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NONDESTRUCTIVE EVALUATION OF FIBER COMPOSITE
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**USE OF AN ULTRASONIC-ACOUSTIC TECHNIQUE FOR NONDESTRUCTIVE
EVALUATION OF FIBER COMPOSITE STRENGTH**

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SUMMARY

This report describes the ultrasonic-acoustic technique used to measure a "Stress Wave Factor." In a prior study this factor was found effective in evaluating the interlaminar shear strength of fiber-reinforced composites. Details of the method used to measure the stress wave factor are described. In addition, frequency spectra of the stress waves are analyzed in order to clarify the nature of the wave phenomena involved. The stress wave factor can be measured with simple contact probes requiring only one-side access to a part. This is beneficial in nondestructive evaluations because the waves can run parallel to fiber directions and thus measure material properties in directions assumed by actual loads. Moreover, the technique can be applied where conventional through transmission techniques are impractical or where more quantitative data are required. The stress wave factor was measured for a series of graphite/polyimide composite panels and results obtained are compared with through transmission immersion ultrasonic scans.

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INTRODUCTION

It is known that elastic and strength properties can be determined from the measurement of ultrasonic-acoustic wave propagation through a material. For example, ultrasonic wave velocities in materials yield measurements of tensile and shear moduli (ref. 1). It has recently been shown that ultrasonic attenuation in composites is sensitive to factors (e.g., microvoids) that influence strength properties. (ref. 2). Conventional ultrasonic methods are currently limited to discovering defects or discontinuities, e.g., delaminations in composites, cracks in metals. There

is considerable interest in nondestructive evaluation (NDE) of material parts that contain only subtle microstructural variations. Advanced NDE techniques are needed to evaluate critical parts in order to ensure that they meet design requirements. The general approach is to treat each hardware item as an unknown until an NDE technique has certified that it has the material properties intended.

The work described herein is a continuation of a previously-reported study of an ultrasonic-acoustic method (ref. 3). In that study it was shown that a "stress wave factor" measurement correlated strongly with the interlaminar shear strength of a graphite-polyimide composite. This stress wave factor is a measure of the efficiency of stress wave energy transmission. It was demonstrated that greater values of this factor corresponded to greater interlaminar shear strength in the composite investigated. This report describes the methodology involved in measuring the stress wave factor. Particular emphasis is given to describing the nature of the ultrasonic-acoustic waves generated by the method. Results using the stress wave factor are compared with results obtained with the conventional through transmission, immersion ultrasonic method.

PROCEDURE AND RESULTS

For the tests described herein, fifteen AS-graphite PMR-15 polyimide panels were fabricated. Each panel was a 12-ply unidirectional laminate made with cure pressures that ranged from 0.345 to 5.52 MPa (50 to 800 psi). Physical dimensions and fabrication conditions are given in table I. Fabrication details were similar to those given in ref. 3. Using only cure pressure as a fabrication variable, it was possible to produce a significant range of material properties.

The variations in material properties are evident in fig. 1 which shows ultrasonic through transmission amplitude scans of selected panels. The ultrasonic scans were produced by a water immersion, two transducer method, described in ref. 3. The scans show variation in ultrasonic attenuation due to factors such as voids, delaminations, resin-richness, etc. Greater attenuation corresponds to lower signal levels relative to the baseline in the amplitude scan images.

Figure 1 shows two sets of scans. The first set, figs. 1(a) through 1(c), shows the "optimum" product obtained with three different cure pressures. The second set, figs. 1(d) through 1(f), shows low quality products all obtained with the same cure pressure of 0.689 MPa (100 psi). These represent potential product variations that might occur even when production controls are in effect.

After being ultrasonically scanned, the panels were subjected to stress wave simulation measurements. For these measurements a sending transducer injects a repeating series of ultrasonic pulses into the material. Each of these pulses produces simulated stress waves that mimic acoustic emission events in the material, ref. 4. A receiving transducer intercepts some of the simulated stress wave energy that radiates from the point of injection.

The stress wave factor value generated for each test area depends on the wave propagation properties of the composite. Microstructural factors that influence the magnitude of the value are fiber/resin ratio, voids, delaminations, etc. The number generated is a relative one that will differ for substantially different specimen geometries, i.e., widths, thicknesses, etc. In this respect the stress wave method does not differ from the through transmission immersion method. In either case, calibration against a standard piece of material is needed as a reference.

