N93-17299

1992

NASA/ASEE SUMMER FACULTY FELLOWSHIP PROGRAM

MARSHALL SPACE FLIGHT CENTER
THE UNIVERSITY OF ALABAMA

POST-IMPACT BEHAVIOR OF COMPOSITE SOLID ROCKET MOTOR CASES

Prepared By: Alton L. Highsmith

Academic Rank: Assistant Professor

Institution and Department: University of Alabama
Department of Aerospace Engineering

NASA/MSFC:

Office: Materials and Processes Laboratory
Division: Non-Metallic Materials Division
Branch: Polymeric Materials Branch

MSFC Colleague(s): Alan Nettles

In recent years, composite materials have seen increasing use in advanced structural applications because of the significant weight savings they offer when compared to more traditional engineering materials. The higher cost of composites must be offset by the increased performance that results from reduced structural weight if these new materials are to be used effectively. At present, there is considerable interest in fabricating solid rocket motor cases out of composite materials, and capitalizing on the reduced structural weight to increase rocket performance. However, one of the difficulties that arises when composite materials are used is that composites can develop significant amounts of internal damage during low velocity impacts. Such low velocity impacts may be encountered in routine handling of a structural component like a rocket motor case. The ability to assess the reduction in structural integrity of composite motor cases that experience accidental impacts is essential if composite rocket motor cases are to be certified for manned flight. While experimental studies of the post-impact performance of filament wound composite motor cases have been performed (1,2), scaling impact data from small specimens to full scale structures has proven difficult. If such a scaling methodology is to be achieved, an increased understanding of the damage processes which influence residual strength is required. The study described herein was an initial investigation of damage development and reduction of tensile strength in an idealized composite subjected to low velocity impacts.

Composite rocket motor cases are cylindrical structures which are fabricated using a filament winding process. When in service, these cylinders are subjected to internal pressures which give rise to tensile stresses in the longitudinal and hoop directions, with the stress in the hoop direction being dominant. The filament wound structure typically contains some combination of helical layers, hoop direction layers, and longitudinal layers. For the present study, it was not practical to fabricate filament wound specimens. Instead, 12 in. by 12 in. flat plate laminates fabricated from Fiberite T300/934 graphite epoxy prepreg tape were used to model the filament wound structure. A repeating pattern of layers similar to that found in filament wound cases was used. However, to reduce the complexity of the damage in this initial study, no counterparts to the longitudinal layers were included in the model structure. The stacking sequence chosen was $[0_4/(\pm 70)_2/0_4/(\pm 70)_2/0_2]_s$, where the 0° plies represent the hoop direction layers in the filament wound structure, and the 70° plies represent the helical layers in the filament wound structure.

A drop tower-type impact testing machine was used to impact the specimens. The specimens were 10 in. long by 3 in. wide, and were held in place by a pneumatic clamping fixture. The clamping plates contained 2.5 in. diameter holes which allowed the specimen to move out of plane during the impact. Impact energy was controlled by adjusting the height from which the crosshead assembly was dropped. Dynamic impact data was collected from the 0.25 in. diameter instrumented impact tup during impact. One important factor influencing the impact response of a solid rocket motor case is whether or not the case has been filled with propellant (3). It was expected that filled cases will develop less damage, since the propellant increases the overall rigidity of the structure. However, impact of the propellant-backed case may in fact be the most critical scenario since the propellant backing impedes the use of non-destructive techniques for damage assessment. For this reason, some specimens were impacted while backed with a 1.0 in. thick layer of inert propellant, and others were impacted without any backing. A solid steel clamping plate was used on the bottom (backing) side of the propellant-backed specimens.

The test matrix used to plan the experimental program in the present study is shown in Table 1. Based on some preliminary impact tests, three impact energies -- low (3.0 in.-lb.), intermediate (7.5 in.-lb.) and high (12.0 in.-lb.) were used. For each combination of impact energy and propellant backing, six specimens were impacted. Three of these specimens were loaded to failure in a tension testing machine in order to determine

Table 1. Test matrix used in designing the present study.

Propellant Backing	Low Impact Energy		Intermediate Impact Energy		High Impact Energy	
	Residual Strength	X-Ray Inspection	Residual Strength	X-Ray Inspection	Residual Strength	X-Ray Inspection
Backed	3	3	3	3	3	3
Unbacked	3	3	3	3	3	3

the residual tensile strength after impact. The other three specimens were treated with an x-ray dye penetrant, and then radiographed in order to determine what damage had been induced by the impact event.

