ESTIMATING RESIDUAL STRENGTH IN FILAMENT WOUND CASINGS FROM NONDESTRUCTIVE EVALUATION OF IMPACT DAMAGE

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ABSTRACT

The purpose of this study is to improve the ability to detect hidden impact damage in thick composites caused by low velocity impact and to predict the remaining strength of those materials. An impact study has been undertaken on filament wound graphite/epoxy casings, such as those proposed for NASA's space shuttle solid fuel rocket boosters. In thick composite materials, low-velocity impact damage may not be visually evident, depending on the impacter shape; yet the damage may compromise the composite's ultimate strength. A model of a filament wound casing was fabricated with one fifth of the diameter (30 inches) but with the full thickness (1.4inches) of the full rocket motor (12 feet and 1.4 inches, respectively). It was impacted with various masses and energy levels using a one inch diameter ball as the indenter. This casing was subsequently cut into coupons of 2 in. width by 12 in. length. These samples were nondestructively examined for the degree of damage. Next, these samples were loaded in tension until failure. Efforts to accurately detect the damage with dye penetrants and x-ray methods have proven unsatisfactory in the samples that displayed no visible damage. In spite of the high attenuation of this material, ultrasonic phase velocity and attenuation images show promise in predicting the residual strength of the coupons. Predictions of the damage profile, and therefore the cross-section of the damage in the direction of loading, were obtained by assuming an "effective" value for the attenuation of the damaged part of the filament wound casing material (15 dB/MHz-cm) and an "effective" value for the velocity of the damaged part of the filament wound casing material (2250 m/s). These estimates were based partially on measurements made on impact damaged thin composite material. The remaining strength predictions from these ultrasonic data showed a significant improvement over the x-ray predictions of remaining strength and the method may be usable for predictions of remaining strength of full scale rocket motors that may have suffered impact damage.

INTRODUCTION

The use of composite materials is rapidly growing in modern industries. Thick composite materials are being introduced into many structures such as filament wound casings (FWC) for solid booster rocket motors and aircraft airframes because of their improved strength to weight ratios. Every time a new composite structure or part is introduced into a system, an important question arises as to the strength of the part and how it can be certified or recertified after use. Engineers are using fracture mechanics to predict the possible failure modes and failure strengths of these materials. Damage or a flaw increases the complexity of the problem.

Impact damage is a potential problem in large FWC's. A large FWC structure when empty can weigh thousands of pounds. When moved, a collision or bump with another structure can create impact damage. This would be a low velocity, but very high momentum, impact. If the structure should collide with a rather sharp object, it will generally leave a damaged mark, gouge or crater on the surface of the composite. On the other hand, a collision with a blunt object may leave no mark; yet hidden damage could exist, and a significant loss of strength be sustained. Accurate knowledge of this hidden impact damage coupled with improved models of fracture mechanics may lead to better predictions of residual strength in thick composites subjected to impact damage. Regrettably, quantitative detection of hidden impact damage is difficult because of large variations in manufacturing properties, which can hide important features.

Our objective in this study was to predict the remaining strength of thick composite samples which were subjected to low velocity impact damage that did not result in visually evident damage. Our approach to the problem was to apply quantitative NDE techniques to impacted thick composite samples and then to predict the remaining strength of these samples based on the NDE results using fracture mechanics.

FRACTURE MECHANICS MODEL

Impact damage in thick composite material differs from that in thin composite plates because the thick composites are much more rigid. Thin composite plates will break on the opposite side of the impact point and display extensive delaminations and matrix fracturing. In thick composite material, it is predicted that at the moment of impact the shear and compressive stresses are greatest below the surface [1,2]. In the case of low enough velocity impact, there is no visible damage at the surface, but there can be considerable internal damage. Various destructive tests show there are internal regions of damage that include fiber and matrix breakage, matrix fracture, and possibly delaminations [3,4]. Figure 1 shows a schematic of a composite with the various damaged regions.

