projectile diameter, mm
h	spacing between bumper and hull, mm
t_1	bumper thickness, mm
t_2	hull thickness, mm
v	impact velocity, km/sec

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SUMMARY

The impact of double-sheet structures is discussed, and typical impact-performance curves, determined by the physical processes by which the rear sheet fails, are defined. It is concluded that, in order for a bumper-hull system to perform effectively, the front- and rear-sheet thicknesses must be larger than certain minimum limits. Tentative values for these limits are: the front sheet should be thicker than 0.25 times the diameter of the largest probable meteoroid; the rear sheet should be thicker than 0.50 times the diameter of the largest probable meteoroid; and the rear sheet should be thicker than the front sheet.

Also, it is concluded that if the sheet-thickness ratios are selected according to both high- and low-speed results (observing the above thickness-ratio minimums), and the sheet spacing is selected according to low-speed results, the structure will perform satisfactorily for all probable impact conditions.

INTRODUCTION

Future planetary missions, deep space probes, and earth-orbiting laboratories are expected to involve flights of relatively large vehicles for long periods of time; many of these flights will traverse the asteroid belt. These factors increase the meteoroid hazard to spacecraft, making it necessary to consider some means of protecting a spacecraft from meteoroid impact.

In 1947, Whipple suggested that "meteor bumpers" could be used to minimize the damage caused by the impact of meteoroids (ref. 1). The validity of this concept has subsequently been verified by experimental impact tests in which the effects of several variables on bumper performance have been investigated. In general, it has been observed that the penetration resistance of a double-sheet (bumper-hull) structure increases with increasing total thickness of the sheets, as well as with sheet spacing, and is strongly dependent on the physical state and distribution pattern of the material emanating from the rear of the bumper (refs. 2-5). However, the usefulness of this information in the design of an optimum bumper-hull structure is rather limited because existing sets of published experimental data are for different velocity regimes and have not been correlated. However, it appears that, for a given impact velocity and given projectile and target materials, an optimum ratio of front-sheet thickness to projectile diameter exists (refs. 5 and 6).

Recently, spacecraft designers have expressed concern that even if a meteor bumper is designed to the optimum thickness for a given impact probability, the impact of meteoroids with properties other than those used to calculate the optimum design (e.g., smaller and/or slower) will cause failure of the structure (e.g., ref. 7). In particular, failure to melt or vaporize the front-sheet material may result in rear-sheet perforations by the individual particles in the meteoroid-bumper debris.

The purpose of this report is to discuss the various modes of failure of double-sheet structures. It will be shown that the seeming disagreement in the published experimental data is a natural consequence of the variation in test conditions for the different experiments, supplemented by variations in the criterion used to assess performance. In other words, the experimental results are found to be consistent when they are evaluated within the framework of the unified double-sheet concept presented here. This concept shows that there is a continuous mechanism between low- and high-speed impact which allows for the design of a minimum weight structure that will resist the impacts of smaller and slower meteoroids than those considered for the high-speed design.

DISCUSSION

As used here, high speed refers to velocities sufficiently high that the projectile and bumper are either broken into very fine fragments,[1] melted, or vaporized upon impact. At the present time, there is no single theory for impacts at all velocities that permits the design of a structure to perform efficiently under high- and low-speed impacts. This situation can be remedied by giving attention to the physical changes, including changes in the type of damage to the rear sheet, that occur during impact as the impact conditions vary.

Consider the penetration resistance of a structure comprised of two sheets of 2024-T3 aluminum with front- and rear-sheet thickness to projectile diameter ratios (t_1/d and t_2/d) of 0.50, as shown by the data in figure 1. The impact velocity v is plotted against the separation distance h between the front and rear sheets divided by the projectile diameter d. In this figure, and in subsequent similar figures, a logarithmic coordinate system is used so that the trends of the data throughout the various impact regimes are readily apparent. For these tests, the projectiles were 3.28-mm-diameter pyrex glass spheres with a density of 2.23 gm/cm^3. Since the projectile diameter was not varied, any projectile size effects are not evident. The projectile diameter is used in this report as a normalization factor for the sheet thicknesses and the separation distance, and the results do not imply the absence of a scale effect such as that observed in reference 8. The data in figure 1 include some of the highest velocity data from reference 2 as well as results from recent tests. The closed symbols denote failure, and the open symbols denote no failure. An impact failure occurs when the rear sheet of a structure is damaged so that it will no longer hold a pressure difference of 1 atmosphere without leaking. The trends shown are of considerable value in understanding the mechanisms involved in structural impact failures and in relating structural impact performance to the various test conditions.