The transducer configuration for simulation of stress waves and measurement of the stress wave factor is illustrated in fig. 2. Stress wave simulation was accomplished with a 2.25 MHz piezoelectric transducer coupled directly to the specimen surface. The receiving transducer was a piezoelectric acoustic emission transducer having a resonant frequency of approximately 0.5 MHz and an effective bandwidth of roughly 1 MHz.

The sending transducer injects longitudinal waves into the specimen. In the zone of signal injection a mode conversion effect occurs. The waves emanating from this zone are therefore complex and have both transverse as well as longitudinal components. The receiver is coupled to the surface through a waveguide. The waveguide transmits only the longitudinal component of the wave that is coupled into it. The waveguide also serves as a delay line that separates the received signal from the input pulse for analytical purposes.

The coupling medium used to bring the probes into contact with the specimen is an important factor in making these measurements. It was found that water with a wetting agent is appropriate to the graphite-polyimide composite of this study. An alternative couplant is glycerin. However, it is necessary to allow for a considerably longer "settling-in" time before the coupling is established: >30 seconds vs. <10 seconds with water. Methyl alcohol gave the shortest settling-in time but it evaporates too fast to be useful.

The signals arriving at the receiver resemble "burst" type acoustic emission events, fig. 2(d). After traveling through the composite, these simulated stress waves bear the imprints of factors that might alter an actual stress wave emanating from the injection zone. The simulated stress waves are repeated at a fixed rate R . The received signal roughly resembles a decaying sinusoid. Each successive "burst" is identical to its predecessors. After amplification, the received signals are sent to a counter that counts the number of oscillations N in each burst exceeding a fixed threshold voltage. The counter is reset automatically after a predetermined time interval G and the previous count is held in a memory and digitally displayed. The displayed count assumes a constant value soon after the specimen is coupled to the probes. It can readily be shown that the oscillation count in each burst is numerically proportional to its energy content as measured by finding the root-mean-square amplitude of the burst waveform. The number that is displayed is $c = GPN$, the stress wave factor.

The number c depends on factors such as signal gain, reset time, threshold voltage, repetition rate, and so forth. All these factors are kept constant for any series of measurements so that c reflects only the material variations of the specimens tested. The stress wave factor is plotted against cure pressure in figure 3, see DISCUSSION for comments.

It is possible to measure the stress wave factor in three directions relative to the (unidirectional) fibers: (1) longitudinally, parallel to the fibers with both probes on one side as in figure 2(c); (2) transversely, perpendicular to the fibers (again with probes on one side); and (3) transversely, through the laminate thickness with probes on opposite sides. All the c values quoted in table I were measured longitudinally, as in case (1). Each c value in table I is the arithmetic mean of 90 uniformly

spaced measurements for each panel.

Frequency spectrum analyses were made of the received signals. Examples of the frequency spectra are shown in figure 4. These spectra correspond to the stress wave travelling parallel to the unidirectional fibers. For the 5.52 MPa (800 psi) panel, the spectrum exhibits a strong peak at about 0.75 MHz, fig. 4(a). As the cure pressure decreases (with a resultant increase in voids), this peak decreases.

It should be recognized that the frequency spectra of the actual stress waves are modified by the transfer function of the receiving transducer and instrumentation. To make sure that the spectra shown are representative of the material variations it is necessary to know the frequency response characteristics of the transducer. The transducer response curve is shown in figure 4(f). From this it can be inferred that most of the signal modulation seen below 0.9 MHz in the previous spectra arose because of material variations in the specimens. Measurement of through thickness transit times indicated that frequencies from 0.3 to 0.8 MHz should be reinforced, ref. 5. The strong 0.75 MHz peak seen in the frequency spectra of figure 3 is apparently primarily due to specimen plate resonance. However, it is seen that the amplitude at this frequency correlates with material properties and hence was a key factor in determining ϵ .

The instrumentation operated within a narrow frequency domain, i.e., between 0.1 MHz and 2.5 MHz. Different results should be expected in case of substantially different frequency domains. The domain used was determined to be suitable for the composite material studied. The main criterion was that the wavelength of the injected pulses be of the order of the specimen thickness. The 2.25 MHz transducer introduced strong frequency components in the resonance regime of the specimen thicknesses involved. This criterion was based on practical considerations. The excitation pulses were injected with a 2.25 MHz transducer because higher frequencies would not yield good stress wave factor measurements for the full range of material conditions. The attenuation would be too high for higher void contents. Frequencies much lower than about 0.1 MHz would not produce wave interactions appropriate to the specimen microstructure.