Since the load carrying strength of a composite is dependent upon the fibers, fiber breakage in the impact zone will result in reduced strength. Figure 2a shows a schematic of an impact damaged coupon. To predict the strength of these impact damaged composites, we employed an elliptical crack model with the plane of the crack being perpendicular to the loading direction as indicated in Fig. 2b. In effect, we are postulating that there are many broken fibers in the impact region that structurally disconnect the composite in the region of the impact and that we can treat the damage as a two dimensional problem. In the case of a pressure vessel such as a rocket motor, the hoop fibers are under a tensile load. Therefore, the fiber breakage cross-section in the hoop direction is important. The motivation for using the elliptical crack model is the existence of theoretical calculations to predict the fracture strength of homogeneous samples [5,6]. The fracture model predicts that a coupon will fracture in two steps (See Fig. 3). The first failure step will involve an initial fracture in the plane of the elliptic cut and will be to the depth of the cut with interlaminar shearing at the

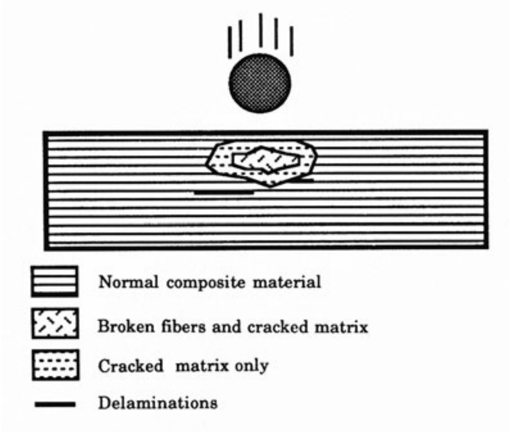

Figure 1. A cross-sectional view of internal damage in impacted thick composites.

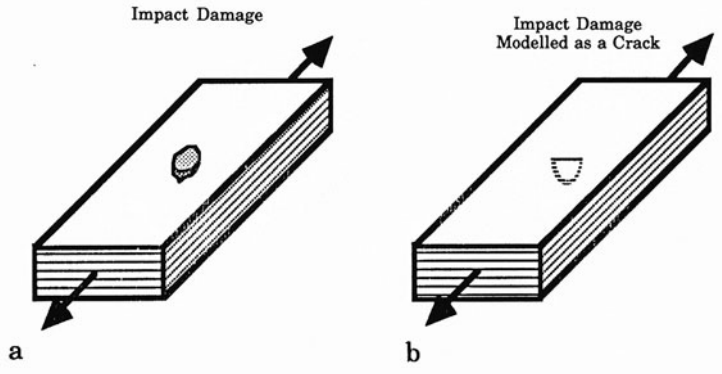

Figure 2. a) A simplified view of impact damage.
b) An elliptical crack that would produce the equivalent loss of the strength as caused by the impact damage. The arrows indicate the direction of tension.

base of the crack. Therefore, the first fracture step results in a thinner coupon or remaining ligament which will have a correspondingly lower strength because of the smaller cross section for the second failure step.

This theory was tested on several of these samples using actual elliptical saw cuts in the surface of the samples [3]. Under tensile loading, these samples did indeed fracture in steps as predicted, but their residual strengths deviated from the calculations slightly. It was speculated that, after the first ligament failure, the load frame did not apply the stress exactly in the direction that was assumed. The remaining strength of those samples behaved in an empirical manner given by

$$S = 30100\ x_d^{-0.278} \tag{1}$$

where S is the strength in units of KSI and x_d is the depth of damage in inches.

The problem then becomes how to quantitatively measure the shape of the fiber fractures with NDE techniques. If the NDE measurements

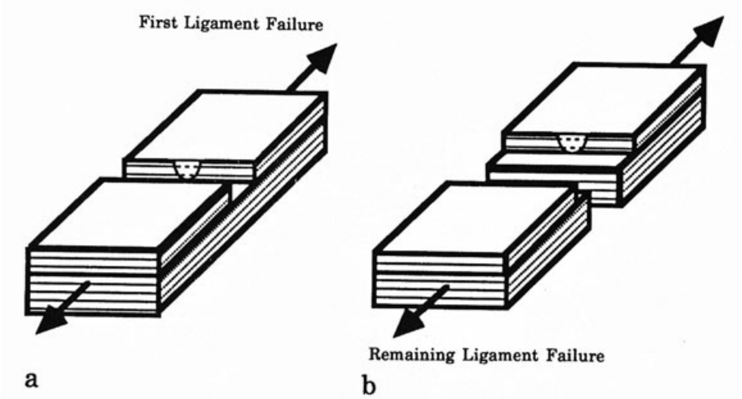

Figure 3. The failure model of a composite with an elliptical crack stressed in tension.
a) The first ligament failure. b) The remaining ligament failure.

are successful, and the model is a reasonable approximation of reality, we should be able to predict the residual strength of a thick composite subjected to low velocity impact damage.