For impacts that occur at low velocities (less than about 3.0 km/sec in fig. 1), the velocity required to cause failure increases slowly as the sheet spacing increases. Thus, increasing the sheet spacing is advantageous even for low-velocity impacts. The implications of this effect will be discussed in more detail later. For certain sheet spacing ratios, the velocity that causes failure is

[1]The exact velocity at which this process occurs depends on the mechanical and physical properties, as well as the dimensions, of both the projectile and bumper. A typical value for this velocity for an aluminum bumper impacted by a glass projectile and a bumper thickness to projectile diameter ratio of 0.50 is about 6.0 km/sec.

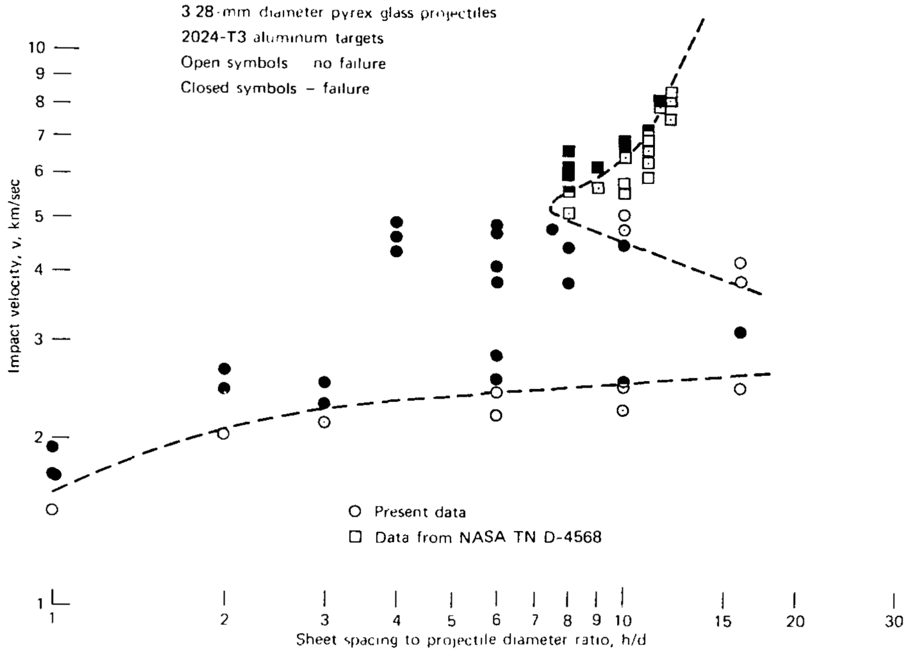


Figure 1.– Penetration resistance of an aluminum double-sheet structure with front- and rear-sheet thickness to projectile diameter ratios of 0.50.

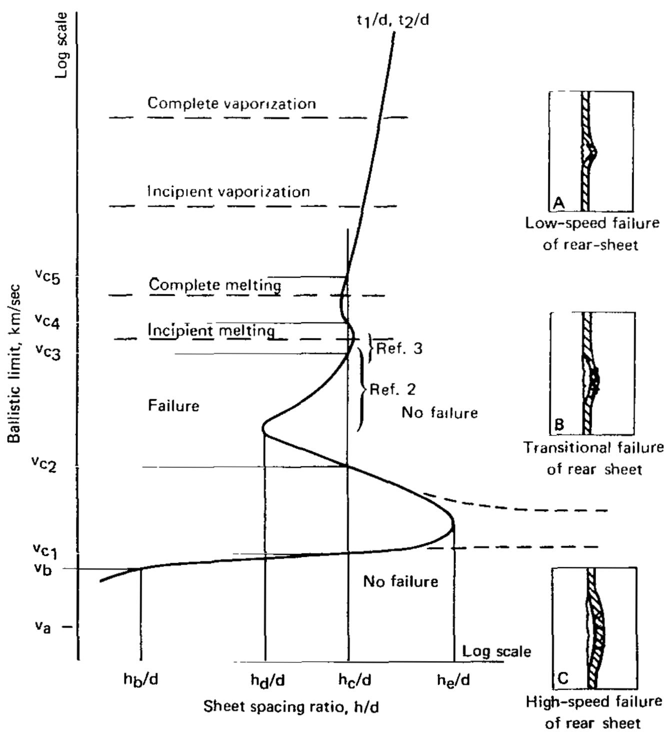
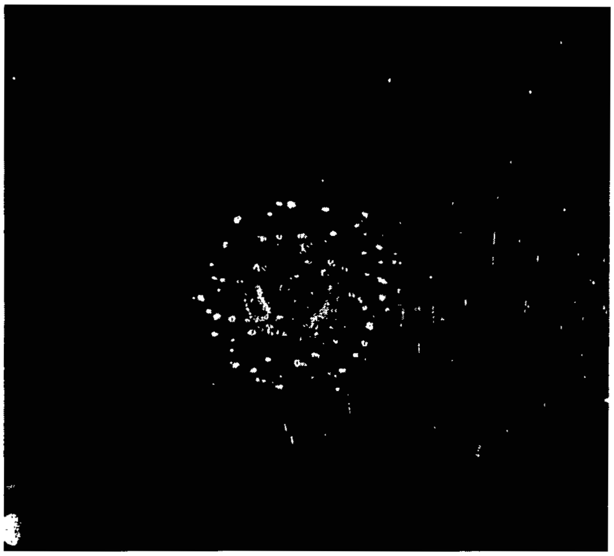