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DISCUSSION AND CONCLUSION

It is significant that the stress wave signal can run parallel to the major fiber direction. Therefore, the stress wave factor can measure material properties in directions that actual loads might assume. Note that the stress wave simulation method requires only one side access and that it immediately returns a number that rates the product. Also, the stress wave factor corroborates and augments the qualitative indications given in the scan images. The stress wave simulation method yields a quantitative rating of material condition. When ϵ values are compared with scan images of the corresponding panels it is clear that lower mean values of ϵ are associated with less satisfactory panels. Higher mean values of ϵ are associated with panels that show less attenuation, for examples compare figs. 1 and 3.

The relation between ϵ and cure pressure is shown in the plot of figure 3. It has been demonstrated (ref. 3) that for the graphite fiber composite type dealt with here, material strength increases directly with cure pressure over the range studied. Hence, higher values of ϵ do correspond to greater interlaminar shear strength. A composite with high values of ϵ would exhibit higher strength because resistance to fracturing is enhanced by the same factors that increase ϵ . Good transmission of ultrasonic energy denotes good transmission of dynamic stresses and loads. Conversely, low values of ϵ would indicate that fracture energy is likely to concentrate near crack nucleation sites and thus induce crack growth.

The curve in figure 3 is actually an upper bound that represents an apparent optimum condition for a given cure pressure. For example, a number of panels that were made at 0.689 MPa (100 psi) varied considerably in the mean ϵ value. When examined by ultrasonic scanning, these panels also exhibited a greater and more chaotic attenuation pattern, see figs. 1(d) through 1(f). This observation demonstrates that the stress wave simulation method can distinguish inferior material that can arise even when a key processing parameter (cure pressure) is controlled.

The various resonance peaks in the frequency domain (figs. 4(a) - 4(f)) indicate the nature of the wave phenomena involved in measuring ϵ . For the relatively thin panels of this study the injected ultrasonic wave reverberated between the panel surfaces. The signal reaching the receiver was therefore modulated according to interlaminar property variations.

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TABLE I. - DESCRIPTION OF GRAPHITE-POLYIMIDE
COMPOSITE PANELS^a

| Panel ^b | Cure pressure ^c | | Thickness ^d | Stress wave ^e |
|--------------------|----------------------------|-------|------------------------|--------------------------|
| | MPa | (psi) | cm | factor |
| 31 | 2.07 | (300) | 0.263 | 10.9±0.7 |
| 32 | 3.45 | (500) | .266 | 12.6±0.5 |
| 33 | 5.52 | (800) | .259 | 13.7±0.4 |
| 34 | 1.38 | (200) | .271 | 2.9±0.4 |
| 35 | 1.38 | (200) | .268 | 4.8±0.3 |
| 36 | 1.10 | (160) | .273 | 2.2±0.4 |
| 38 | .689 | (100) | .276 | 4.5±1.3 |
| 39 | .689 | (100) | .280 | 4.8±0.8 |
| 40 | .345 | (50) | .310 | 5.8±0.8 |
| 41 | .689 | (100) | .277 | 3.5±0.6 |
| 42 | .689 | (100) | .265 | 7.3±0.7 |
| 44 | 1.38 | (200) | .230 | 9.9±0.4 |
| 46 | 1.10 | (160) | .231 | 8.9±0.6 |
| 47 | .689 | (100) | .250 | 1.6±0.5 |
| 48 | .862 | (125) | .256 | 2.1±0.3 |

^aMaterial was AS-graphite PMR 15 polyimide.

^bOverall panel dimensions were 22.8 by 7.6 cm (9 by 3 in.).

^cPanels were cured at 315 C (600 F) for one hour.

^dThickness was 12 plys, unidirectional with long axis.

^eArithmetic mean of 90 uniformly-spaced measurements.