SAMPLE PREPARATION AND HANDLING

The samples used in this study were taken from a specially wound scale model of a filament wound cylinder that had a 30 inch diameter and a 1.4 inch thickness. Generally, the hoop fibers are tangentially oriented in FWC composites and are therefore curved. In order to obtain straight hoop fibers in the loading direction in a standard load frame, the fiber layup was rotated ninety degrees so that the tangential fibers were oriented along the axis of the cylinder. This cylinder was cut into 12 inch wide rings. These rings were impacted with various mass and energy levels using a one inch diameter ball for the impacter. Next, the rings were cut into coupons that were 2 inches wide by 12 inches long and 1.4 inches thick. Each coupon contained one impact site at the center of the coupon surface. These coupons were x-rayed and ultrasonically tested. Finally, the coupons were stressed in a tensile fashion until failure. These impacted samples broke in steps which supports the fracture model. (See references 3 and 4 for a more detailed description of the sample preparation and fracture mechanics tests.)

X-RAY MEASUREMENTS

For x-ray measurements, the damaged regions were soaked in a radioopaque dye and then x-rayed. Figure 4 shows photographs of the results of typical x-rays of a sample before and after loading. Before stress is applied to the impacted samples, the dye often fails to enter the matrix and indicates no damage as seen in Fig. 4a and 4c which show a top view and a side view of one of the coupons. In this case, the depth of the damaged fibers is not known. When a small hole is drilled into the composite surface at the point of impact, the dye can then be taken up and the matrix damage is seen as very extensive [3]. After loading the samples to the point of the first ligament failure, the surface was broken and the dye was taken up by the fissures. Figures 4b and 4d show the resulting damage. The extent of the depth of the damage after the first ligament failure is now evident in Fig. 4d.

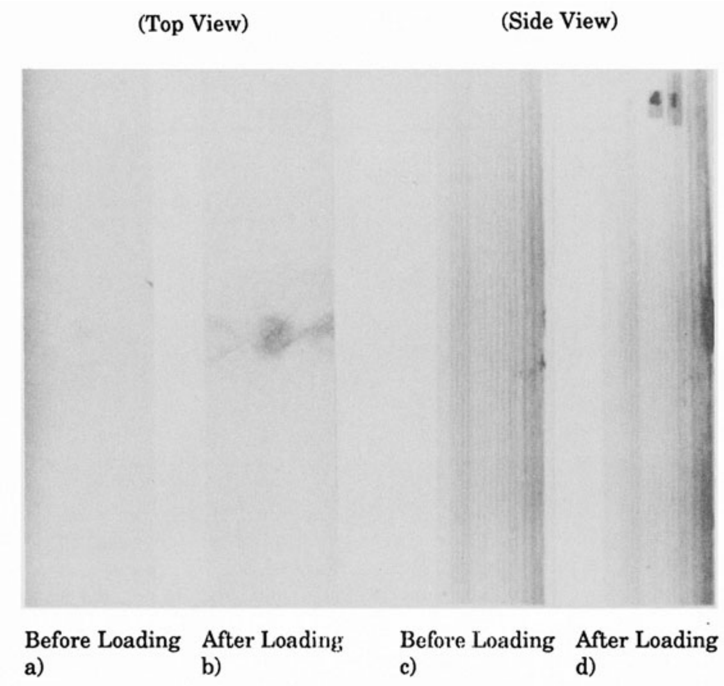

Figure 4. X-ray views of impact damage. a) Top view before loading. b) Top view after first ligament failure. c) Side view loading. d) Side view after first ligament failure.

ULTRASONIC MEASUREMENTS

The goal for these measurements was to detect the profile of the broken fibers, since fiber breakage was the main concern in the fracture model that had been employed. The ability to measure the profile of the broken fibers was very difficult in these samples due to the inhomogeneity of the medium as well as the complexity of the physical damage. For example, some of the scattering techniques that are sensitive to fiber breakage are also sensitive to other defects, and this produces images that are difficult to interpret. Velocity and attenuation measurements made in transmission have an integrating effect on the material inhomogeneities and therefore can give more stable measurement values although they also are not specific to fiber damage. An example of this fact is that attenuation measurements are also sensitive to the number of matrix cracks in a composite [7]. From Fig. 1, there are many unknown parameters that are needed to relate the transmission attenuation or velocity to the profile of the fiber fracture region. For these samples, the velocities or attenuation parameters that were related to the regions of fiber and matrix breakage, regions of matrix fracture, or possible delaminations were not known. In general, there are too many unknowns to solve the equations. In order to circumvent this problem, a simple linear relationship of a two component model or an "effective" damage model (see Fig. 5) was chosen for this complex state of the material. The sample contained either regions of good composite or damaged composite. This "effective" damaged region would then be related to the degree of broken fibers in the sample. This approximation reduces the number of variables and the problem becomes tractable. For phase locked loop velocity measurements [8] the equation is