Figure 2.– Hypothetical impact performance curve for double-sheet structures.

double-valued, and there is a range between the two failure velocities in which failures do not occur. The data in figure 1 clearly show the occurrence of this phenomenon at $h/d = 10.0$. For this ratio the structure fails for the first time at an impact velocity of 2.5 km/sec. It continues to fail as the velocity increases further until a velocity of 4.6 km/sec, when failure ceases. The structure does not fail again until the velocity is increased to about 6.4 km/sec. Thus, the structure goes through several fail-and-no-fail regimes as the impact velocity increases. This same phenomenon is observed for a number of other ratios of h/d (most notably, an $h/d = 8.0$), and the observations are consistent with those for $h/d = 10.0$. Clearly, some physical changes in the bumper spray material that occur as the impact velocity is increased must cause this phenomenon.

Figure 2 presents a hypothetical impact performance curve for a representative double-sheet (bumper-hull) structure. The ballistic limit of the structure (i.e., the impact velocity required to cause failure) is plotted against the sheet spacing ratio. A curve in these coordinates may be drawn for each double-sheet structure; and the curve will be continuous as shown by the solid line, discontinuous as shown by the dashed extensions to the solid lines, or restricted to low-velocity impacts to the extent that the portion of the curve above the lower dashed line does not exist. The corresponding curves for structures with different total sheet thicknesses and/or different material mass distributions between the front and rear sheets would be displaced somewhat but, for the present purposes, it is the shape of the curves that we wish to emphasize. The region to the left of the curves represents conditions at which failure of a structure occurs, whereas the region to the right of the curves denotes the no-failure conditions.

(a) Spray cluster.



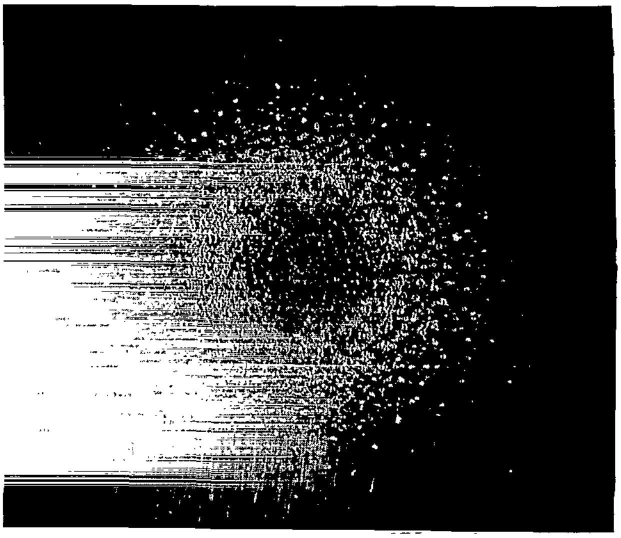
(b) Rear-sheet damage.

Figure 3.– Characteristic features of low-speed impact.

