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A Brief Overview of the Effects of Impact Damage to Rocket Motor Cases

A.T. Nettles
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September 2020

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National Aeronautics and
Space Administration

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PREFACE

Rocket motor cases are typically made of filament-wound composite structure and have been since the 1960s when glass and aramid fibers were mainly used. With the introduction of carbon fibers in the early 1980s and their use to make small pressure vessels, coupled with the concern with impact damage to carbon fiber aircraft components in general, some government laboratories raised a scare in the rocket motor industry that rocket motor cases made of carbon fiber may have poor damage tolerance based on their results from testing on small pressure vessels. Thus, an influx of funding, especially with the Space Shuttle filament-wound case being introduced, contributed to a wave of research into impact damage to rocket motor cases around this time. This Technical Memorandum gives a brief overview of some of these earlier studies with pertinent results.

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LIST OF ACRONYMS

FWC	filament-wound case
LAS	Launch Abort System
MSFC	Marshall Space Flight Center
MICOM	U.S. Army Missile Command
NDE	nondestructive evaluation
SHM	structural health monitoring
SLS	Space Launch System
TM	Technical Memorandum
TPS	thermal protection system
TTD	through-thickness delamination
VDT	visible damage threshold

TECHNICAL MEMORANDUM

A BRIEF OVERVIEW OF THE EFFECTS OF IMPACT DAMAGE TO ROCKET MOTOR CASES

1. INTRODUCTION

This Technical Memorandum (TM) presents pertinent results from past experimental work concerning impact damage to composite rocket motor cases. A rocket motor case in this TM refers to filament-wound pressure vessels of a substantial size intended to be used for launch vehicles, such as the new Space Launch System (SLS) rocket. In the early 1980s, as carbon fiber composites were becoming increasingly used on aircraft, concerns about the effects of foreign object impact damage grew, since the compressive strength properties of these composites could be severely affected by impact damage. The tensile properties were not as affected by foreign object impact damage which is fortunate for rocket motor cases as they are driven by tensile loads (burst strength). While great improvements to both carbon fibers and resins have resulted in far superior toughness values compared to the early generation of carbon/epoxy systems, the stigma of composite rocket motor cases being easily damaged and the burst strength compromised persists.

Since rocket motor case structures are driven by tensile loads and are relatively thick, they are actually robust structures with respect to impact damage resistance and tolerance. The author has often stated that if any part of a launch vehicle is to be made of composites and damage tolerance is a concern, then rocket motor cases are the one piece of hardware that should cause the least concern. While working on the Launch Abort System (LAS) rocket motor case of the SLS program, the author had a section of a full-scale rocket motor case in his laboratory at NASA Marshall Space Flight Center (MSFC) and invited program managers to come and beat on it with a hammer just to get a realistic idea of what impact levels these type of structures could withstand. Rather than shattering, as many expected, the hardest blows from the hammer could barely be noted (but most certainly could be heard). As part of the LAS rocket motor case damage tolerance study, impact events were video recorded so the author could demonstrate what a 150 ft•lb impact consisted of (and sounded like). A photograph of the impact apparatus used for the LAS rocket motor case program is shown in figure 1. Even at the early stages of this damage tolerance study some of the author’s colleagues were convinced that a 50 ft•lb impact would “punch a hole in the case,” when in reality this impact level was too low to produce any notable damage and was not even considered in that study.

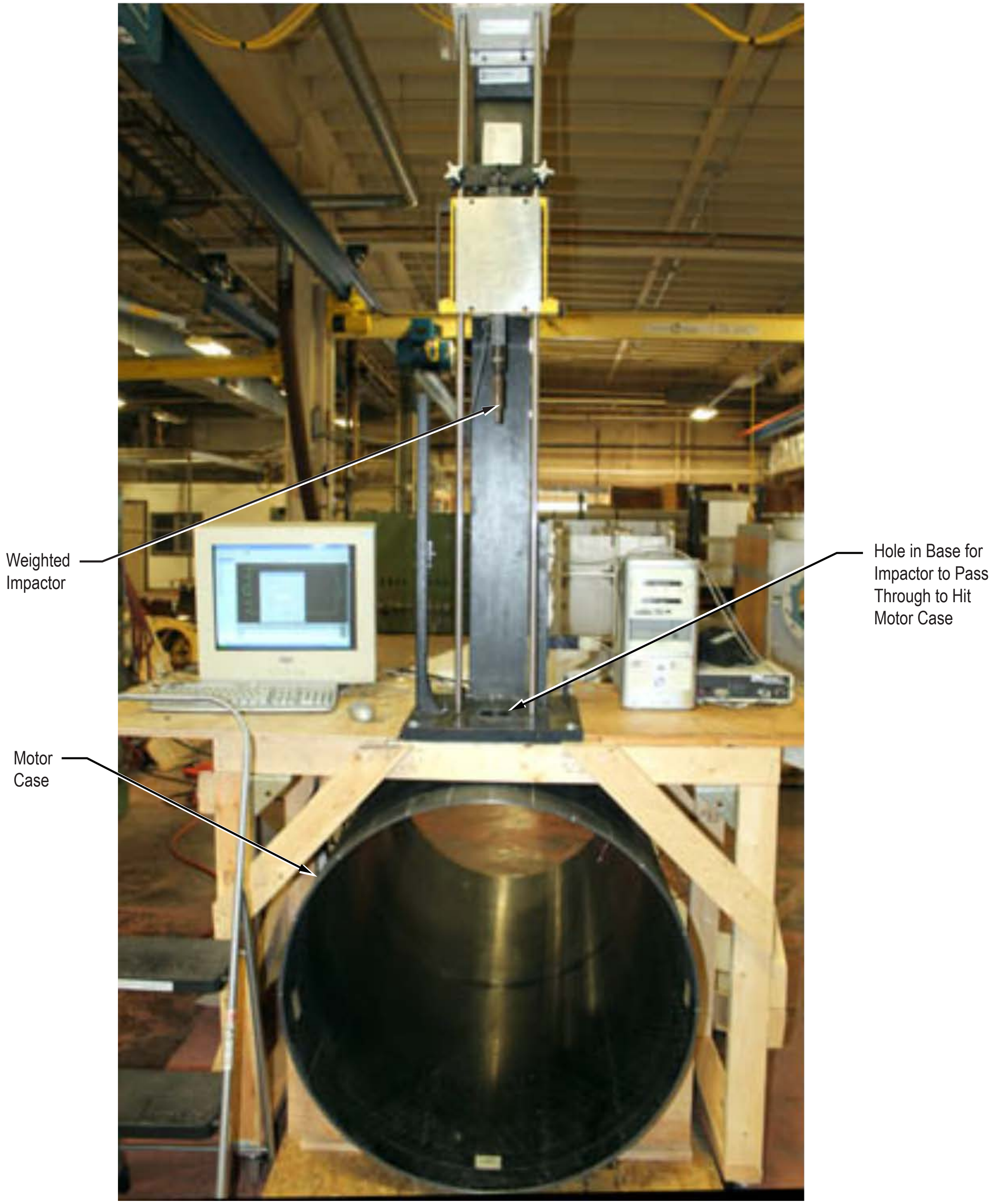

Figure 1. Photograph of impact apparatus used for the LAS rocket motor case damage tolerance program performed by the author circa 2017.

2. PAST STUDIES

The effects of impact damage to filament-wound pressure vessels were first studied heavily in the early 1980s due to concerns raised from the U.S. Army Missile Command (MICOM) relative to the Pershing II rocket motor case and by NASA concerning lightweight filament-wound solid rocket boosters that were being considered as a Space Shuttle upgrade at the time. Most of this early research was performed by Morton Thiokol (MICOM-funded) and Hercules Incorporated (NASA-funded).

2.1 Morton Thiokol Tests

Some of the first research published on damage tolerance of filament-wound pressure vessels was published by Morton Thiokol[1–3] in which small diameter pressure vessels, called ‘bottles’ (5.75-inch diameter, which conforms to a popular ASTM Standard), along with some pressure vessels of larger diameter (18 inches) were impacted and tested for burst strength. One of the key findings was that if no hoop fiber damage was present, then the burst strength never decreased. This result was also found by the author during some 5.75-inch bottle damage tolerance testing in the early 1990s (data never published). Another key finding was that the small bottles responded to impact much differently than the larger bottles. The hoop fibers in the small bottles were seen to fail in compression whereas the hoop fibers in the larger bottles failed in tension due to the geometrical effects of the differently sized bottles. Figure 2 shows photomicrographs taken by the author of impact damage to a 5.75-inch-diameter pressure vessel and a 36-inch-diameter pressure vessel where the different fiber failure mechanisms are apparent.

