

NONDESTRUCTIVE EVALUATION OF DAMAGE AND DEGRADATION OF MECHANICAL
PROPERTIES IN COMPOSITE PANELS SUBJECTED TO IMPACT

H. Nayeb-Hashemi and N. Zheng

Department of Mechanical Engineering
Northeastern University
Boston, MA 02115

EXPERIMENTS

Materials. The materials used in this research were T300/5208 unidirectional graphite/epoxy composite panels supplied by the Army Materials Technology Laboratory. The panels were in square form of 12 in. by 12. in. with nominal thicknesses of 0.042 in. (7-ply) and 0.144 in. (24-ply) respectively. All of the panels were subjected to c-scan examination for uniformity and integrity. The properties of the material are presented in Table 1. A schematic of the unidirectional composite is shown in Fig. 1.

Ultrasonic and impact tests were conducted in panels in as received forms. The tensile test specimens were cut with a diamond wheel saw from the impacted panels. Details of tensile specimen preparation can be found in [1].

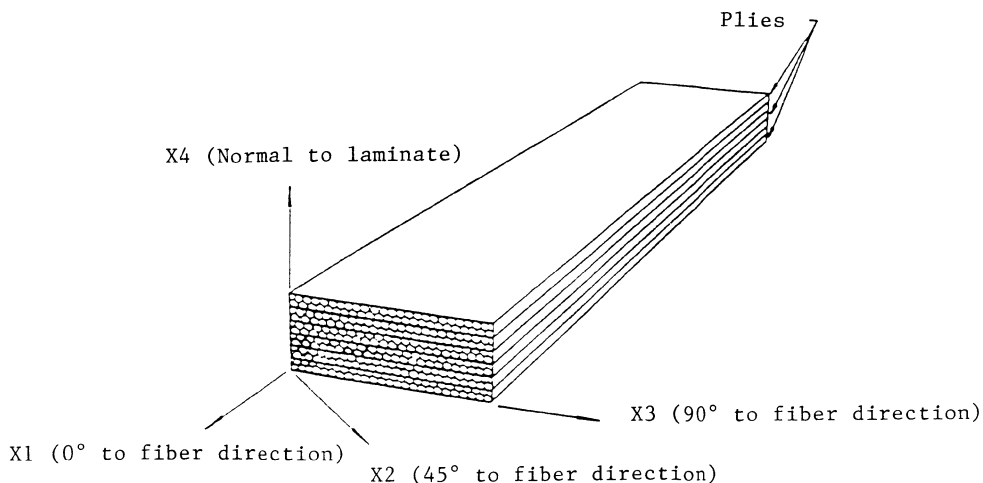


Fig. 1 Schematic of Graphite/Epoxy Composite Laminate Showing Principal Directions.

Table. 1. Properties of T300/5208 Unidirectional Graphite/Epoxy Composite Material*

a. General Properties

Material System: T300/5208
 Prepreg by: Narmco
 Nominal Ply Thickness: 0.006 in.

Constituent	Material	Volume Fraction
Fiber	Union Carbide Thornel Graphite	$V_f = 0.63$
Matrix	Narmco 5208 Epoxy Resin	$V_m = 0.37$

b. Mechanical properties

Direction**	Property	Value
X	ultimate tensile strength σ_x^{tu}	211×10^3 psi
	tensile modulus E_x^t	21.3×10^6 psi
	tensile strain at failure ϵ_x^t	0.991%
	ultimate compressive strength σ_x^{cu}	204×10^3 psi
	compressive modulus E_x^c	19.0×10^6 psi
	poisson's ratio ν_{xy}	0.38
Y	ultimate tensile strength σ_y^{tu}	6.1×10^3 psi
	tensile modulus E_y^t	1.58×10^6 psi
	tensile strain at failure ϵ_y^t	0.386%
	ultimate compressive strength σ_y^{cu}	34.0×10^3 psi
	compressive modulus E_y^c	1.45×10^6 psi
	poisson's ratio ν_{yx}	0.0202
	interlaminar shear strength τ	15.89×10^3 psi
	inplane shear strength τ_{xy}	16.87×10^3 psi
	inplane shear modulus G_{xy}	0.85×10^6 psi

* Data were extracted from the information provided by the Army Material Technology Laboratory, also from reference [34].

** X denotes the direction of fiber.

Ultrasonic Test

A ultrasonic system generated a sinusoidal signal of required frequency. The signal was further amplified and gated to narrow-band or broad-band signal according to experimental requirements. The signal was then transmitted to a composite panel by the transmitting transducer and collected by a receiving transducer and a digital oscilloscope. The signal was analyzed by a waveform analysis software in a PC system. The software provided the capability of examining the received waves in both time and frequency domains. Details of ultrasonic set-up can be found in [1].