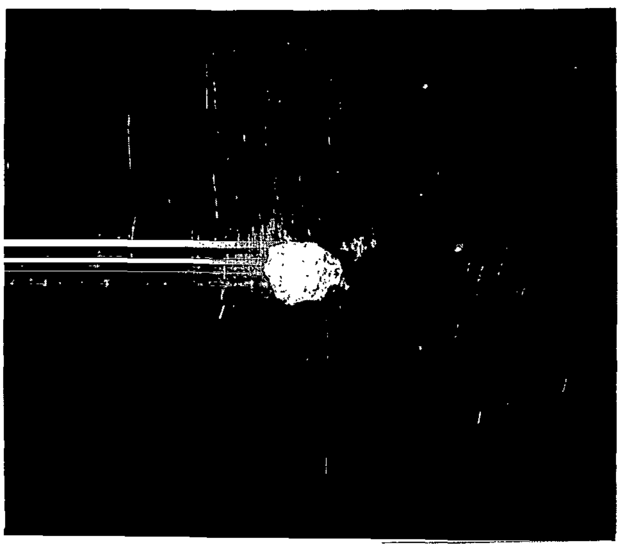
When the spacing is zero, the structure fails at an impact velocity v_a near that required to penetrate a single sheet of material of thickness equal to the total sheet thickness of the structure. If the velocity remains the same and the two sheets are separated, for example, to h_b, the structure is no longer penetrated because the projectile and corresponding bumper material, which have broken into a number of fragments, are dispersed over a somewhat larger area of the rear sheet. Thus, a higher velocity, v_b, is required to penetrate the structure. Within this velocity range, the fragmenting capability of the bumper is very limited and the projectile and bumper material tend to form a cluster of fairly large fragments, as shown in figure 3(a). Failure of the rear sheet tends to result from a punching-out process or penetration by the interfering impacts of a number of the large projectile and bumper fragments, as shown in figure 3(b) and schematically illustrated in insert (A) in figure 2. Further increases in spacing require increases in impact velocity, not only because of the dispersal of spray debris over larger areas of the rear sheet but also because the fragments are broken into smaller and smaller bits as the velocity increases. Eventually, the spacing must become so large that the spray fragments will impact the rear sheet as individual particles and there will be no collective cratering effects. If the particles are very small and their velocities are too low for them to penetrate the rear sheet, then the impact performance of the structure will be represented by the solid curve in figure 2. On the other hand, if the individual particles can penetrate the rear sheet, the structure's impact performance curve will be discontinuous, as shown by the dashed extensions to the solid curve. The impact conditions that lead to this situation will be discussed later.

Although the fragments become smaller as the impact velocity increases, the velocities of the individual particles also increase. Each of these particles produces a shock wave in the rear sheet. At some impact velocity the cumulative effects of the shock waves produced by each of the impacting particles will spall material from the rear surface of the rear sheet, thereby weakening it. In addition, as each of the particles impacts the rear sheet, material is ejected from the front face of the sheet. These effects create a force that acts more or less like a pressure loading on the sheet, tending to rupture it.

Now consider the failure of a structure with a constant spacing h_c as the impact velocity is increased from zero. At a velocity of v_{c_1}, the spray particles collectively perforate the rear sheet (i.e., low-speed failure). As the impact velocity increases above v_{c_1}, the spray particles become smaller and, because of their slightly higher velocities, are still able to penetrate the rear sheet. At v_{c_2}, the particles become so small that, even though their velocities are higher, they cannot penetrate the rear sheet and the structure no longer fails. However, within the velocity range from v_{c_2} to v_{c_3}, the combined strength of the shock waves produced in the rear sheet by the particle impacts increases so that material is spalled from the rear surface of the rear sheet. As the velocity increases within this range, more and more material is spalled from the rear sheet until finally, at v_{c_3}, the target fails once again. This time, the rear sheet fails because of the combined effects of particle cratering, rear-sheet spallation, and the impulsive load applied to the front of the rear sheet. This behavior defines what we shall call a transitional failure and is generally characterized by small cracks radiating outward from the center of the damaged area, clearly indicating the rupturing effect of the pressure on the rear sheet. Figures 4(a) and (b) are photographs of the front and rear surfaces of a rear sheet that failed in this manner. This transitional failure is illustrated schematically in insert (B) in figure 2. Note that for structures



(a) Front surface of rear sheet.