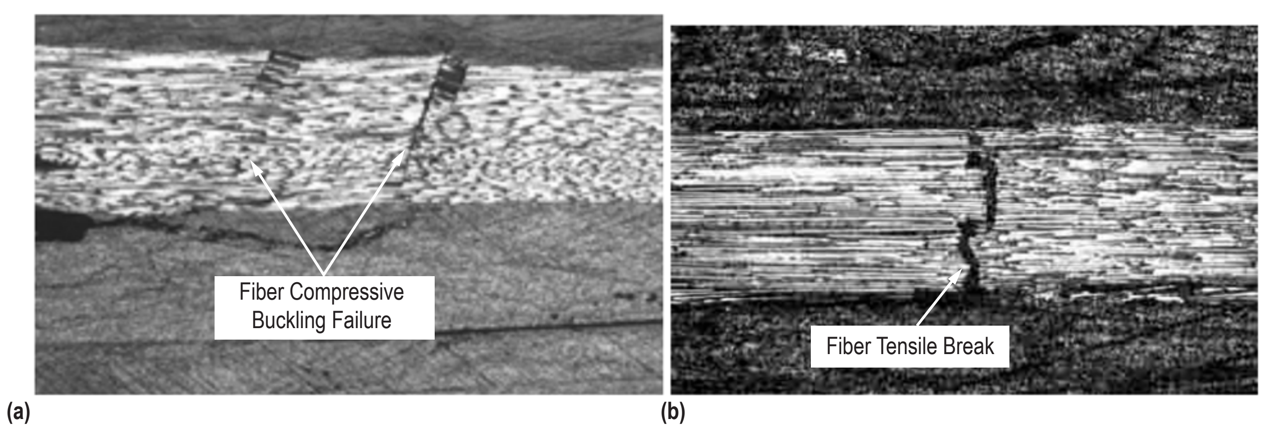

Figure 2. Broken layer of fiber damage due to impact for (a) 5.75-inch-diameter cylinder and (b) 36-inch-diameter cylinder (both photographs at ×200 magnification).

Carbon fibers have a lower compression strength than tensile strength. Additionally, the smaller bottles were about ⅓ the thickness of the larger bottles. These features contributed to the small bottles having poor damage tolerance due to hoop fiber breakage, which was thought to scale to the larger bottles. However, the data in these studies showed that the larger bottles (18-inch diameter) never lost burst strength despite being impacted with ×4 the impact energy as the small bottles (5.75-inch diameter). These studies also found that bottles filled with inert propellant were more damage tolerant than empty ones since the propellant acted as a 'backing' and prevented large deflections, resulting in less fiber breakage. The director of the research program at Morton Thiokol stated that scaling up from the small 5.75-inch-diameter 'ASTM bottles' was not feasible, and the results only served to "scare everybody that a larger diameter case would also not be damage tolerant" (E. Walcott, personal communication, May 20, 1993).

2.2 Space Shuttle Filament-Wound Case

About this same time (mid 1980s), research into the effects of impact damage to the Space Shuttle filament-wound case (FWC) was being undertaken at NASA Langley Research Center (LaRC) and by the prime contractor Hercules Incorporated (now Northrop Grumman).[4–7] The FWC was a very thick structure (1.4 inches) with a very large diameter (144 inches).

2.2.1 NASA Langley Research Center Tests

The methodology to assess the damage tolerance of the FWC in this study[4,5] was to impact full thickness (1.4 inches) cylinders of a smaller diameter (30 inches, rather than 144 inches), then excise tensile specimens that contained the damage and test these for residual strength. To obtain tension specimens that would align with the hoop fiber direction such that tensile specimens could be excised from the rocket motor case in the hoop direction so as to not have lengthwise curved specimens (which could not be tensile tested), all winding angles were rotated 90°. This is shown schematically in figure 3 for clarification. Shims were used in the gripping fixture to compensate for the curvature in the specimen width direction.

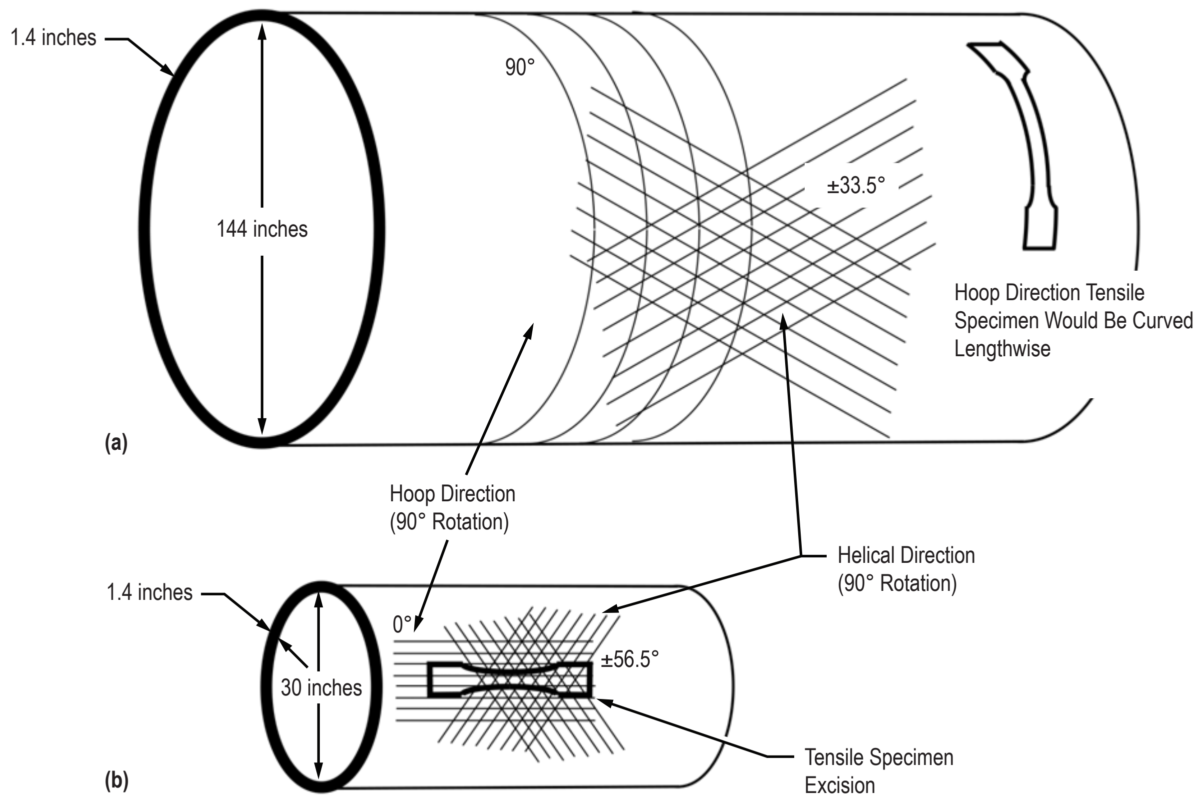

Figure 3. Schematic of wind pattern used to obtain tensile specimens in references 4 and 5, at (a) full scale and (b) subscale.

Up to 329 ft•lb of energy were used in this study, and the smallest energy used was 30 ft•lb, which is still greater than a typical tool drop (3–10 ft•lb). This study stated that “the reductions in tension stress for first-ligament failure were about 30% for nonvisible damage.” (So-called ‘first ligament’ failure will be defined shortly). However, the tensile specimens used in this study were dog bone-shaped with a width of only 1.5 inches within the gauge section. Having a specimen with similar thickness and width can cause large edge effects that reduce the measured strength even without damage. Tests of undamaged tensile test specimens in this study gave an average strength value of 50.1 ksi, whereas the expected strength based on subscale burst tests was predicted to be about 74 ksi. The lower tensile strength was attributed to the 0° fibers in the subscale damage tolerance case having wrinkles due to being hand-placed and the helical plies being wet wound over them. The possible reduction in strength due to edge effects was not considered. The main problem with the tensile testing of the impacted specimens in this study was that the specimens that did show a drop in ‘first ligament failure’ strength had subsurface damage that spanned the majority of the width of the specimen which will obviously give artificially low strength values. Because the damage was so wide with respect to the specimen width the specimens were seen to fail in two phases the author called first ligament and ‘remaining ligament’ failures. The specimens would experience a load drop when some of the outermost plies failed and delaminated away from the specimen (first ligament failure), but the majority of the specimen remained intact. Upon continued loading, the remainder of the specimen carried more load until it failed by massive delaminations (remaining ligament failure). A schematic of this failure sequence is shown in figure 4.