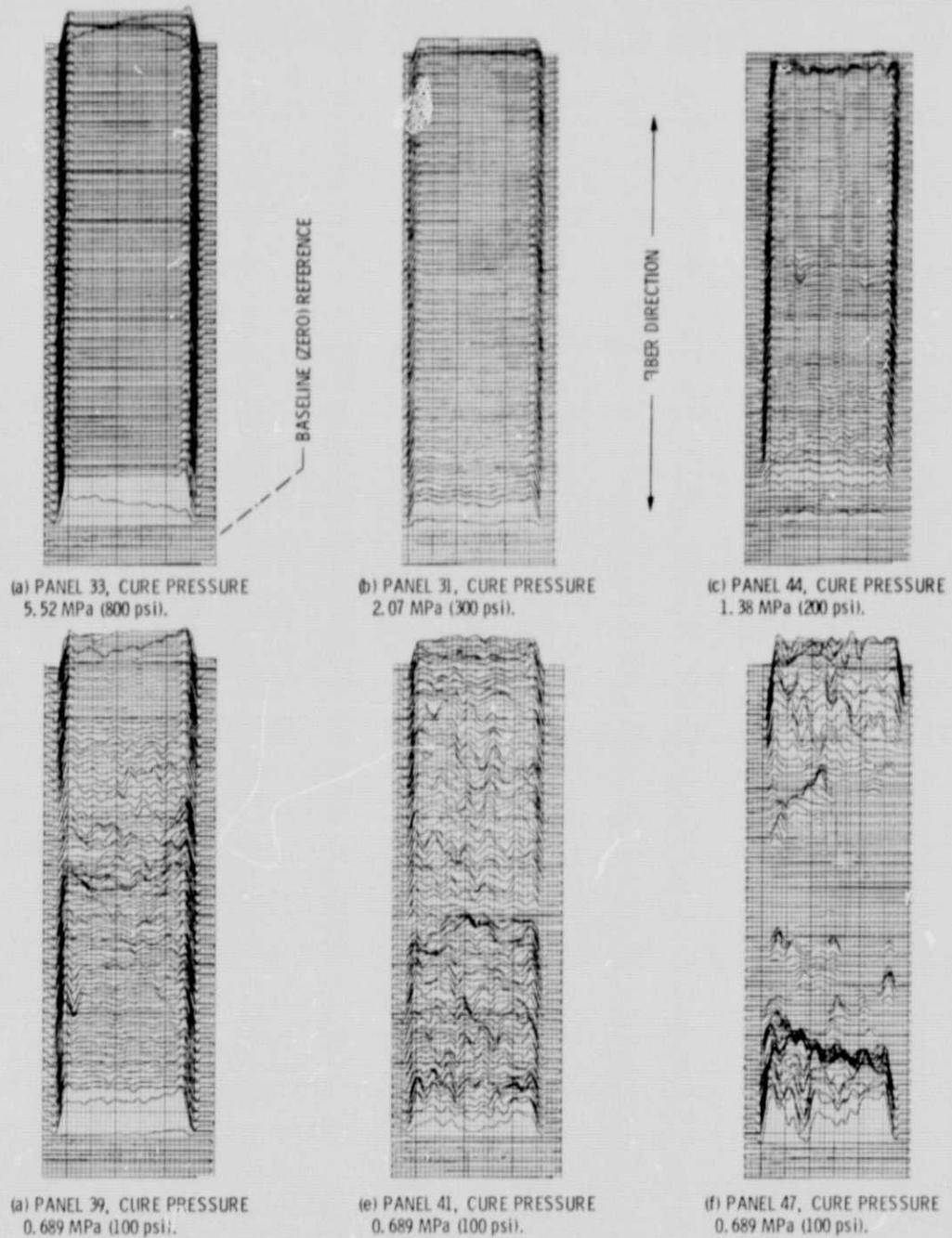
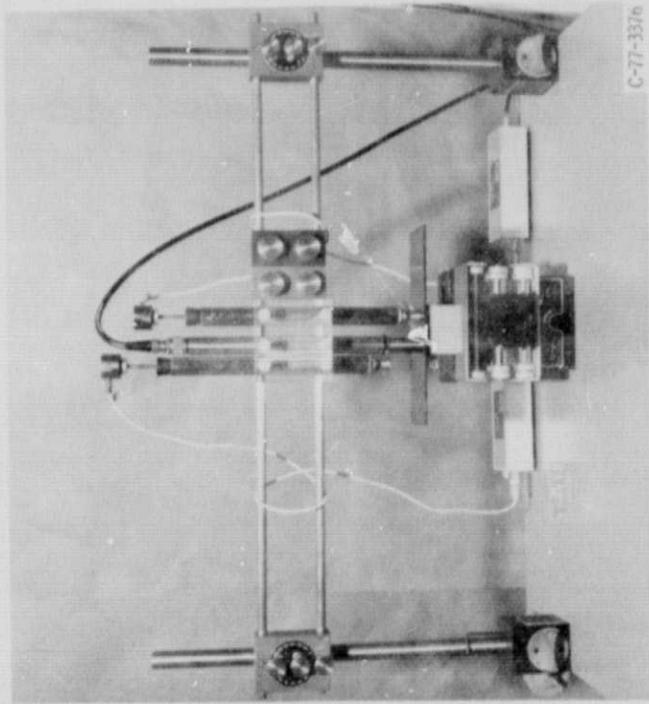
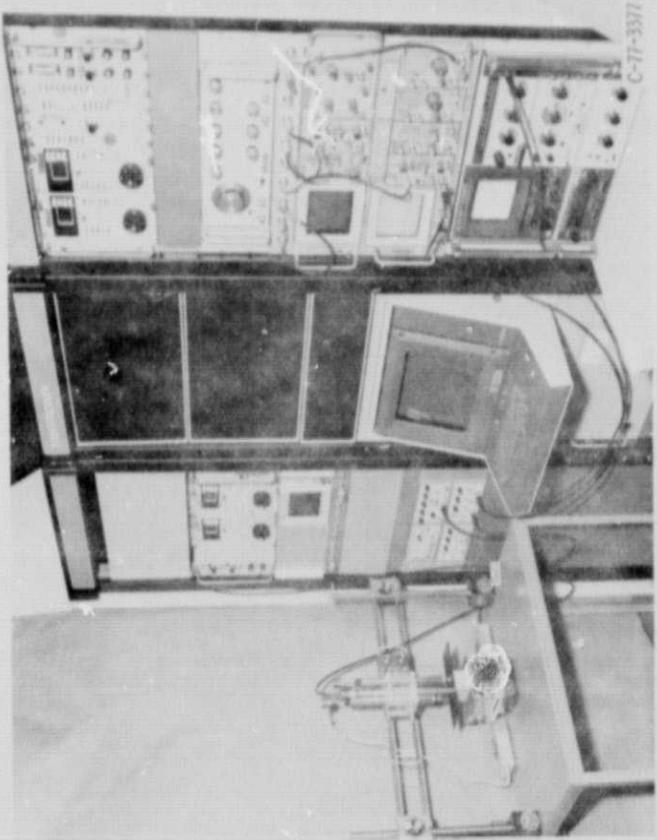