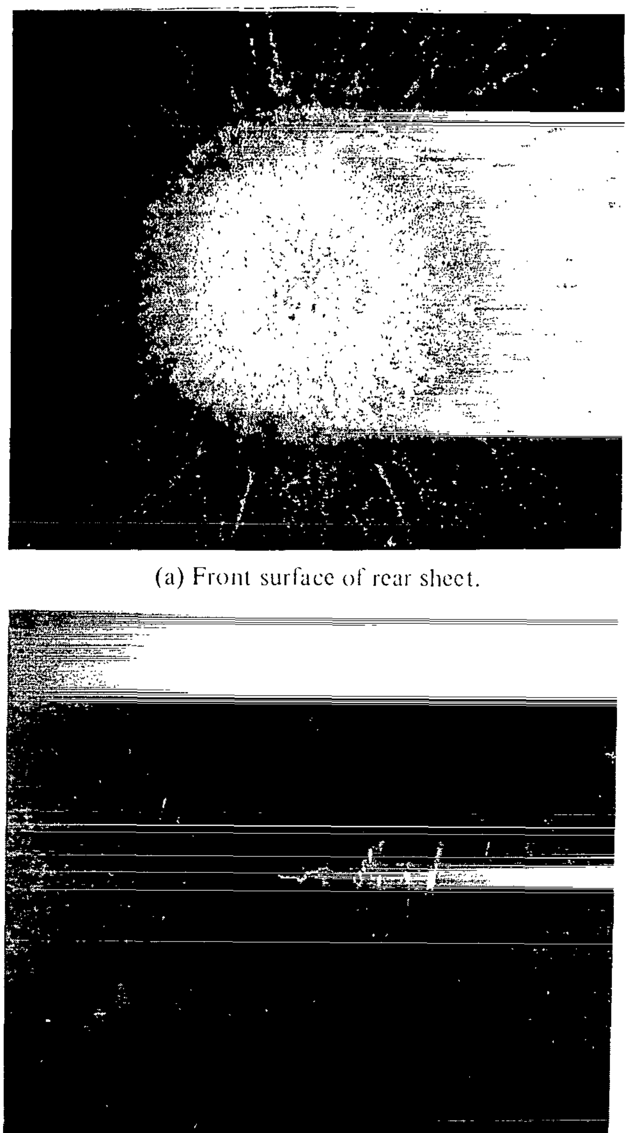


(b) Rear surface of rear sheet.

Figure 4.– Characteristic features of transitional failure damage.

with spacings less than h_d, once the velocity for low-speed failure has been exceeded, one or the other of the failure modes will cause failure at all higher impact velocities; and for structures with spacings greater than h_e, the spacing is always large enough to prevent failure according to either the low-speed or transitional-failure criterion for those structures with continuous impact-performance curves. For structures with discontinuous curves, there will be a velocity range in which individual particles will always penetrate the structure, as represented by the region between the dashed curves.

Although data for defining the impact performance curve at velocities above v_{c_3} are very limited, the curve has been extended into this velocity range on the basis of observations and the rationale that follows. As the impact velocity increases above v_{c_3}, the impact pressures generated in the projectile and the bumper also increase. Ultimately, these pressures must get so high that the internal energy of the materials after they have returned to zero pressure is sufficient to melt some of the projectile or bumper or both, depending upon the heat of fusion of the materials involved (refs. 9 and 10). With further increases in impact velocity, more and more material melts and individual particles become smaller with resulting shallower crater depths even though the specific energy of the spray debris has increased. Consequently, the shock wave produced in the rear sheet by the impacting particles has propagated only a short distance when the rarefaction waves from the free surfaces of the particle and rear sheet start to attenuate it. The net result is that, although the initial shock-wave strength for the melted spray case may be greater than that for the unmelted spray case, the relieving rarefaction waves overtake the shock wave sooner causing it to be reduced in strength by the time it reaches the rear surface to the extent that rear surface spallation tends to be reduced. At v_{c_4}, rear-sheet cratering should be negligible and the other contributions to failure may not be sufficient to cause the rear sheet to fail. As the impact velocity increases, the impulsive loading on the rear sheet gradually increases and the structure should eventually fail again at an impact velocity of v_{c_5}. This type of failure defines the high-speed failure mode and is depicted in insert (C) in figure 2 and is shown in figure 5. With further increases in impact velocity, the residual internal energy of the projectile and bumper-spray material increases,



(a) Front surface of rear sheet.

(b) Rear surface of rear sheet.

Figure 5.- Characteristic features of high-speed failure damage.

additional melting and heating take place, and the structure should continue to fail according to the high-speed failure mode. Eventually, vaporization will occur, and it may well be that an ultra-high-speed failure mode will define failures within this regime.

This model helps to explain some of the variations in current ballistic-limit results. As an example, the highest velocity data of references 2 and 3, where extrapolations of the ballistic limit curves are observed to vary with the square and the fifth power of the sheet spacing, represent transitional-mode failures for different degrees of spray-debris melting. The general failure regimes that these data include are shown in figure 2. On the other hand, the data of references 6 and 7, which were acquired at a constant impact velocity and represent a large range of sheet thicknesses, include failures by both the transitional and low-speed modes. This distinction between the failure modes of structures was not considered, however, when the data were correlated.