$$x_d = n_\lambda \, (f_{ref} - f_m) \, (v_c \cdot v_d) \, / \, ((f_{ref} \cdot f_m) \, (v_c - v_d)) \qquad (2)$$

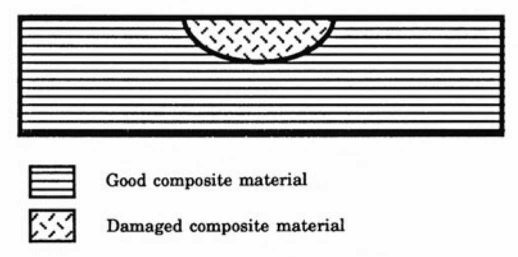

Figure 5. Model for ultrasonic treatment of impact damage.

and for the attenuation measurements the equation is

$$x_d = x_s (\alpha_m - \alpha_c) / (\alpha_d - \alpha_c) \tag{3}$$

where x_d is the damage thickness, n_λ is the number of wavelengths to the phase lock point, f_{ref} is the reference frequency of the phase lock loop system set in the normal composite region, f_m is the measured frequency, v_c is the velocity of normal composite, v_d is the velocity of damaged composite, x_s is the thickness of the sample, α_m is the measured attenuation, α_c is the attenuation of normal composite, and α_d is the attenuation of damaged composite. Most of these parameters are known or can be measured in the experiment. By knowing the appropriate attenuation and velocity of the damaged composite material we can infer the correct damage cross section to use in the fracture model .

Transmission measurements were made using a 1.125 inch diameter weakly focused 1.0 MHz transducer as the transmitter, and a 0.5 inch diameter planer 1.0 MHz transducer as the receiver, which was apodized to 0.2 inches. Narrowband relative velocity values were measured using a pulsed phase locked loop system. Attenuation measurements were made simultaneously by detecting the amplitude of the transmitted tone burst. The samples were scanned in a water tank in one mm steps over a square region of 50 mm by 50 mm. The system was calibrated for attenuation by measuring the amplitude of the transmitted tone burst with the sample removed. A reference velocity for normal composite material was determined by time of flight measurements through the sample in regions remote from the impact site. Quantitative greyscale images were then produced for evaluation.

The attenuation and velocity of normal composite material were derived from measurements in regions remote from the impact site. The values for normal composite material were in the range of 5-9 dB/cm for the attenuation parameter and about 2600 m/s and 0.8 MHz for the velocity. For the "effective" attenuation of damaged composite material, we extrapolated from measurements of thin impacted unsupported plates. The extensive delaminations in thin impacted plates will contribute significantly to the attenuation values measured at all frequencies because of the many interface reflections that can occur, a feature which is not as important in thick samples. In composites the attenuation can be approximately treated as a linear function with frequency and characterized by intercept and slope terms. The intercept indicates contributions to the attenuation from interface losses or reflections which are generally frequency independent and occur at delaminations [9]. Therefore, from thin impacted composite material, the slope of attenuation was used to predict the attenuation of damaged composite material and the intercept of the attenuation was attributed to the delaminations which were assumed to be negligible in the thick composite samples. A value of 15 dB/cm-MHz was chosen as the slope of attenuation for damaged composite. This was typical of the values measured at impact damage sites in similar thin composite material used in our laboratory. A value of 2250 m/s for damaged composite material was chosen by comparing estimates of the depth of damage between attenuation measurements and velocity measurements in only one sample. This velocity value was then used in equation 2 for all the impact samples.