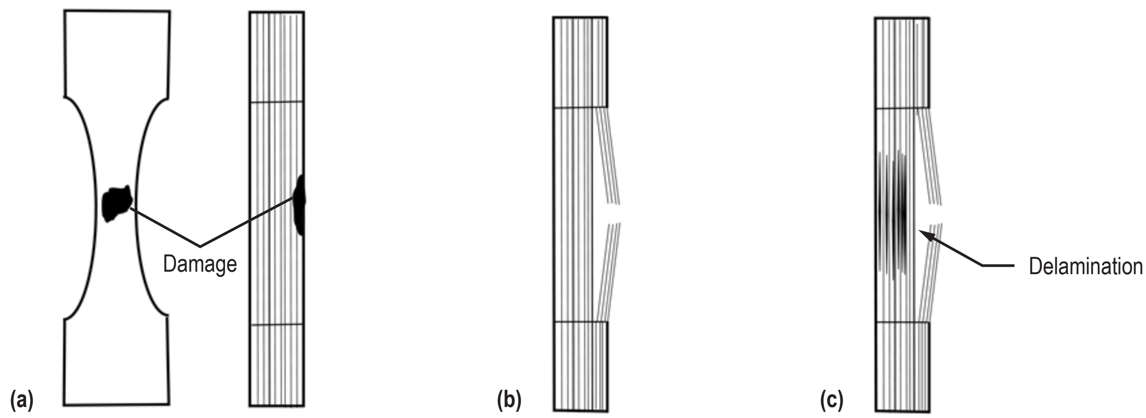

Figure 4. Schematic of two-phase failure sequence of impact-damaged tensile specimens used in references 4 and 5, showing (a) start of test (front view, left; side view, right); (b) first ligament failure (side view); and (c) remaining ligament failure (side view).

When a curved laminate is put in tension, through-the-thickness interlaminar tensile stresses develop.[8] There are many factors that contribute to the magnitude of this through-the-thickness tensile stress and they are quite complex to calculate (much beyond the scope of this paper). However, they are not insignificant and tensile testing of a curved specimen can be used to determine the interlaminar tensile strength.[9] In addition, uneven loading of the specimen due to the slight warpage causes one side of the specimen to experience more stress and thus premature failure rather than if the load was evenly distributed across the cross-section of the tensile specimen as it is assumed to.

A wider specimen (or a full-scale rocket motor) would not experience this two-phase type of failure or as much drop in strength. The remaining ligament failure stress was plotted in this study and seen to fail at an average of about 90% of the undamaged strength regardless of impact energy, even though the reduced cross-section of the first ligament failure was not accounted for.

One of the problems with using conventional tensile testing techniques to assess the residual strength of impact-damaged rocket motor case structures is that a rocket motor case is under a state of bi-axial tension, stresses in the helical direction being one-half those in the hoop direction. A few results on tests of notched laminates in a bi-axial state of tensile stress has shown mixed results with regard to ultimate strength. Results using laminates with quasi-isotropic lay-ups has shown that the ultimate longitudinal tensile stress is higher if a transverse tensile load is also applied which is the expected result due to Poisson's effect.[10–12] However, results from a laminate with a lay-up of $[0_2/\pm 45]_S$ showed the ultimate longitudinal tensile stress decreased when a transverse tensile stress was also applied, which is surprising since this lay-up has a very high Poisson's ratio and the tensile strain in the longitudinal direction would decrease as a transverse tensile load is applied.[13]

2.2.2 Hercules Filament-Wound Case Damage Tolerance Testing

In parallel to the NASA study, Hercules[6,7] undertook damage tolerance studies for the FWC program that ultimately ended in a full-scale burst test of a rocket motor case with various forms of inflicted damage throughout the case. The first of these studies resulted in a fracture control document in which four quarter-scale (36-inch diameter, 0.35-inch wall thickness) rocket motor cases with impact damage were burst tested.[6] These preliminary results showed that a severe impact (100 ft•lb with a blunt impactor) that is clearly visible in the membrane section (the vast majority of the area) of the rocket motor case degraded the burst strength by 16%, and a 25 ft•lb impact with a sharp corner impactor degraded the burst strength by 11%. These impacts had no effect when the impacts were in the transition region (the buildup of plies into the joints at the ends of the case). Importantly, embedded delaminations intentionally wound into the rocket motor case, even large ones, did not degrade the burst strength of quarter-scale rocket motor cases. However, cuts 10 inches long and 0.02 inches deep did degrade case burst strength.

In a subsequent study,[7] results from burst testing a full-scale motor case and a number of ring test articles were presented. A full-scale rocket motor case was first used to establish a visible damage threshold (VDT) and characterize a wide range of impact severity levels by excising the damaged area and using a thermal deply technique to look for depth of fiber breakage since it had already been established that delamination did not cause burst strength degradation. The VDT was a dent of 0.005-inch depth or greater. This corresponded to a 90 ft•lb impact with a 1-inch-diameter impactor, a 20 ft•lb impact with a 0.5-inch impactor, and a 10 ft•lb impact with a sharp corner impactor. Two impacts of each of these types were inflicted on the full-scale motor case in the membrane region and the burst strength was 1,452 psi, which was within the scatter of the average value of 1,518 psi for three undamaged full-scale rocket motor cases. This corresponded to a failure strain in the hoop direction of 1.48%. In addition, the failure zone did not pass through any of the six impact sites.

A second full-scale motor was impacted at 15 locations, such that 12-inch-wide ring sections could be cut with one of the damage zones in each ring (with four controls), as shown schematically in figure 5. All impacts were at or above the level of visual impact damage used for the full-scale burst test mentioned above. The rings were then pressurized using a special round steel fixture with an inflatable bladder, as shown schematically in figure 6.

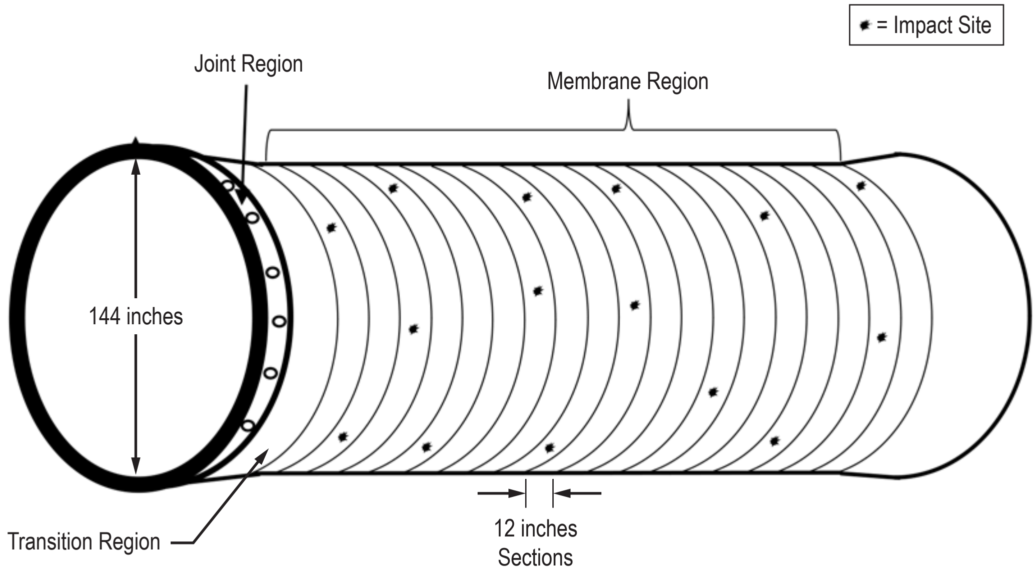

Figure 5. Schematic of impacts on full-scale rocket motor case for eventual ring burst testing. Nineteen 12-inch rings with 15 impacts and 4 controls.

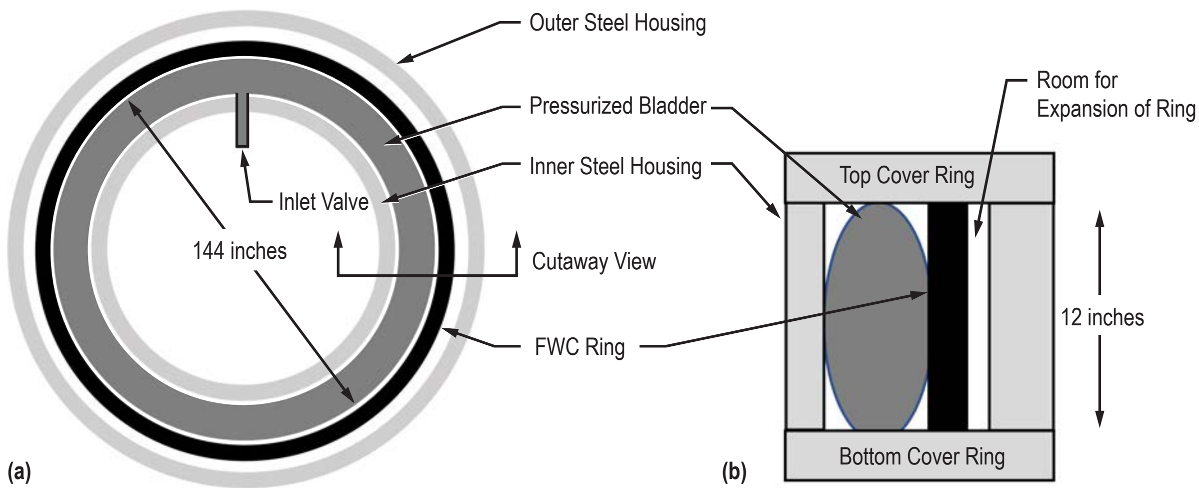

Figure 6. Schematic of fixture used to pressurize and burst rings from full-scale rocket motor case, showing (a) top view and (b) cutaway view.