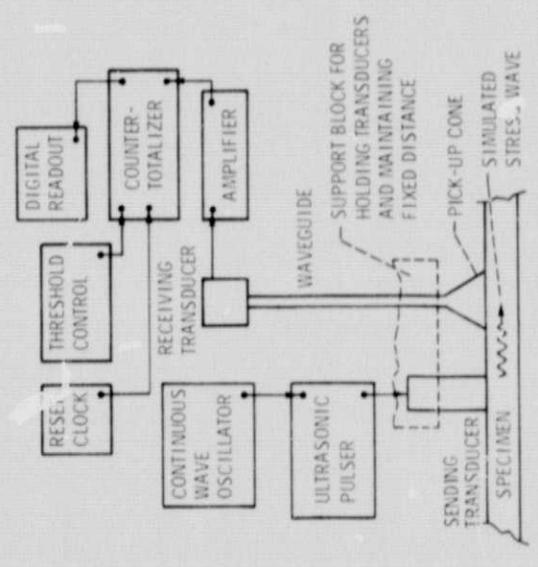
Figure 1. - Through transmission immersion ultrasonic amplitude scans of graphite-polyimide composite panels. Scans show amplitude of transmitted signal referred to zero transmission baseline reference at bottom.



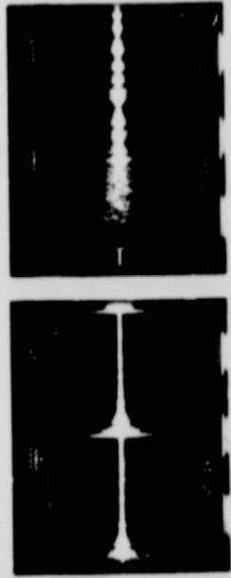
(a) DETAIL VIEW OF PROBES AND FIXTURE.



(b) OVERALL VIEW OF ULTRASONIC SYSTEM.



(c) APPARATUS FOR STRESS WAVE SIMULATION & MEASUREMENT.



OSCILSCOPE TRACE SHOWING CONTINUOUSLY REPEATING BURSTS OF SIMULATED STRESS WAVES.

SINGLE BURST WAVEFORM. THRESHOLD OF OSCILLATION COUNTS IS ± 0.5 SCALE DIVISION.

(d) SIGNALS USED FOR STRESS WAVE OSCILLATION COUNT.