Attenuation and Group Velocity Measurements

Attenuation and group velocity changes in the thickness direction were measured in the X1, X2 and X3 directions, by transmitting and receiving a 2 MHz narrow band pulse oscillator in the thickness direction. Based on the understanding that impact damage would occur at the impact center and its close vicinity, test points were arranged around the impact point.

Stress Wave Factor Measurements

In measuring the SWF, a broad band pulse was introduced into the panel. The transmitter and receiver transducers were lined up on the same side of the panel and separated by a distance of 1.5 in. (a minimum distance allowed by the transducer structure). The SWF measurements were recorded in the X1 direction. Different locations for the SWF measurements were selected along the X3 direction to monitor the extent of impact damage. Signal analyses of the SWF waves were accomplished in both the time domain (ringdown SWF analysis) and the frequency domain (frequency spectral properties analysis). For time domain analysis, four different threshold levels were selected: 0.008v, 0.006v, 0.004v and 0.002v. The lowest level (0.002v) was set right above the noise level of the wave packet.

Impact Test

After virgin panels were characterized by the ultrasonic methods, they were subjected to low velocity impact. The objectives of the impact test were: 1) to generate damage consisting of contact and bending effects, 2) to record the dynamic responses of the panel such as impact induced strains, stresses and impact force, and 3) to study the geometry of the surface damage area by Greszczuk's theory [2].

In order to understand effects of specimen boundary condition, and projectile geometry, weight and speed on the generated damage zone, many trial experiments were conducted. The impact weight and speed were varied from 7 lbs to 15.3 lbs, and 160 in/s to 200 in/s respectively. Projectile curvatures of 1 inch and 1.5 inches were used. The specimen boundary condition was changed from clamp to simply supported configuration. Further more specimens were supported at the point of impact (in order to reduce bending deformation and study the contact damage) by either a soft or a hard material of 1 inch diameter. A strain gage was attached to this support, in order to monitor impact force.

Multiple rebounding was prevented by holding impactor after initial impact.

Tensile Test

After impact test, the panels were re-evaluated ultrasonically. Tensile specimens were then cut from the panels for mechanical property measurements.

RESULTS AND DISCUSSION

The results are divided into three groups: 1) results of impact tests, 2) changes of ultrasonic (UL) and mechanical (ME) parameters due to impact, and 3) comparison of changes in UL and ME parameters.

Effects of specimen boundary conditions, and projectile geometry on the induced damages were investigated. It was found that clamping the boundary of the specimen eliminate excessive vibrations and rebounding. Different projectile curvatures resulted in no significant variation in the damage zone beyond the impact center. For this reason, a projectile with 1.5 inch curvature was used in subsequent experiments. For specimens with no support at the impact point, the bending damage was dominant damage mechanism. The bending damage was substantially reduced with composite supported on Maraging steel. The induced damages were in form of fiber/matrix interfacial cracks, propagating in the thickness and along the fiber, delamination, and local buckling of sublaminates.

In 24-ply composites both impact induced axial (σ_{11} in X1 direction) and transverse (σ_{22} in X3 direction) stresses remained strong past the impact duration. However, in 7-ply composite, while axial stress remained strong, transverse stress was negligible beyond impact duration. This was attributed to the developed fiber/matrix interfacial cracks and separations, which resulted in eliminating impact energy propagation in the X3 direction. The damage was thus confined to a narrow width around the impact center. In the thick composites (24-ply) the interfacial cracks were shorter and had not propagated through the thickness completely.

The changes in attenuation, and group velocity along the X1, X2, and X3 directions due to impact were measured. The attenuation was measured both from the change of the amplitude of the received signal and from the amplitude of the center frequency in the frequency spectra. The changes in attenuation and group velocity in X3 direction were related to the loss of mechanical properties (elastic modulus, ultimate tensile strength, and toughness) in this direction. The results indicate the loss of mechanical properties at the impact point, can be related to the change in attenuation at this point. However, the attenuation change beyond the impact center did not correlated with the degradations in mechanical properties. The attenuation change at 0.5 inch away from impact point was almost zero, while degradation in E and UTS was about 80%. Over the entire test region, attenuation change coverage to zero much faster than the property degradations. Figure 2 shows a typical comparison of the changes in attenuation with mechanical property degradation. It can be concluded that while micro-cracks have drastic effect on mechanical properties, they have negligible effect on wave propagation characteristic. Similar conclusion was drawn for the changes of the group velocity and their relation with the mechanical properties degradation.