The ring burst data showed no significant decrease in burst strength even at the two most severe impact levels, 500 ft•lb with a blunt impactor and 250 ft•lb with a sharp corner impact. The thinner case wall of the quarter-scale motor case was the reason a 100 ft•lb impact with a blunt impactor and a 25 ft•lb impact with a sharp corner impact reduced the burst strength of the pressure vessels in reference 6, but the thicker full-scale walls could sustain much more severe impacts without strength degradation, as seen in the ring burst tests.

After the full-scale testing of rings was completed, a more thorough examination of damage tolerance of quarter-scale rocket motors was undertaken in an attempt to use quarter-scale ring burst tests to assess the damage tolerance of a full-scale rocket motor for future programs. A total of seven quarter-scale rocket motors were tested. Two of these were used to obtain a baseline burst strength, two were impacted at 80 ft•lb with a 0.5-inch blunt diameter impactor, one was used for preliminary impact and thermal de-ply analysis, and two were used to produce ring burst specimens. The hoop strain of the motor cases was used as a parameter that the various motor cases and rings were evaluated against, since this parameter drives burst failure and the pressure to obtain equivalent hoop strains is different for the tanks and rings due to bi-axial versus uniaxial loading. A summary of the results from these tests is shown in figure 7. The results of the full-scale tests are on the left side of the figure and the quarter-scale test results are on the right side of the figure. The legend on the bottom shows the impactor shape with the impact energy in ft•lb listed below the shape.

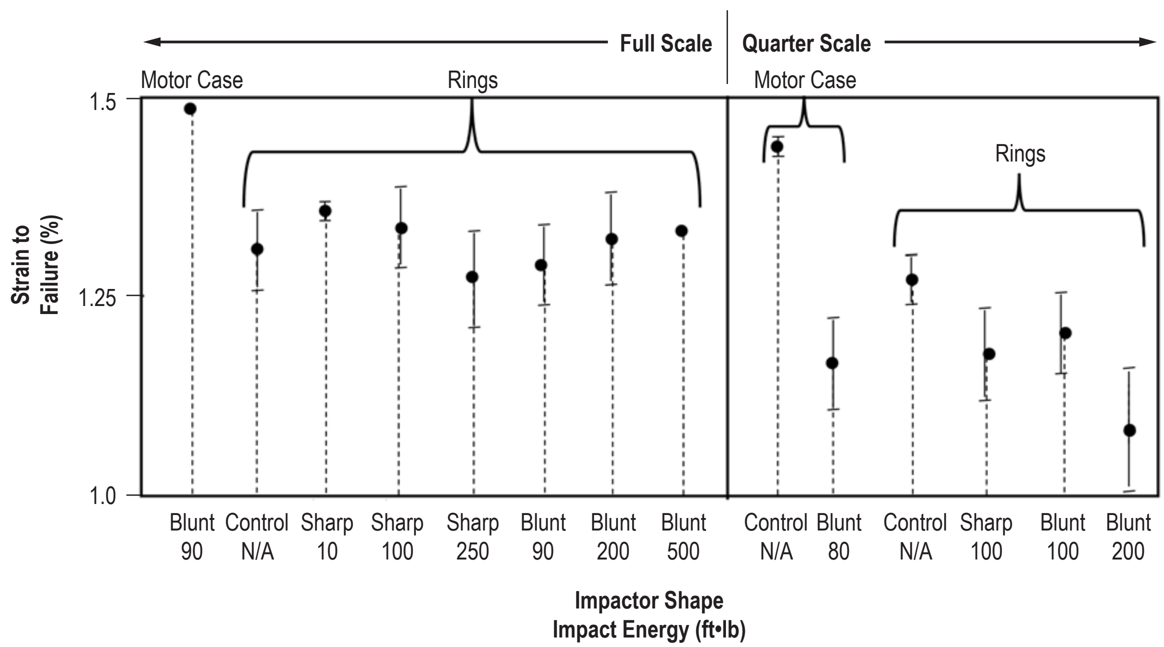

Figure 7. Summary of hoop strain to failure of various test elements evaluated in reference 7.

Going from the motor case to ring burst tests, there was about a 15% drop in burst strength for both the full-scale and quarter-scale test articles. The reason for this was not fully known, but edge effects in the ring tests were suspected. All of the impacts in figure 7 were clearly visible, and none of the impacts on the full-scale rings caused a significant loss of ring burst strength. For the quarter-scale rings, a small average drop in burst strength was seen mainly because the case walls are one-fourth the thickness. In summary, the Hercules FWC studies showed that ring testing could be evaluated to a degree against a full-scale motor case with respect to whether burst strength degradation would occur for a given impact. Also, for the full-scale motor case, no detrimental damage that could lower the burst strength was noted despite the high levels of impact severity used.

2.3 Scaling Work by Hercules

In response to the few number of full-scale burst tests that can feasibly be conducted, a program was undertaken by Hercules in the late 1980s and early 1990s into scaling impact damage and residual strength called the Damage Assessment of Composite Cases program.[14–16] This program was funded by the Air Force Space Command and was aimed more at smaller missile-type solid rocket motors. This study used maximum motor case sizes of 20-inch diameter.

Most of this work was analytical and centered on finding what type of flat plate and what type of boundary conditions could be used to represent an equivalent filament-wound cylinder with respect to the transverse load versus deflection response up until damage is formed (i.e., only in the elastic region). The majority of residual burst strength data generated in this scaling study was on 4-inch-diameter tubes that consisted of 8 plies. Equivalent flat tensile specimens were only 0.25 inches wide and suffered the same problem as the narrow tensile specimens used in references 4 and 5 in that the damage spanned the entire width of the test specimen. Additionally, the lay-up of these laminates was $[+18/–18/90_2]_S$, which is prone to edge delamination when a tensile load is applied. The fact that all four load-bearing plies were clumped in the center of the laminate also led to large areas of delamination forming due to the impact events. Scaling up of the tensile specimens was done such that the lay-ups were $[+18_n/–18_n/90_{2n}]_S$ with n = 2 (16-ply) or 4 (32-ply). This made the ply clumping problem even worse, and very large delaminations formed due to an impact event. A well-designed rocket motor case would most certainly have the hoop plies and helical plies more interspersed, and most rocket motor cases are also not midplane symmetric. But they were in this study, so that equivalent flat plates would not warp. Thus, there are practical limitations to these results.

In the second phase of this program, the researchers realized that tensile specimens at least 3 inches wide would be needed to include the entire damage area such that the damage did not interact with the edge effects. Unfortunately, only one full-scale, 20-inch-diameter, impact-damaged pressure vessel was burst, so it was deemed that comparisons could not be made. Thus, any scaling from flat plates to cylinders of a size that would be used on a launch vehicle were not made.

2.4 1994 Summary Commissioned by Marshall Space Flight Center

In 1994, MSFC generated a summary report of impact damage of rocket motor cases.[17] This report focused heavily on nondestructive evaluation (NDE) techniques which have greatly progressed in the decades since this report was published. Analytical techniques to reduce or eliminate full-scale testing were also examined in this review paper, but little progress has been made in this area in the decades since, and full-scale motor case testing with impact damage is still the accepted validation technique. Most pertinent experimental results with respect to large motor cases were based on references 4 and 5, the problems of which have already been examined in section 2.2.1.

2.5 Composite Case Reliability Assurance System

Most recently (2015), as part of a NASA Research Announcement, Orbital ATK (now Northrup Grumman) performed a comprehensive program into Composite Case Reliability, which mostly included effects of impact damage to analog full-scale rocket motor cases.[18] MSFC funded this research program as part of the SLS program, as program managers were concerned about impact damage to composite rocket motor cases. The goal of the program was to ensure that no critical impact damage on a composite rocket motor case would go undetected before launch. Two 96-inch-diameter rocket motor cases were manufactured as analogs to a 146-inch-diameter rocket motor case that was sized for the SLS vehicle. The wall thickness of these cases was 0.82 inches. One case was to be used for trial impacts with various shapes and sizes of impactors at a wide range of impact energies with post-impact interrogation in the form of NDE and thermal deply. The other case was impact damaged with levels up to 150 ft•lb and then pressurized to failure. One of the key components about rocket motor cases that was continually highlighted in this study was that the hoop fibers are critical to the burst strength of the case with the innermost hoop plies carrying more load than the outermost hoop plies. The main function of the helical plies is mainly to add axial stiffness to the case, and thus localized damage in these plies do not affect their intended purpose. This program examined four main elements with respect to impact damage to large rocket motor cases as follows: (1) case design, (2) protective coverings, (3) structural health monitoring (SHM), and (4) in-field NDE techniques.