The previous remarks have been directed toward the failure of a double-sheet structure with a "brittle" rear sheet. The impact-performance curve for a structure with a "ductile" rear sheet will probably have different characteristics since the results of Fish and Summers (ref. 11) show that spallation is drastically reduced by ductility. At low speeds, however, the failure of "ductile" rear sheets should be comparable to that of "brittle" rear sheets since rear-surface spallation is not a factor in either case. The impact velocity required to penetrate equally thick brittle and ductile structures with the same sheet spacing should be somewhat lower for structures with ductile rear sheets, provided the yield strength of a brittle material is higher than that of a ductile material. As the impact velocity increases, however, and rear-surface spallation becomes a factor for brittle sheets, the ductile rear sheet may be able to resist a velocity that will defeat the brittle rear sheet. At impact velocities sufficiently high that there is little solid material in the spray debris, rear-surface spallation, once again, is not a factor and brittle rear sheets might be expected to perform somewhat better than ductile rear sheets. Rear-sheet ductility, which determines the mode of failure, and yield strength, which determines the impact conditions required to cause failure, are believed to be the most important material properties in rear-sheet performance although other material effects are probably present.

The performance curves just described have several important limitations regarding their general applicability. For example, if the front-sheet is so thin that the shock wave produced in the projectile by the initial impact is completely attenuated by the free-surface rarefaction waves regardless of the impact velocity, then a portion of the projectile will always remain undamaged and will cause failure of the rear sheet according to the low-speed failure mode. In this case, sheet spacing is almost totally unimportant since the projectile is not properly fragmented but is just reduced in size. Information presented in reference 9 indicates that this minimum allowable ratio of t_1/d decreases with increasing impact velocity and that 0.12 appears to be a reasonable average. However, a more conservative value is about 0.25.

Another limitation concerns the thickness of the rear sheet. When a bumper is impacted at high velocity, most of the damage to the rear sheet is contained within a relatively well-defined circular area. The debris that caused this damage may be solid, liquid, or vapor, or any combination of these phases. However, even when most of this material is vaporized, small solid particles are ejected at low velocities and large inclinations onto the rear sheet during the late stage of hole formation in the bumper. If the rear sheet is so thin that these late-stage fragments can penetrate the rear sheet, the structure will always fail according to the low-speed failure mode, and the upper portion of the structure's impact performance curve will not exist. Furthermore, when the projectile velocity is low, large fragments of projectile and bumper are produced as has been stated earlier. If the rear sheet is so thin that these fragments can individually perforate it, then sheet spacing will have no effect, and the performance curve will be discontinuous. From the tests presented in references 2 and 3 it appears that these situations do not occur when the rear sheet is thicker than 0.50 times the projectile diameter and the rear sheet is thicker than the front sheet. (Note that the values for these limits are based on observations of tests that were not particularly intended to assess these limits. It is expected that when relevant tests are completed, the values will differ somewhat from those given here. Moreover, it is thought that the minimum rear-sheet thickness will be determined from low-speed penetration effects, consequently, late-stage fragment penetrations will not occur.)

It is clear from the foregoing discussion that different projectile (as well as bumper) properties are important during different impact velocity regimes. This fact becomes critical when a projectile to be tested in the laboratory is to be representative of meteoroids. In particular, if an experimental program is to investigate the effects of low-velocity meteoroid impacts, the test projectile must shatter and fragment in a manner similar to that expected of a stoney or low-density meteoroid. Test projectiles are therefore limited to rather fragile materials such as glass, stone, or some low-density composite. However, for impacts at high velocities, energy considerations become important, and materials that will melt and vaporize at laboratory impact velocities are probably more representative of meteoroids.

The performance-curve limitations given provide a first step toward the design of an efficient bumper-hull system; namely, the front sheet should be thicker than 0.25 times the diameter of the largest probable impacting meteoroid; and the rear sheet should be at least as thick as the front sheet and thicker than 0.50 times the meteoroid diameter. Since one can calculate from the available meteoroid size distribution models the largest expected mass for a given encounter probability, the bumper and hull thickness should be based upon the diameter of this meteoroid within the limits just noted. It is then necessary to show, as we will below, that the proper design of a bumper-hull system will accommodate impacts that deviate from the optimum design conditions, namely those of meteoroids with lower velocities or smaller diameters than expected.