The stress wave factor was measured at several threshold levels. Figure 3 shows the stress wave factor becomes scattered as the value of threshold increased. In both 7-ply and 24-ply panels, the lowest threshold level (0.002V) gave the most orderly behaved SWF whose changes were in accordance with the degradation profile. Figure 4 shows a

comparison between the changes in SWF with the changes in mechanical properties for 7-ply panels.

Since frequency spectrum of the received signal depends on the damage level, the extent of the damage can be studied by evaluating properties of the frequency spectrum. Various moments of the frequency spectrum about a convenient axis are defined [3] as:

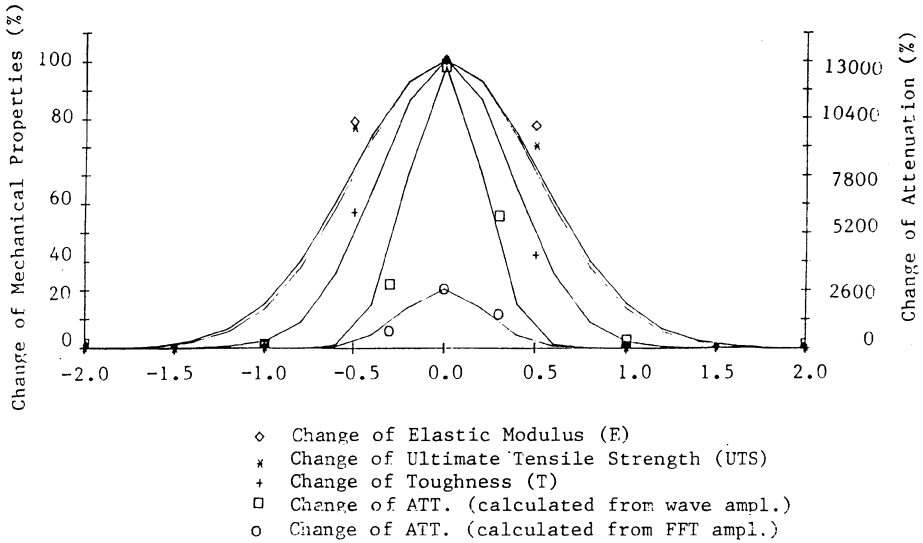


Fig. 2. Comparison of Changes in Attenuation and Mechanical Properties in 7-Ply Composite Panels (Along X3 Axis).

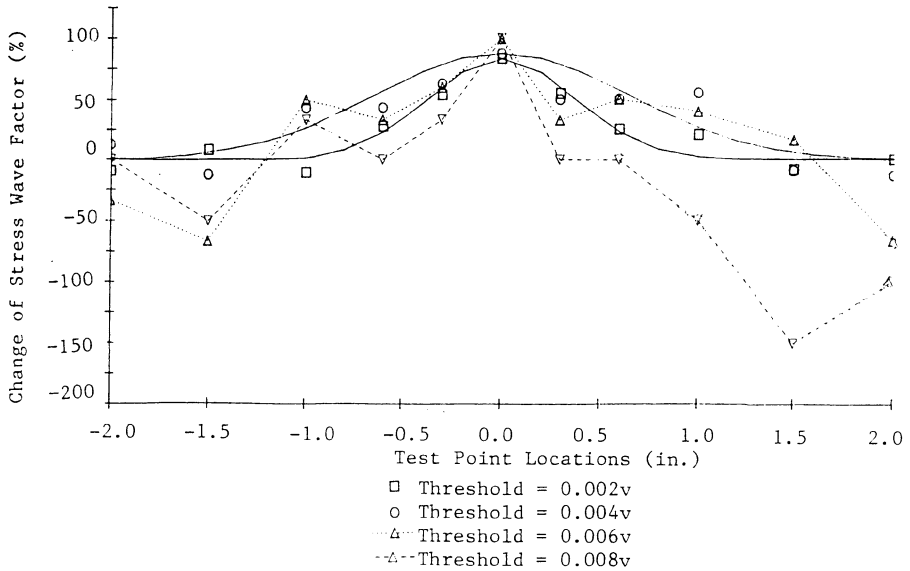


Fig. 3. Changes of Stress Wave Factor Values Along X3 Axis in 7-Ply Composites for Different Threshold Levels.