Using these values for the "effective" attenuation and velocity of damaged composite, one could then predict the thickness of the damaged material. Figure 6 shows a scan image of the relative velocity as an example of the measurements that were obtained. If this figure were reoriented and then viewed in the direction of the applied stress the image would display a thick band of values for normal composite velocities and a bump that would represent the damaged values. Similar views were evident for attenuation. This material displayed a large variance for the values of phase velocity and attenuation measured in the good composite materials. If the measured minimum extremum values for good composite material are used for the values of the f_{ref} in equation 2 and the maximum extremum values for α_c in equation 3, a smooth dividing point between good and bad material would be generated. The values used for f_{ref} and α_c were determined for each coupon individually. This provided a way in which to project the depth of damage onto two dimensions. Figure 7 shows the result of viewing the effective depth of damage profile in the direction of the applied stress and reduced in the manner discussed above from a velocity measurement. In this figure the vertical axis shows the depth of damage into the sample, and the horizontal axis is the distance across the coupon. An elliptical shape was fitted to the damage shape and was superimposed on the depth of damage for visual reference. These damage depth values are used with the fracture strength equation to calculate the remaining strength.

RESULTS

Figure 8 shows the results of the x-ray measured depths versus the equivalent elliptical cut depths required to produce the actual measured fracture strengths (Eq. 1). It is quite obvious from the indicated one-to-one correlation line that the x-ray measurements indicated too shallow of a depth of damage. Even in the samples where a mark or dent was evident, the x-rays indicated shallow depths. This indicates that the radio-opaque dye failed to enter the matrix. In general, these measurements would predict strengths that would be too large compared to the actual fracture strength.

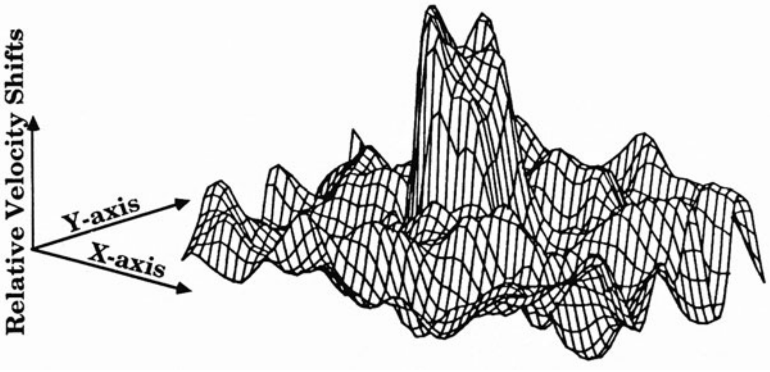

Figure 6. A two dimensional scan showing the velocity profile measured in frequency units from a pulsed phase locked loop measurement system [8]. The upward direction represents shifts to a lower velocity.

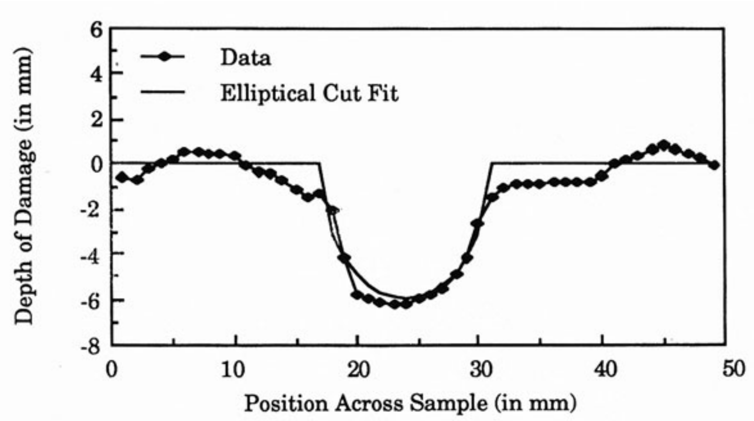

Figure 7. The cross-sectional view of the "effective" damage profile in the direction of loading from a velocity measurement scan. The solid line shows the elliptical fit to the damage profile and is for visual reference.