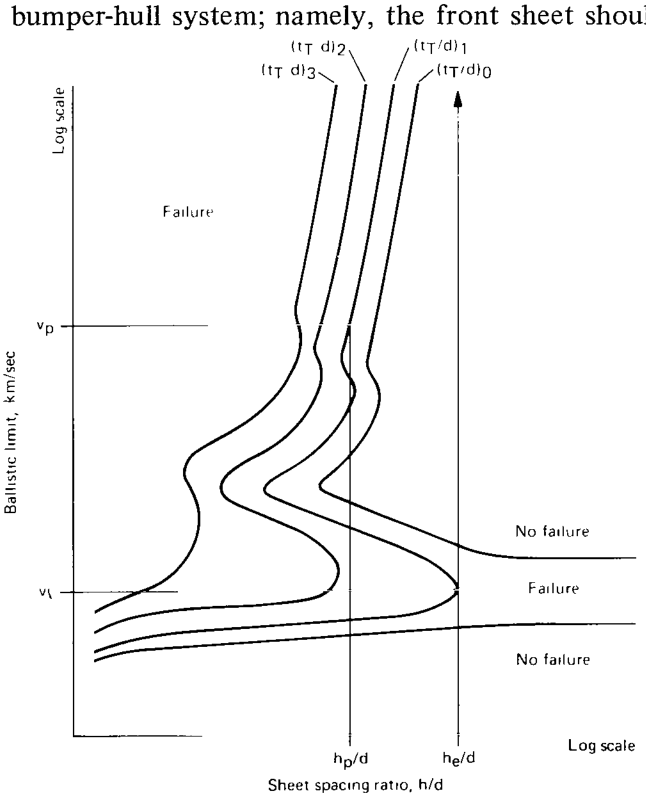


Figure 6.– Family of double-sheet impact performance curves for various sheet thickness ratios.

Figure 6 presents a family of hypothetical performance curves. These curves may represent structures with a constant front-sheet thickness and varying rear-sheet thickness, or, conversely, structures with a constant rear-sheet thickness and varying front-sheet thickness.

Data that define portions of the curves within the transitional-failure mode regime for several different front- and rear-sheet thickness ratios have been presented in references 2, 3, and 12, from which it is concluded that for a given sheet spacing, the ballistic limit increases with increasing total sheet thickness. The increase is strongly dependent upon how the increased thickness is distributed; in particular, it appears that the maximum increase in structural impact performance is obtained by increasing the thickness of only the rear sheet.

In figure 6, $(t_T/d)_3 > (t_T/d)_2 > (t_T/d)_1 > (t_T/d)_0$. The curve for the structure denoted by $(t_T/d)_0$ is discontinuous because it is not above the minimum thickness limits given earlier. Obviously, the optimum structure will have the least mass per unit area in the total sheet thickness and still exhibit a continuous impact-performance curve. In figure 6, the optimum structure is represented by the $(t_T/d)_1$ curve. If the probable meteoroid velocity, v_p, is interpreted as the required ballistic limit of the structure, then the $(t_T/d)_1$ performance curve immediately sets the required sheet-spacing ratio at h_p/d. This structural design represents the bumper-hull system that is designed to the optimum condition for high-velocity impacts. Now, consider the impact of a meteoroid of the same diameter but with a lower velocity, say, v_ℓ. From figure 6, it is evident that this impact would cause the structure to fail according to the low-speed failure mode. If, however, the sheet spacing is increased from h_p to h_e, this failure will not occur since, as was shown earlier, this spacing is always large enough to prevent failure by either the low-speed or transitional failure criterion. Thus, a structure can be designed to accommodate impacts of both low-speed and high-speed meteoroids by selecting sheet-thickness ratios from structures with continuous impact performance curves and the sheet-spacing ratio according to low-speed results, that is, h_e/d for the particular thickness ratio selected. This procedure actually corresponds to designing a structure to resist penetrations by meteoroids with velocity, v_e, which is higher than the probable velocity, v_p. If the probable meteoroid velocity is higher than v_e, then low-speed impact is not a problem because the sheet-spacing ratio required to resist high-speed impacts is greater than h_e/d. Moreover, if other structural considerations require that inefficient structures (those with discontinuous impact performance curves) must be used, then one can include the probability of impact by a meteoroid at a velocity within the range required to penetrate the structure in the total failure probability calculations. It may well be that when a total probability of penetration is calculated for a particular vehicle and a specific mission, the optimum structure in terms of weight and overall performance will have a discontinuous impact performance curve.

The final consideration involves the more probable impacts of meteoroids of smaller diameters than the maximum. In these cases, since the actual sheet thicknesses remain the same, any decrease in the meteoroid diameter causes the relevant performance curve to be shifted to a larger ratio of $(t_T/d)_i$, that is, to one of the curves to the left of $(t_T/d)_1$. Also, the sheet spacing, h_e, has been fixed by the original design and a decrease in the meteoroid diameter increases the effective spacing ratio of the structure. Figure 6 clearly shows that this increase in the h/d ratio prevents the failure of structures with ratios of $(t_T/d)_i$ larger than $(t_T/d)_1$.