Uniaxial tension tests were performed to assess strength reduction resulting from impact. The load was applied in the 0° (hoop) direction. Gripping tabs were applied to those specimens which were tested for tensile residual strength. The tabs were approximately 3.25 in. long by 3 in. wide. Some specimens were equipped with 0.1875 in. thick glass/epoxy composite tabs, while others were equipped with 0.25 in. thick aluminum tabs. The tabs were bonded to the specimens using a fast-acting cyanoacrylate adhesive. Generally, the glass/epoxy tabs and the aluminum tabs worked equally well. It was found that specimens that were tested shortly after the tabs were bonded failed at relatively low loads, and failure was associated almost entirely with the gripped region. A cure time of 16 hours or more was found to circumvent these premature failures.

As mentioned previously, some of the specimens were inspected via dye-penetrant enhanced x-ray radiography (4) after being impacted. The dye penetrant used was a zinc iodide solution (60 g zinc iodide, 10 ml. water, 10 ml. isopropyl alcohol, 10 ml. Kodak "Photo-Flo 200"). A small dam encircling the impact site was made using plumbers putty. This dam was filled with the zinc iodide solution, which was allowed to seep into the specimen for at least one hour. The dye penetrant filled those damage events (matrix cracks, delaminations) which it could flow into. The zinc iodide thus rendered these areas more opaque to x-rays that the surrounding undamaged regions. Three radiographs were taken of each specimen using different angles of incidence of the x-ray beam -- one with an angle of incidence of 82.5°, one with an angle of incidence of 90°, and one with an angle of incidence of 97.5°. The 90°, or normal incidence x-ray provided a planform view of damage in the specimen. The other two x-rays formed a stereo pair and, when viewed using a stereo viewer, provided a three dimensional view of damage in the specimen (4). Using such a stereo imaging process, it was possible to resolve the location of damage through the thickness of the specimen.

It is appropriate to note that the test matrix shown in Table 1 does not reference specimens that are tested for residual strength after x-ray inspection. There was some concern that the x-ray dye penetrant might affect the residual strength, and therefore the original plan required that specimens tested for residual strength should not be treated with x-ray dye penetrant. However, as mentioned previously, there were some premature failures attributed to an inadequate cure of the adhesive used to bond the gripping tabs to the specimens. Specimens used for damage inspection via radiography were used to provide residual strength data for the case of unbacked specimens subjected to low impact energy. Residual strengths obtained from these specimens were consistent with other residual strengths obtained in this study. Certainly this study was too limited to resolve the question of whether or not the dye penetrant affects residual strength. the original plan specimens tested for residual were not to be radiographed. However, resolution of this issue should be considered as part of some future study. If the dye penetrant were found not to affect the residual strength, the dye-penetrant enhanced x-ray technique could be safely used to inspect actual structural components.

Figure 1 shows residual strength versus impact energy for both backed and unbacked materials. All of the individual test results are presented in the figure. In order to obtain reference strength data, two specimens were tested for tensile strength without being subjected to any impact loading. The tensile strengths for these specimens correspond to the two solid circles plotted at zero impact energy. There is significant scatter in the tensile strength data. Some of this scatter can be attributed to the inherent variability of the composites, and some of this scatter has been attributed to the influence of the grips on failure. While all of the specimens represented in Fig. 1 exhibited significant damage development and growth within the test section during the tensile test, in many of the specimens, the final fracture occurred within the gripped regions. The use of longer test specimens with a streamlined (dogboned) test section would help reduce this data scatter.

The average residual strength data for each of the impact levels, indicated by the lines in Fig. 1, reveal some interesting trends. Neither the backed nor the unbacked specimens exhibit appreciable changes in residual strength resulting from the low and intermediate energy impacts. The backed specimens might show a slight reduction in residual strength after the high energy impact. On the other hand, the unbacked specimens exhibit a 10 percent reduction in tensile strength after the high energy impact. As expected, the unbacked specimens are more susceptible to tensile strength reduction after impact than the backed specimens.