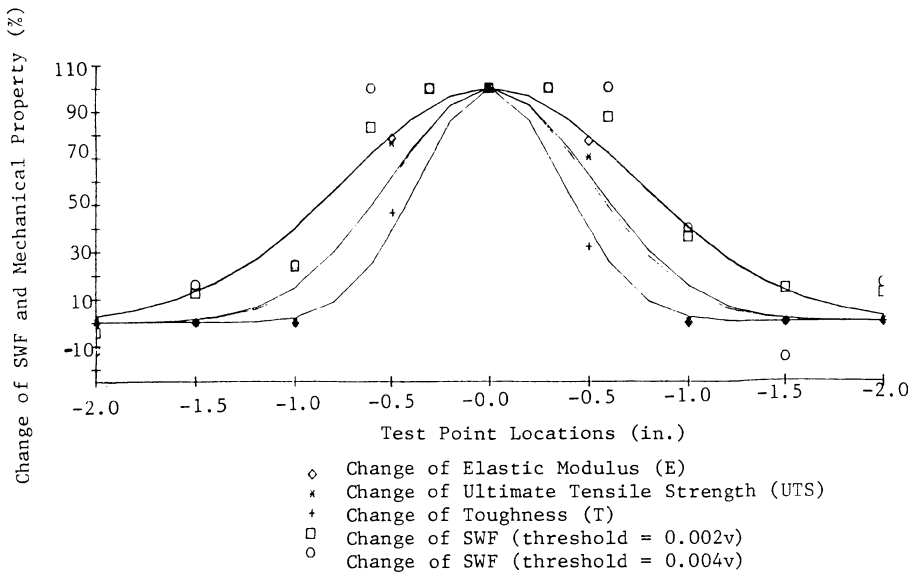


Fig. 4. Comparison of Changes in Stress Wave Factors and Mechanical Properties in 7-Ply Composites (Along X3 Axis).

$$M_r = \int_{f_1}^f S(f) f^r df \quad (1)$$

where $S(f)$ is the amplitude at frequency f , and r is a constant depending on specific moment. M_0 defines the area of the frequency spectrum, and $M_0^{1/2}$ is defined as the root mean square value of the spectrum. The centroid location f_c , and frequency of mean value, f_0 , and frequency maxima f_p are described as:

$$f_c = \frac{M_1}{M_0} \quad (2)$$

$$f_0 = \left[\frac{M_2}{M_0} \right]^{1/2} \quad (3)$$

$$f_p = \left[\frac{M_4}{M_2} \right]^{1/2} \quad (4)$$

These parameters were evaluated along X3 axis during SWF experiments. The changes in spectral properties (M_0 and $M_0^{1/2}$) are compared with the degradations in mechanical properties in 7 and 24-ply composites. Figure 5 show that both M_0 and $M_0^{1/2}$ are very sensitive to the damage and correlate closely to the degradations of E and UTS over the entire impact affected area.

The ultrasonic NDE methods applied in this research assess the collective effects of various damage induced by impact loading and the resultant variations in mechanical properties. Damage in matrix, fibers, fiber-matrix bondings and interlaminar bonds are factors that underline the degradations in mechanical properties as well as ultrasonic parameters. In ultrasonic evaluation, the damage is characterized by the variations in amplitude of wave form components in the time and frequency domains. Vary [4] has pointed out these time and frequency domain features are related to one or more material and structural factors. A particular wave or frequency component can be most relevant to a parti-

cular material property or damage state. In order to assess a collective damage state by the ultrasonic methods, every component of the ultrasonic wave packet should be taken into account. However, in attenuation and group velocity measurement, only the amplitude variation of one peak of the entire wave form (or the amplitude variation of the central frequency in the frequency domain) is considered. A single peak or a single frequency component is not sufficient to describe an integrated damage state.

CONCLUSIONS

The dominant failure mechanisms observed in unidirectional graphite/epoxy composite panels subjected to impact were matrix cracking along the fiber direction, delamination, fiber fracture, and local buckling of sublaminates. Matrix cracking was initiated in an early stage of impact, followed by other failure mechanisms in sequence or in combination. Different stages of damage generation were indicated by the short peaks and irregularity in the loading portion of the impact force curve. We believe that flexural stress waves were the major energy carrying mechanism contributing to propagation of damage and distribution of impact energy. The initiation and propagation of the cracks in the matrix led to a reduction of energy transmission efficiency of the composite panels. It further resulted in impact energy concentration in and near the center of impact. Consequently, heavy damage occurred in that area. However, the dynamic responses and damage pattern of 24-ply panels suggested that if a composite material is capable of restraining the propagation of transverse cracking, its energy transmission efficiency will be maintained, resultant damage can then be reduced.

A significant decrease in elastic modulus E was accompanied with delamination and local buckling of sublaminates. Matrix cracking parallel to the fiber direction alone did not significantly affect E , however such cracking reduced ultimate tensile strength UTS and toughness T significantly.