For the case design element of impact damage, the rather basic concept of placing more helical plies on the outside of the motor case was determined to be one of the best solutions if more damage tolerance is desired. Helical plies could likely be redistributed such that some of the inner helical plies could be moved to the surface. This acts as a natural protection system as localized damage to the helical plies is not detrimental to the rocket case performance. The dome sections of the rocket motor case where the helical plies are dominant are 'inside' the skirt sections of the rocket motor case and are thus protected from foreign object impact, as shown schematically in figure 8.

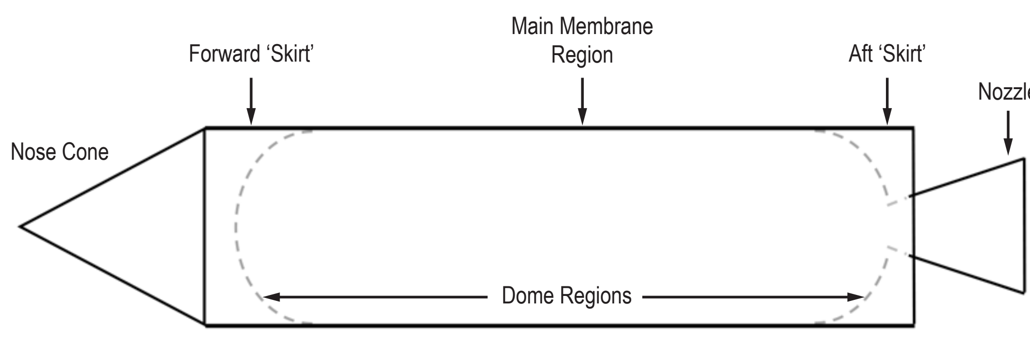

Figure 8. Schematic of rocket motor case showing dome sections 'inside' the main cylinder and thus protected from foreign object impact.

Part of the design of a rocket motor case depends on its 'design space' and what foreign object impacts the rocket motor case will need to withstand. This is contained in the so-called 'damage threat assessment' that was also defined in the scope of work of this study. The aircraft industry designs composite structures that must be used after sustaining impact events (two obvious examples are runway debris and hailstones). In addition, it is not economically feasible to take an airplane out of service for inspection and possible repair every time a part is inadvertently impacted by a foreign object. Thus, a knowledge of common impact events that the composite part has to withstand are in the design space during the design of the aircraft, and parts are sized to withstand these impacts. Launch vehicles have the luxury of being inspected after any (prelaunch) impact event. In addition, the environment is such that launch vehicle hardware is never expected to be impacted by a foreign object, and thus foreign object impacts are not typically in the design space of launch vehicle structures. If a damage threat is deemed credible to a launch vehicle structure, then it is much simpler to remove or minimize the threat rather than design the structure around the threat. Airplanes simply cannot do this. This study examined some historical impact events on launch vehicle hardware, and, based on the few incidences that have occurred, determined an upper impact energy limit of 200 ft•lb for a rocket motor case of the size studied here is an upper bound on the design space of these structures. The first significant conclusion of this program was listed in the summary report as: "Mitigation against any and all impact damage threats is neither technically feasible nor programmatically reasonable."

For the size of rocket motor case examined in this study, some of the significant conclusions (in no particular order) were:

- Blunt impacts are more critical than sharp impacts as they are less visible for a given amount of subsurface damage.
- Over 130 ft•lb of impact energy is needed to cause damage to the outermost hoop ply fibers.
- Up to 500 ft•lb of impact did not significantly degrade the hoop fibers.
- The burst case withstood a maximum impact energy of 150 ft•lb without degradation.
- Permanent protective coatings can be effective in protecting the rocket motor case, but they also reduce inspectability, which is essential.
- Removable covers can protect the rocket motor cases to some degree (about 41% more impact energy is needed to produce a given damage state for the best cover used in this study).
- Current portable NDE techniques work well to obtain thorough thickness delamination data. However, subsurface fiber breakage cannot be detected.
- A rocket motor case of the size examined in this study (or larger) designed with sufficient outer helical plies exhibits a response to an impact event that would enable a conservative, unambiguous, and reliable technique for hardware inspection.
- SHM had promise but is not at a technology readiness level to be used at this time. One of the problems is the number of sensors needed and the associated wiring. A photograph of an SHM system being used for a small section of a rocket motor case is shown in figure 9, and, as can be seen, the wiring is much too cumbersome even if the technology were at a readiness level to be used.

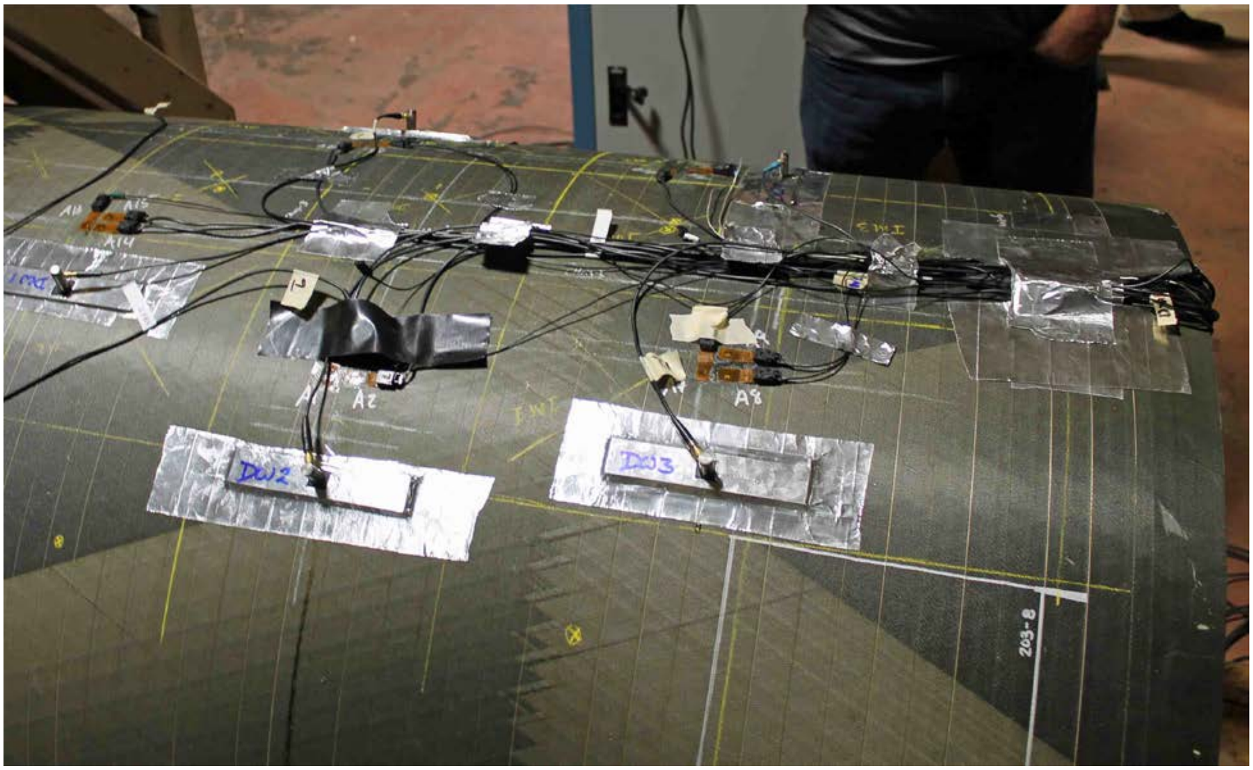

Figure 9. Photograph of SHM system showing massive amount of instrumentation and wiring used.

In this study, a phenomenon called through-thickness delamination (TTD) was discovered, which consistently occurred at impact energies above about 130 ft•lb. A TTD consisted of delaminations progressively larger in size from surface to inside of the motor case (a conical shape) with some small (on the order of one tow width or about 0.10 inches) fiber breakage distributed throughout. A schematic of this damage is sketched in figure 10.

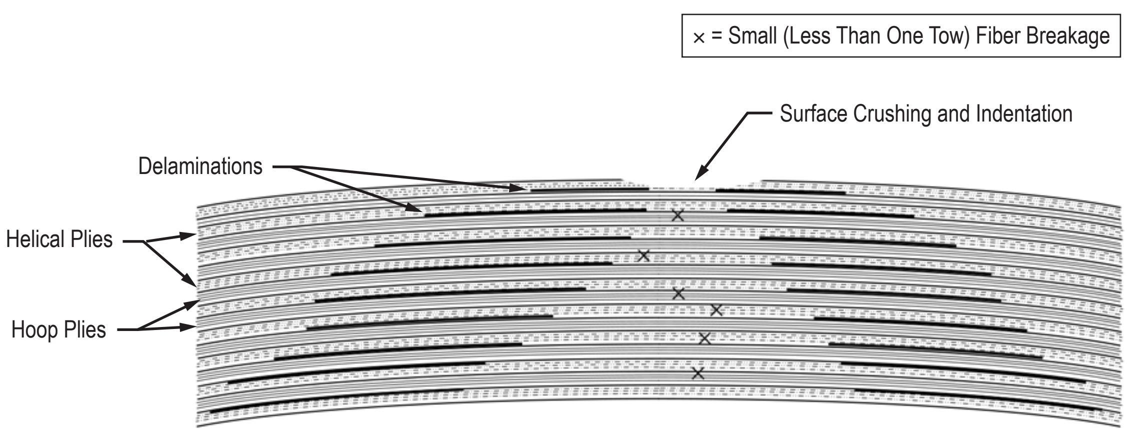

Figure 10. Schematic of cross-section of TTD that occurred at impacts above about 130 ft•lb.