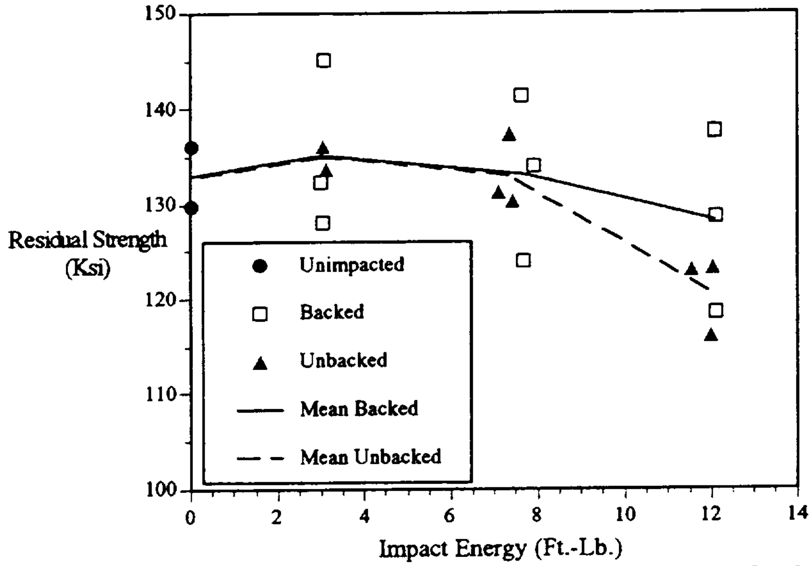
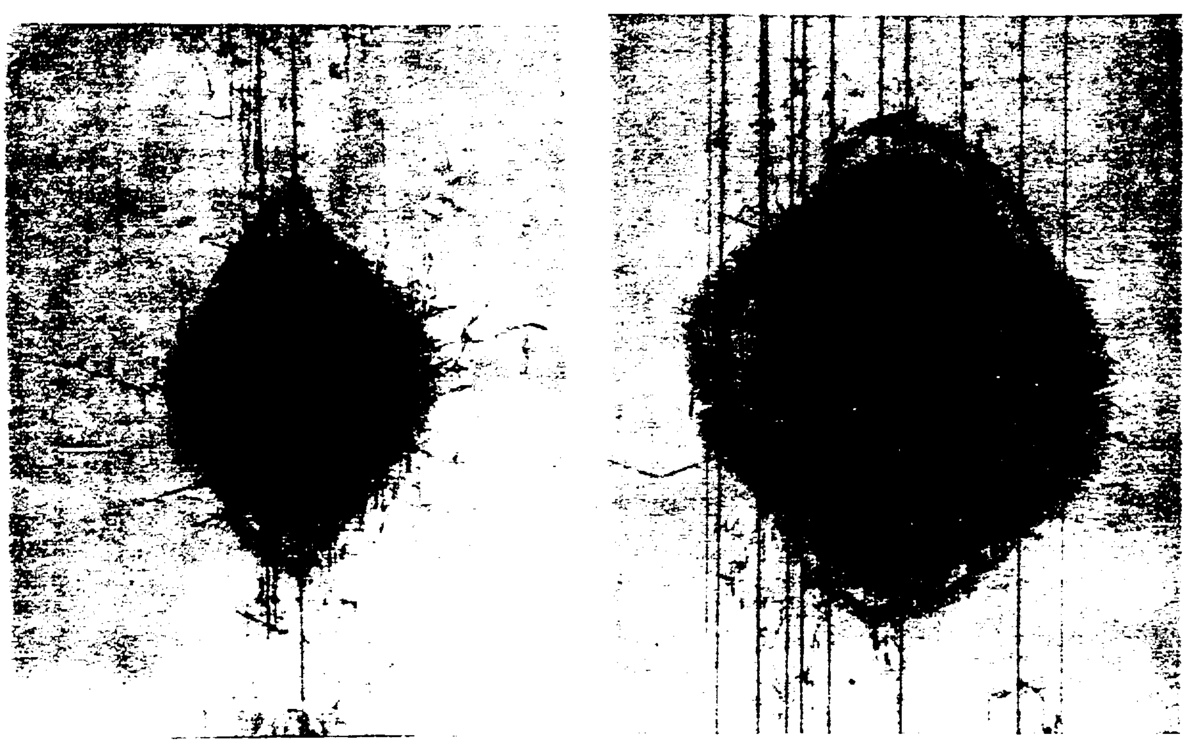


Figure 1. Plot of residual tensile strength versus impact energy for backed and unbacked specimens.