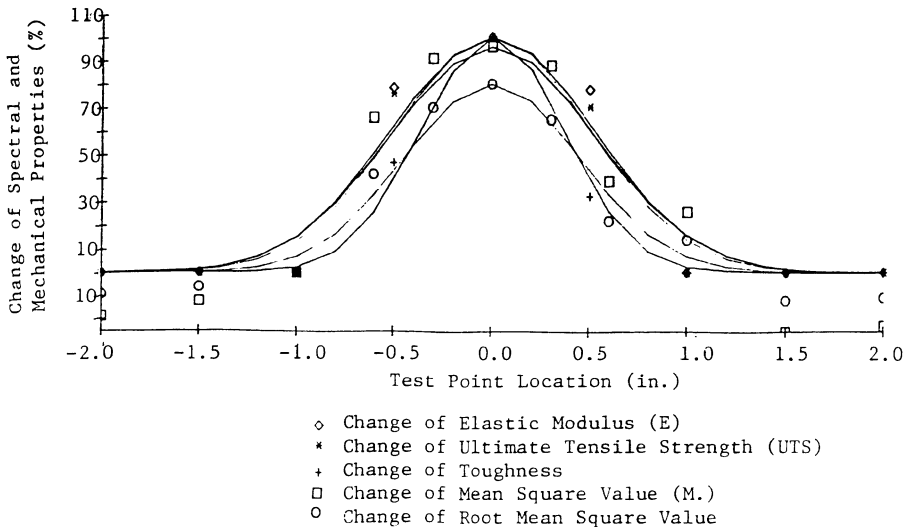


Fig. 5. Comparison of Changes in Frequency Spectral and Mechanical Properties in 7-Ply Composites.

The comparison of observed impact damage with theoretical results indicated that Greszczuk's theory for low velocity impact to composite materials is reliable.

For nondestructive evaluation, group velocity and attenuation are ineffective ultrasonic parameters for degradation assessment: measured group velocity did not reveal impact induced variations in mechanical properties when such variations were below the level of 25% degradation in E (or 65% degradation in UTS). The major disadvantage of attenuation is that it does not respond correlatively to degradation of mechanical properties beyond the impact center.

Stress wave factor, however, is damage sensitive, its change is correlative to degradation of mechanical properties. The change of SWF at the impact center correlated closely with degradation in E, UTS, and T. However, if the trends of the degradation over a broad range and at different damage levels were also of concern, SWF gave reliable assessment of degradation in E only.

The threshold level for the SWF measurements was 0.002v. As a general guideline, threshold level should be set just above the noise level of the wave packet. Furthermore, the time zone for ringdown count should be selected so as to truncate the trailing 2 to 3 cycles of the wave packet for better noise elimination.

Among the five frequency spectral properties evaluated, the mean square value M_0 and the root mean square value $M_0^{1/2}$ of the spectrum were found useful for degradation measurement. The changes of M_0 and $M_0^{1/2}$ correlated closely to the degradation in E and UTS over the entire impact affected area. Experimental results also suggested that M_0 is more suitable for assessing degradation at the impact center, while $M_0^{1/2}$ is more reliable in assessing the extent of degradation over a broad range.

The evaluation of ultrasonic methods also suggested that to determine an integrated degradation state of a composite material, rational assessment can be reached only by the ultrasonic methods that give weight to every component of the entire received waveform packet.

ACKNOWLEDGMENTS

The authors are grateful to Dr. Al Broz from Army Material Technology in Watertown, Mass, for many useful discussions and financial support. Special thanks to Mary Traboulsy for typing the manuscript in a short notice.

REFERENCES

- 1 N. Zheng, "Nondestructive Evaluation of Damage and Degradation of Mechanical Properties in Composite Panels Subjected to Impact Loading", M. S. Thesis, Dept. of Mech. Eng., May 1989, Northeastern University, Boston, MA 02115
- 2 Greszczuk, L. B., and H. Chao, "Investigation of Brittle Fractures in Graphite-Epoxy Composites Subjected to Impact", USA-AMRDL-TR-75-15, May 1975.
- 3 Talreja, T., A. Govada, and E. G. Henneke, II, "Quantitative Assessment of Damage Growth in Graphite Epoxy Laminates by Acousto-Ultrasonic Measurements," Review of Progress in Quantitative Nondestructive Evaluation, Vol. 3B, D. O. Thompson and D. E. Chimenti, Eds., 1984, pp. 1099-1106.
- 4 Vary, A., and K. J. Bowles, "Ultrasonic Evaluation of the Strength of Unidirectional Graphite/Polyimide Composite," Proceedings of the 11th Symposium on Nondestructive Evaluation, 1977, pp. 242-258.