Figure 2. - Apparatus and signal treatment used for measuring stress wave factor.

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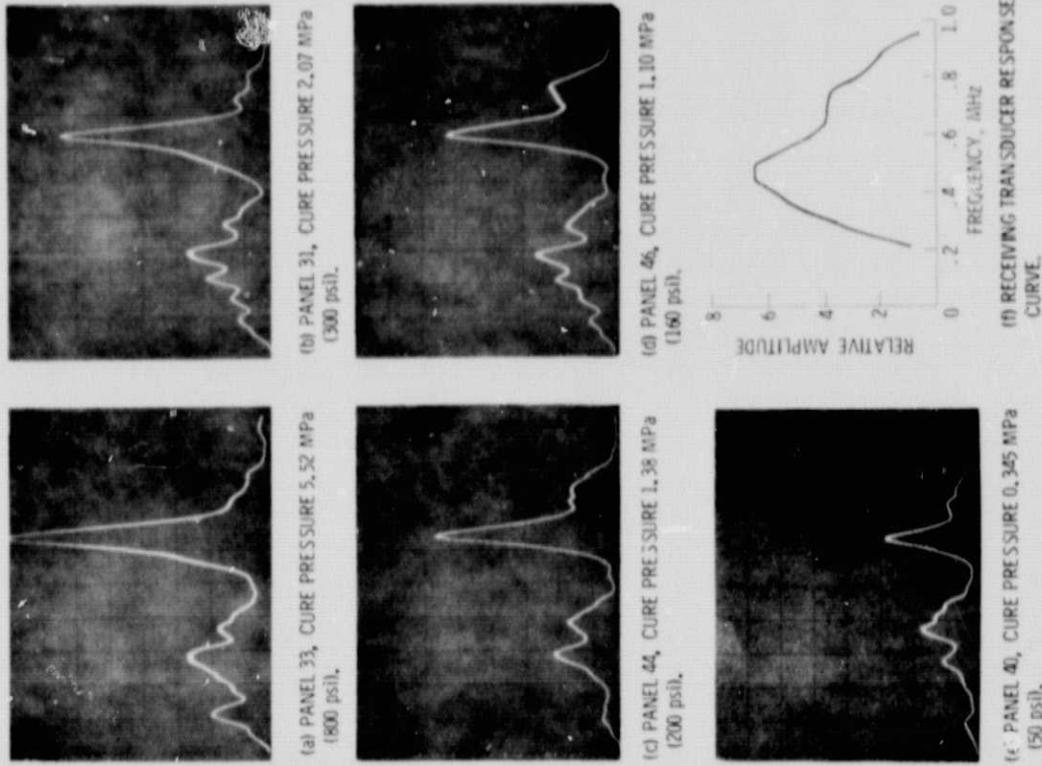


Figure 4. - Frequency spectra of stress wave signals, (a) through (e). Receiving transducer response curve is plotted in (f). Frequency spectra in (a) through (e) have coordinate scales identical to those in (f).

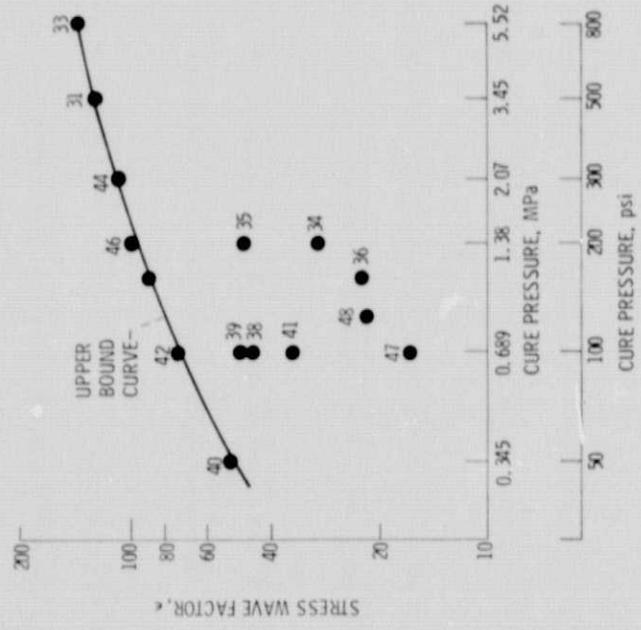


Figure 3. - Stress wave factor as a function of cure pressure for graphite-polyimide composite panels. Numerical identifications of data points correspond to panel identifications in table I.