This TTD was a binary event in that up to a certain critical impact energy range (130–135 ft•lb) it did not occur. After this critical impact energy range, the TTD-type damage always occurred. Figure 11 schematically demonstrates this in the plot of the planar size of damage, as detected by NDE techniques with impact energy.

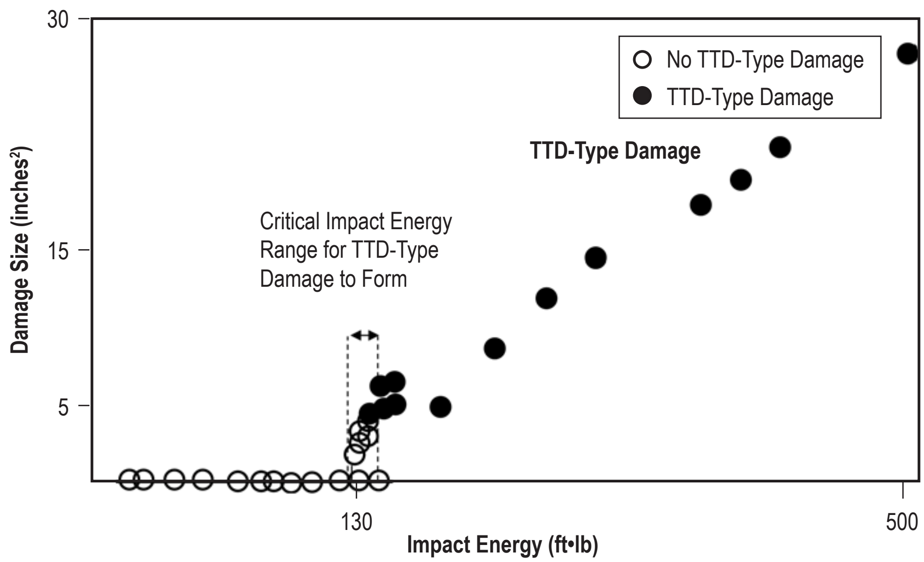

Figure 11. Schematic of damage size as detected by NDE versus impact energy (not actual data).

The research team attempted to answer how this TTD-type damage may affect the burst strength using 20-inch-diameter burst rings with the same wall thickness and lay-up of the 96-inch motor case used in this study. To represent TTD-type damage, tows of fiber were intentionally cut in the hoop plies during processing of the rings. The maximum damage induced was three cut tows spread between three hoop layers with all of the cuts being in the same radial location to simulate the small deep fiber breaks seen when TTD damage forms. The burst strengths of these rings were the same as baseline rings with no damage; thus, it was concluded that the small fiber breaks were not detrimental to the burst strength of a rocket motor case. In addition, the 96-inch-diameter motor case used for a burst strength test had an impact damage (150 ft•lb) that contained TTD-type damage, and it did not fail at this damage zone.

The overall conclusion from this comprehensive program was that current rocket motor practices are sufficient to ensure no un-noted impact damage would go undetected, but, if more resources are available, even more assurance could be obtained with additional costs and complexity.

2.6 Space Launch System Launch Abort System Damage Resistance Study

The LAS rocket motor case underwent a recent damage resistance study at MSFC in which the impact energy needed to break hoop fibers was assessed using blunt and sharp impactors.[19] The rocket motor case had a diameter of 36 inches and a wall thickness of 0.39 inches. Throughout most of the rocket motor's life (when it is susceptible to handling damage), the motor case is filled with propellant and has a thermal protection system (TPS) coating on it. To represent a propellant-filled rocket motor case, a piece of inert propellant was pressed against the inside of the motor case using a spanner beam as shown in figure 12. The inert propellant was excess taken from the inside of a 5.75-inch pressure vessel that was slated to be tested by the author for a damage tolerance program at MSFC in the early 1990s. To press the inert propellant to the inside surface of the case, a 2-by-4 was used as a spanner beam across the diameter of the case. The spanner was fastened to a 'tightening block' as shown in figure 12, such that two nuts could be turned to raise the 2-by-4 wooden spanner, thus applying pressure to the inert propellant and pressing it against the inside of the motor case.

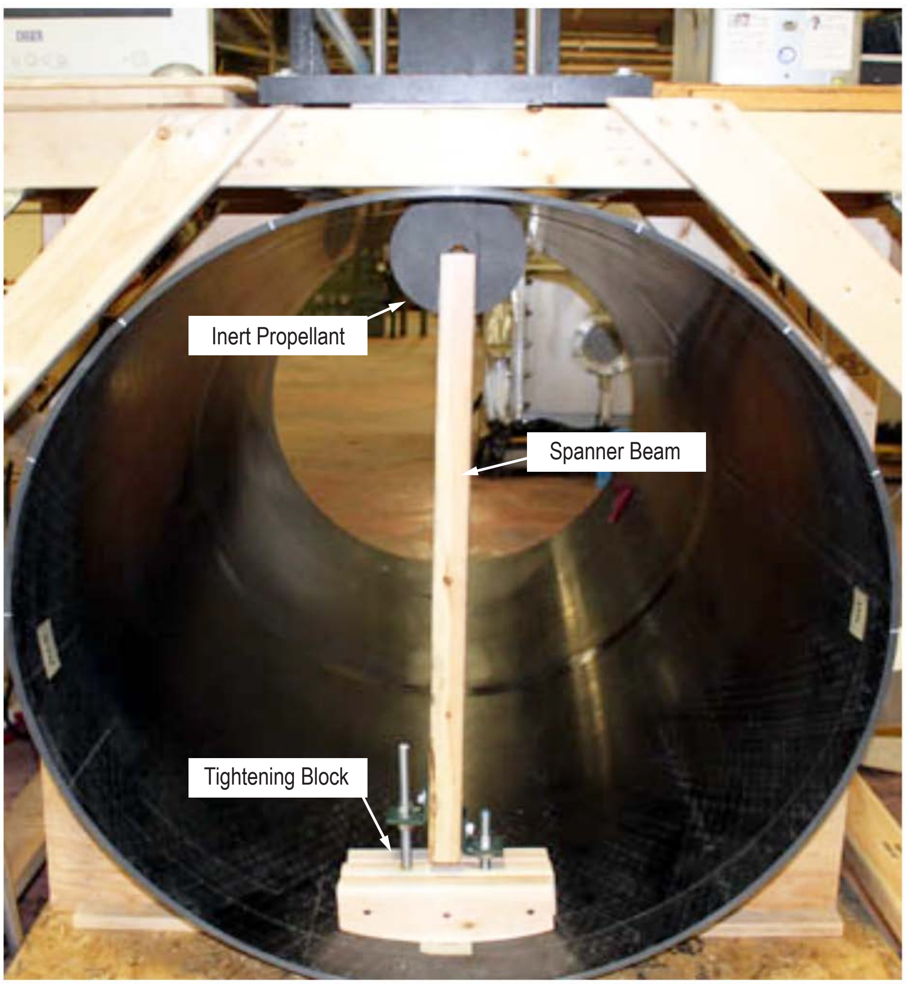

Figure 12. Method to simulate propellant-filled rocket motor case during the LAS rocket motor case damage tolerance study.

To simulate an impact scenario of the rocket motor case after application of the TPS, a small piece of the insulation was stuck to the motor case surface at the area to be impacted with double-sided tape on some of the impact zones of the motor case prior to impact. The TPS was called Vamac® and was basically a 0.25-inch-thick sheet of rubber. A photo of a piece of the TPS is shown in figure 13.

Figure 13. Piece of TPS to be stuck with double-sided tape on outside of motor case over impact area to represent TPS coating.

A total of four types of impactor shapes were used in this study. One was a standard 0.5-inch-diameter, hemispherical blunt which represents most typical foreign object impacts. Two types of 'sharp' impactors were also used to confirm the results of previous studies that showed impactor shape was not a factor with respect to broken hoop plies. Finally, a 'bolt-type' impactor was developed to represent a rocket motor case bumping into a protruding bolt during movement (an event that actually happened in 1992). Photographs of the four types of impactors used in this study are shown in figure 14.