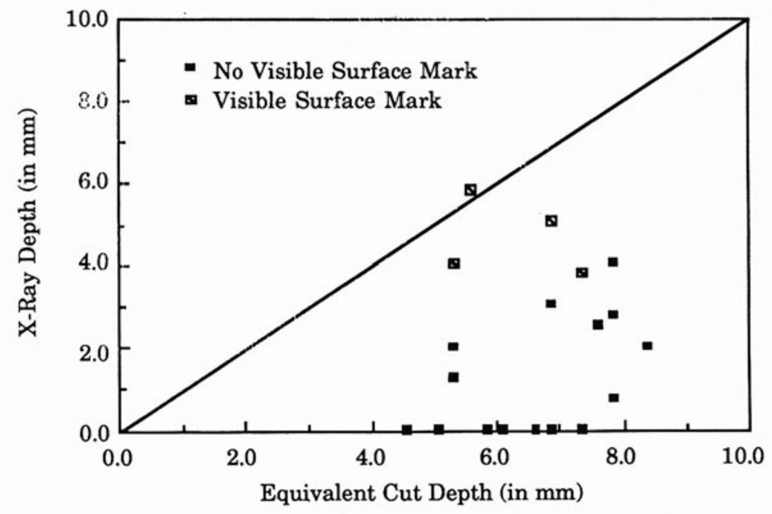

Figure 8. X-ray determined depth of damage versus the equivalent elliptical cut depth required to produce the measured strengths. The solid line is the one-to-one correlation line for reference.

Figure 9 shows the results comparing the ultrasonic predictions of the remaining strength after first ligament failure versus the actual measured fracture strengths. The remaining strength after the first ligament failure was the ultimate strength of these impacted samples. The inset shows how the data lie within the range of 0 to 60 KSI. The solid line shows the line of unity slope. The dotted line represents

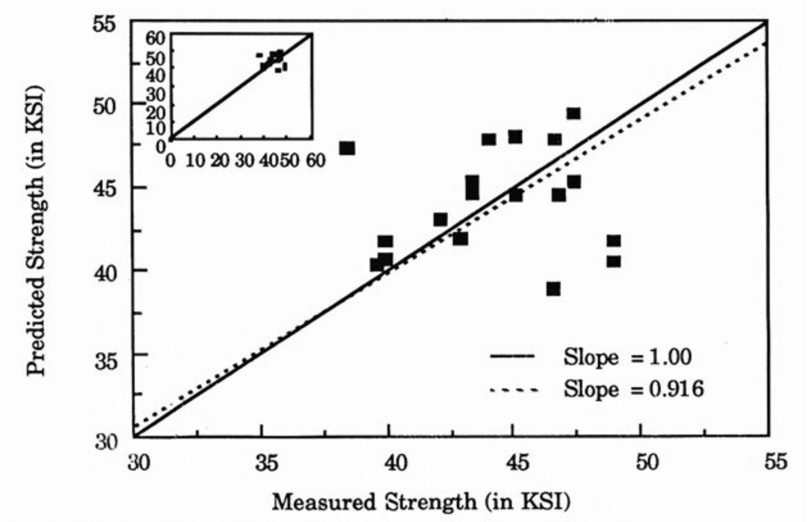

Figure 9. Predictions of strength from ultrasound measurements versus the actual measured strengths. The solid line is the unity slope line and the dotted line is the least square fit to the data. The inset figure shows how the data lie from 0 to 60 KSI.

the least squares fit to this data. The slope of that line is 0.916. All the data scatter about the one-to-one correlation line, and although a few points of the data show large scatter, 80% of the points lie within a few percent of the unity slope line. In this figure, no distinction is made between attenuation or velocity determined strengths because both systems appeared to be equal in the quality of their predictions. The data deviations from the one-to-one correlation line exhibit about a ±10% variance in this experiment. The failure loads of 18 undamaged samples also exhibited a ±10% strength variation and this fact could account for the deviations of our predictions from the actual strengths [4]. Similar variances in strength have been seen in other FWC samples measured at other facilities [3]. This technique is clearly superior to the standard x-ray technique used in this instance.

CONCLUSIONS

Our goal in this work has been to use quantitative NDE to answer the question of how strong a material is after damage has been detected. Both transmission attenuation and velocity measurements can be used to predict the depth of damage in thick composites with a simple ultrasonic model. Then, from a fracture mechanics model, the depth of damage can be used to predict the composite failure strength caused by low velocity impact exhibiting no visible indications of damage. These algorithms could be adapted to measurements made in a reflection mode made on a rocket motor mounted in place and loaded with rocket fuel, since access to both sides of the casing is not always possible.

This is a first step in solving the problem of damage in thick composites. There were significant assumptions made in the fracture mechanical model as well as the NDE model that must be addressed. It is hoped that this work will lead to better models as well as strong collaborations between fracture mechanic and NDE researchers to better answer the important question of material strength.

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