The inert propellant does provide sufficient reinforcement to limit the deflection of the composite, and hence reduce the effect of the impact.

Normal incidence x-ray radiographs taken from backed and unbacked specimens subjected to high energy impacts are presented in Fig. 2. The sharp lines that appear in the radiographs correspond to matrix ply cracks that were decorated with dye penetrant. Careful inspection of the radiographs reveals ply cracks in three different directions corresponding to the three different ply orientations. The most obvious ply cracks are



(a) (b)

Figure 2. X-ray radiographs of (a) backed and (b) unbacked specimens subjected to high energy impacts.

the long vertical cracks, or longitudinal splits, in the 0° layers. All of the 0° layers exhibit some splitting. Most of the damage is concentrated in the center of the specimen, around the impact site. The various shaded regions that form elliptical or "cloverleaf" shapes correspond to delaminations that were decorated with dye penetrant. Stereo imaging shows that damage near the impact site is distributed in a conical region radiating from the impact site through the specimen thickness.

As seen in Fig. 2, more extensive damage developed in unbacked specimens than in backed specimens for a given impact energy. Unbacked specimens showed significant damage development at all three impact energy levels. In contrast, specimens that were backed with inert propellant exhibited an impact energy threshold for damage development. None of the backed specimens showed damage development when subjected to the low energy impact. Of the three specimens which were subjected to the intermediate energy impact and then x-rayed, one specimen showed no damage development, one specimen showed very slight damage development, and one specimen showed significant damage development. All of the unbacked specimens developed damage patterns similar to that seen in Fig. 2a when subjected to the high energy impact.

What is most intriguing about the experimental results obtained in the present study is that some specimens that exhibited significant damage after impact showed little reduction in tensile residual strength. Radiographic inspection of unbacked specimens subjected to low and intermediate energy impacts, and backed specimens subjected to high energy impacts, indicated that significant damage was produced by the impact event. Although this damage was present, there was virtually no loss of tensile strength. What distinguishes the unbacked, high impact energy case, which did show a loss of tensile strength, from these other cases, is the presence of significant 0° fiber fracture at the impact site. In these specimens, a microscopic examination of the radiographs reveals lines of fiber fracture in the 0° layers, typically within the circular region of contact between the impacting tup and the specimen, which is at the center of the region of concentrated damage in the radiographs. Since the 0° fibers are the primary load carriers, it is not surprising that the tensile strength would decrease if a sufficient number of these fibers were fractured during impact. The ply cracks and delaminations which comprise most of the damage seen in the radiographs have little effect on tensile strength. In fact, some of this matrix damage develops during the failure process of initially undamaged material. It is important to note that stability issues make this matrix damage much more significant for residual compression response after impact.

As expected, composite specimens which were backed with inert propellant developed less damage during impact than specimens which were unbacked. Further, backed specimens showed a distinct impact energy threshold for damage development. Finally, as far as residual tensile response is concerned, the composite was found to be quite tolerant of matrix damage. Specimens with extensive ply cracking and delamination but little or no fiber fracture exhibited little or no reduction in tensile strength, while specimens with more extensive fiber fracture showed more pronounced reductions in tensile strength.

REFERENCES

1. Madsen, C.B., Morgan, M.E., and Nusimer, R.J., "Scaling Impact Response and Damage in Composites. Damage Assessment for Composites - Phase I Final Report," AL-TR-90-037, Hercules Aerospace Co. for Astronautics Laboratory, AFSC, Edwards AFB, CA, August 1990.

2. Morgan, M.E., Madsen, C.B., and Watson, J.O., "Damage Screening Methodology for Design of Composite Rocket Motor Cases," JANNAF Propulsion Meeting, Indianapolis, Feb. 1992.

3. Dombrowski, D.C. and Knight, G.K., "Residual Strength of Carbon/Epoxy Pressure Vessels Subjected to Low Velocity Impacts," Morton Thiokol, Inc./Strategic Operations, Brigham City, Utah.

4. Jamison, R.D., "Advanced Fatigue Damage Development in Graphite Epoxy Laminates," Ph.D. dissertation, Virginia Polytechnic Institute and State University, Aug. 1982.