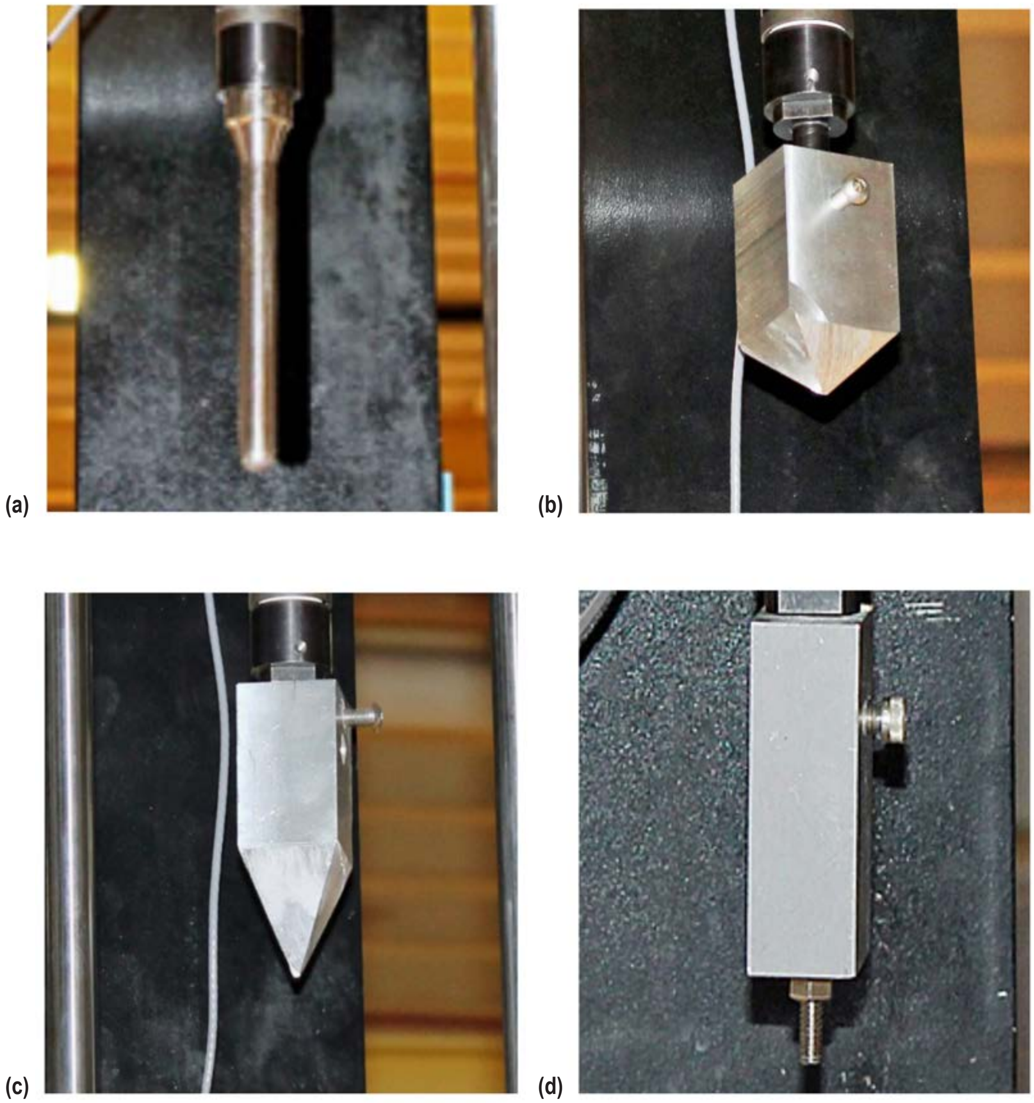

Figure 14. Photographs of the four types of impactors used in this study:
(a) blunt, (b) sharp, (c) very sharp, and (d) bolt.

One of the key findings of this study was that the TPS acted as an excellent visual indicator of damage and added some damage protection. A photograph of a visual indication of impact with the blunt impactor at 49.4 ft•lb (a relatively low impact severity level) is shown in figure 15. Thermography images of impact damage produced by a blunt impactor at 149 ft•lb are shown in figure 16. As imaged, the TPS helped protect the motor case from damage.

Figure 15. Visual indication of impact with the blunt impactor at 49 ft•lb on TPS.

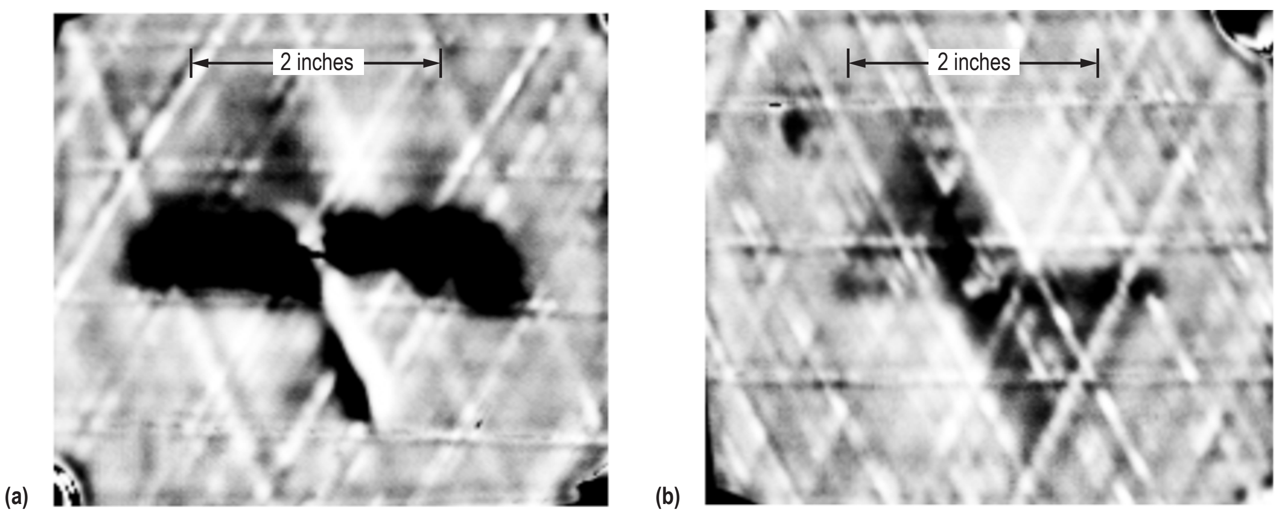

Figure 16. Thermography signatures of 149 ft•lb impacts with blunt impactor (a) without TPS (bare case) and (b) with TPS.

The hoop fiber damage in this study was classified as none, partial, and complete. Cross-sectional photographs of each of these three types of fiber damage are shown in figure 17.

Figure 17. Cross-sectional photomicrographs of three levels of hoop fiber damage found in this study: (a) none, (b) partial, and (c) complete.

The results showed little difference in damage for all impactor types, except the bolt. This was the result found in all of the past studies that have examined sharp corner versus blunt impactors. Figure 18 shows cross-sections of the damage zone for a 149 ft•lb impact with the very sharp and blunt impactors with the TPS present.