Thus, a bumper-hull structure designed by the technique described will resist penetration under all meteoroid impact conditions which are more likely to occur than those included in the probability calculation. This technique, however, requires impact performance curves for materials of interest over a broad velocity range. Unfortunately, this type of information is very limited at the present time. A great deal of the needed data can be obtained at low-test velocities, well within the capability of present experimental facilities. Additional research toward this end should be conducted with particular emphasis upon the effects of rear-sheet strength and ductility upon structural ballistic limits. Eventually, it should be possible to evaluate the impact performance of more complicated structures, for example, incorporating fillers or honeycomb between the front and rear sheet, in the same way.

CONCLUSIONS

For the design of double-sheet (bumper-hull) meteoroid protection system, it is useful to consider impact-performance curves for which ballistic limit velocity is plotted as a function of the sheet spacing to projectile diameter ratio, at constant sheet thickness. Emphasis is placed on the physical processes by which the rear sheet fails, which, in turn, depend primarily on the rear-sheet ductility and strength. In general, failure of a "brittle" rear sheet is the result of: (1) individual particle cratering for low-speed impacts; (2) the combined effects of individual particle cratering, rear-surface spallation, and impulsive loading for medium-velocity impacts; and (3) the effects of impulsive loading for high-speed impacts. For "ductile" rear sheets, the contribution of rear-surface spallation to rear-sheet failure may be reduced and structural failure and impact performance may be altered accordingly.

In order for a bumper-hull system to perform effectively, the front- and rear-sheet thicknesses must be larger than certain minimums. Tentative limits are: (1) the front sheet should be thicker than 0.25 times the diameter of the largest probable meteoroid; (2) the rear sheet should be thicker than 0.50 times the diameter of the largest probable meteoroid; and (3) the rear sheet should be thicker than the front sheet.

It is concluded that if a double-sheet structure is designed to the optimum sheet-thickness ratio based upon the continuity of the structure's impact performance curve and the sheet spacing as determined from the low-speed maximum, then the structure will perform satisfactorily for all probable impact conditions.

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REFERENCES

1. Whipple, Fred L.: Meteorites and Space Travels. Astronomical J., no. 1161, Feb. 1947, p. 131.
2. Nysmith, C. Robert: Penetration Resistance of Double-Sheet Structures at Velocities to 8.8 km/sec. NASA TN D-4568, 1968.
3. Nysmith, C. Robert: An Experimental Impact Investigation of Aluminum Double-Sheet Structures. AIAA Paper 69-375, 1969.
4. Swift, Hallock F.; and Hopkins, Alan K.: The Effects of Bumper Material Properties on the Operation of Spaced Hypervelocity Particle Shields. AFML-TR-68-257, Sept. 1968.
5. McMillan, A. R.: Experimental Investigations of Simulated Meteoroid Damage to Various Spacecraft Structures. NASA CR-915, General Motors Corp., 1968.
6. Swift, Hallock F.; Carson, Lt. J. M.; and Hopkins, A. K.: Ballistic Limits of 6061-T6 Aluminum Bumper Systems. AFML-TR-67-324, Oct. 1967.
7. Cour-Palais, Burton, G.: Meteoroid Protection by Multiwall Structures. AIAA Paper 69-372, 1969.
8. Denardo, B. Pat; Summers, James L.; and Nysmith, C. Robert: Projectile Size Effects on Hypervelocity Impact Craters in Aluminum. NASA TN D-4067, 1967.
9. Maiden, C. J.; and McMillan, A. R.: An Investigation of the Protection Afforded a Spacecraft by a Thin Shield. AIAA Paper 64-95, 1964.
10. Bjork, R. L.; and Olshaker, A. E.: The Role of Melting and Vaporization in Hypervelocity Impact. RM-3490-PR, The Rand Corp., May 1965.
11. Fish, R. H.; and Summers, J. L.: The Effect of Material Properties on Threshold Perforation. 7th Hypervelocity Impact Symposium, Tampa, Florida, Nov. 1964.
12. Nysmith, C. Robert; and Summers, James L.: An Experimental Investigation of the Impact Resistance of Double-Sheet Structures at Velocities to 24,000 Feet Per Second. NASA TN D-1431, 1962.

NASA-Langley, 1970 —— 32 A-3562

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