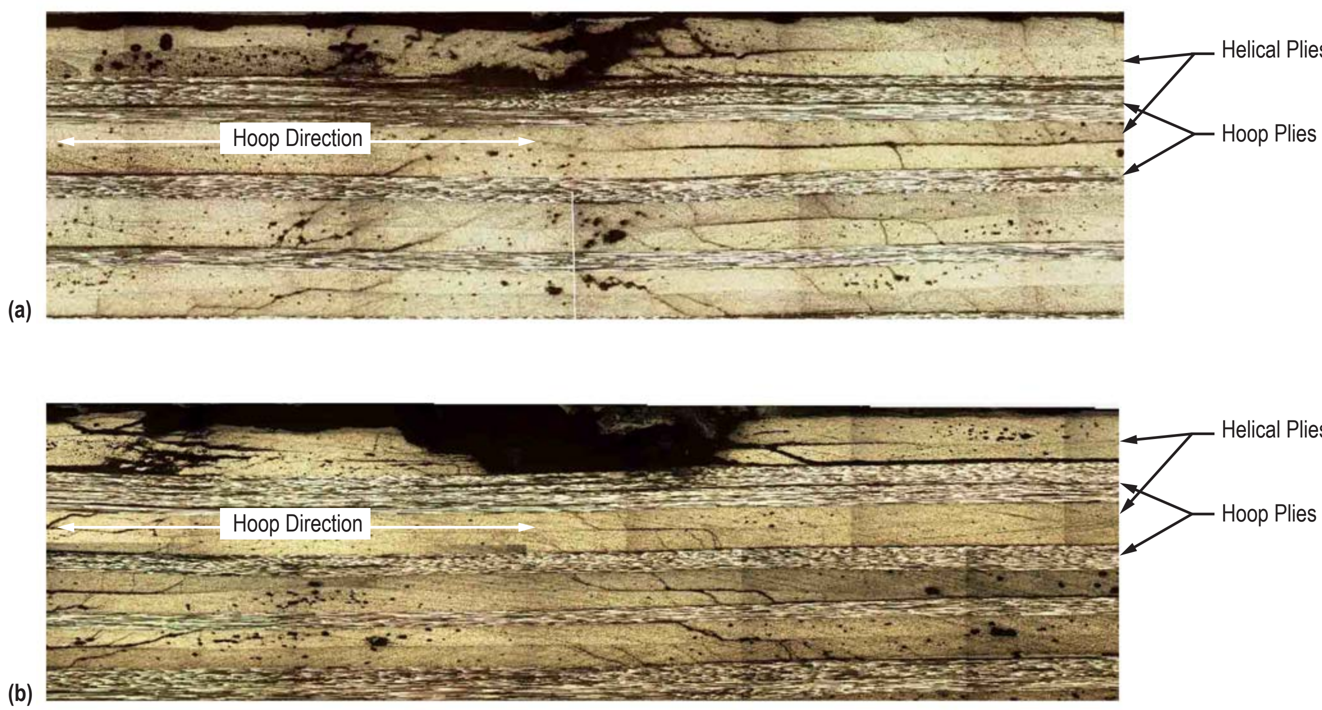

Figure 18. Cross-sections of impacts at 149 ft•lb with (a) blunt impactor and (b) very sharp impactor on TPS-covered motor case.

The only impacts with these impactors (with the exception of the bolt type) that contained complete hoop fiber breakage (in the outermost hoop ply) was near the maximum level of impact that could be attained with the apparatus used (≈150 ft•lb) and with no TPS covering (i.e., directly on the bare case). Partial hoop fiber breakage was seen with the TPS, but complete fiber breakage was not. Whether the impact was performed with the simulated propellant had little effect in the resulting impact damage formation.

One of the only known significant impact events to a rocket motor case that warranted investigation was due to an unprotected rocket motor case hitting a wall that happened to have a protruding stove bolt sticking out of it during a crane lifting operation in 1992.[20] With this in mind, a series of impacts were undertaken to represent a rocket motor case slamming into a protruding bolt. The impactor being used in this study was retrofitted with a mechanism that allowed a bolt to impact the rocket motor case. This methodology was used during the aforementioned 1992 rocket motor case investigation.

For the first type of protruding bolt type test, a ¼ × 20 standard grade (Grade 5) bolt that protruded 1 inch was used. A photograph of the impactor retrofitted with the attached protruding bolt is shown in figure 19. The highest obtainable impact energy was used (149 ft•lb).

Figure 19. Photograph of protruding bolt impactor.

The toughness of the rocket motor case is evidenced by the post-impact photo of the protruding bolt in figure 20, which shows that the impact event bent the bolt.

Figure 20. Photograph of protruding bolt impactor after 149 ft•lb impact.

The NDE thermography of the ¼ × 20 standard bolt impact on a motor case with the TPS covering showed an indication about the same size as those seen for the blunt impactor at an equivalent impact energy. The flash thermography indication is shown in figure 21.

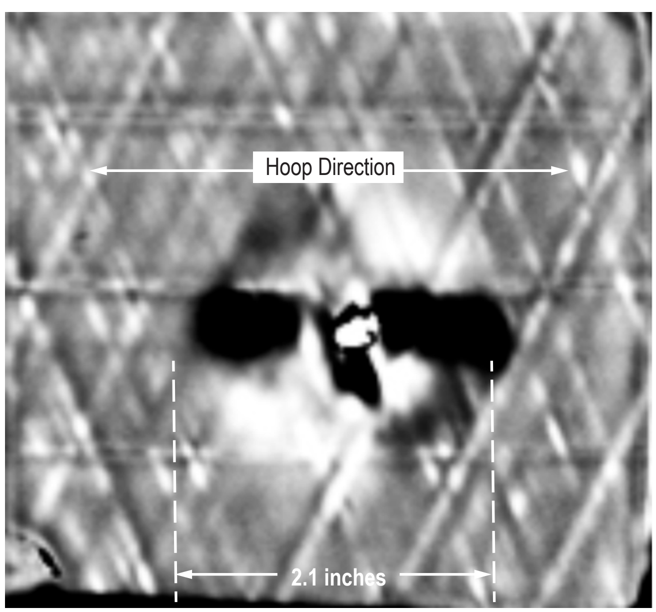

Figure 21. Thermography image of damage caused by ¼ × 20 standard grade bolt impact at 149 ft•lb with TPS covering.

Upon sectioning, the damaged area showed fiber damage down to the fourth hoop ply as shown in figure 22. Thus, significant hoop fiber damage was finally seen for a simulated rocket motor case with TPS. However, the damage was clearly obvious and represents a very unlikely scenario of slamming a motor case into a protruding bolt.

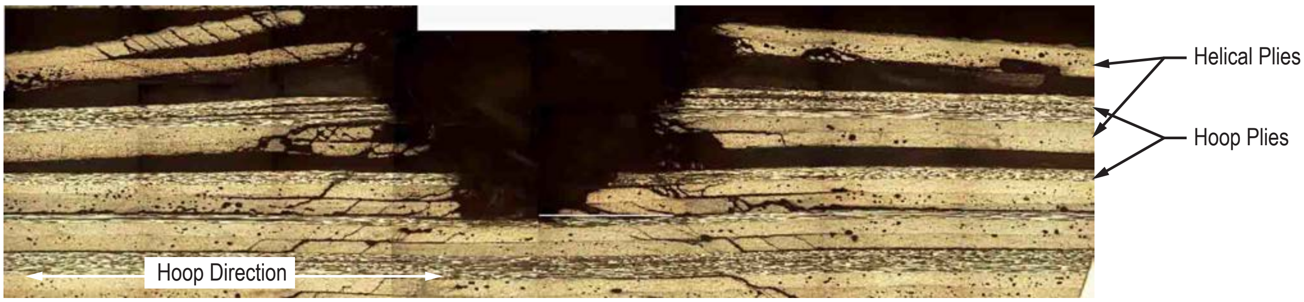

Figure 22. Photomicrograph of damage caused by ¼ × 20 standard grade bolt impact at 149 ft•lb on motor case with TPS coating.

3. CONCLUSIONS

Preventing non-visible damage from degrading the burst strength of the rocket motor case is of practical importance to the safety of the launch vehicle. There is never a 0% chance that foreign object impact (or impingement) damage will not occur. What needs to be assured is that no detrimental damage goes undetected using whatever inspection methods are used in prelaunch. The easiest inspection method is a visual one with the unaided eye. This is why there is so much emphasis in the literature on a composite laminate's behavior with barely visible impact damage. Thus, a very conservative methodology to use for large rocket motor cases is to disposition any visual damage with possible hoop fiber breakage. If damage cannot be seen, then it cannot be detrimental to the case burst strength.

It is well documented that the burst strength of a filament-wound pressure vessel is reduced only when hoop fiber damage occurs. Also, for rocket motors of the size considered for launch vehicles, the damage severity level needed is much higher than a typical tool drop and is always visible, especially when a TPS covers the outside of the case. Reference 21 states, "The resulting damage, though undetectable to the naked eye, can be severe enough to cause a catastrophic motor failure," with nine references cited to support this claim. However, one of the citations was the work done in references 4 and 5, and the other eight involved small bottles rather than rocket motor cases of any appreciable size.

In summary, some of the consistent results among all of these studies follow:

- Rocket motor case burst strength will not degrade if hoop fibers are not broken.
- The TPS that typically covers a rocket motor case acts as an excellent visual indicator of an impact event.
- No evidence of hoop fiber damage to a rocket motor case due to a foreign object impact without some visual indication on the surface has ever been presented.
- A rocket motor case, the size of which would be used on a launch vehicle, needs over 100 ft•lb of impact energy before burst strength degradation is even considered.
- Ring burst testing appears to be the most economical way to assess residual burst strength of a rocket motor case, as long as the damage is larger in size than the ring width.

Future work with respect to impact damage to rocket motor cases is to verify that T1100 carbon fiber rocket motor cases have similar (or better) damage resistance than rocket motor cases made with IM7 carbon fiber as part of the Booster Obsolescence and Life Extension program as part of the SLS program using sections of a full-scale, filament-wound structure.

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14. ABSTRACT

Rocket motor cases are typically made of filament-wound composite structure and have been since the 1960s when glass and aramid fibers were mainly used. The introduction of carbon fibers in the early 1980s and their use to make pressure vessels, coupled with the concern with impact damage to carbon fiber aircraft components in general, helped to contributed to a wave of research into impact damage to rocket motor cases around this time. This Technical Memorandum gives a brief overview of some of these earlier studies with pertinent results.

15. SUBJECT TERMS

rocket motor case, man-rated, damage tolerance, burst strength, launch vehicles

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