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Testing of Fiber Composites

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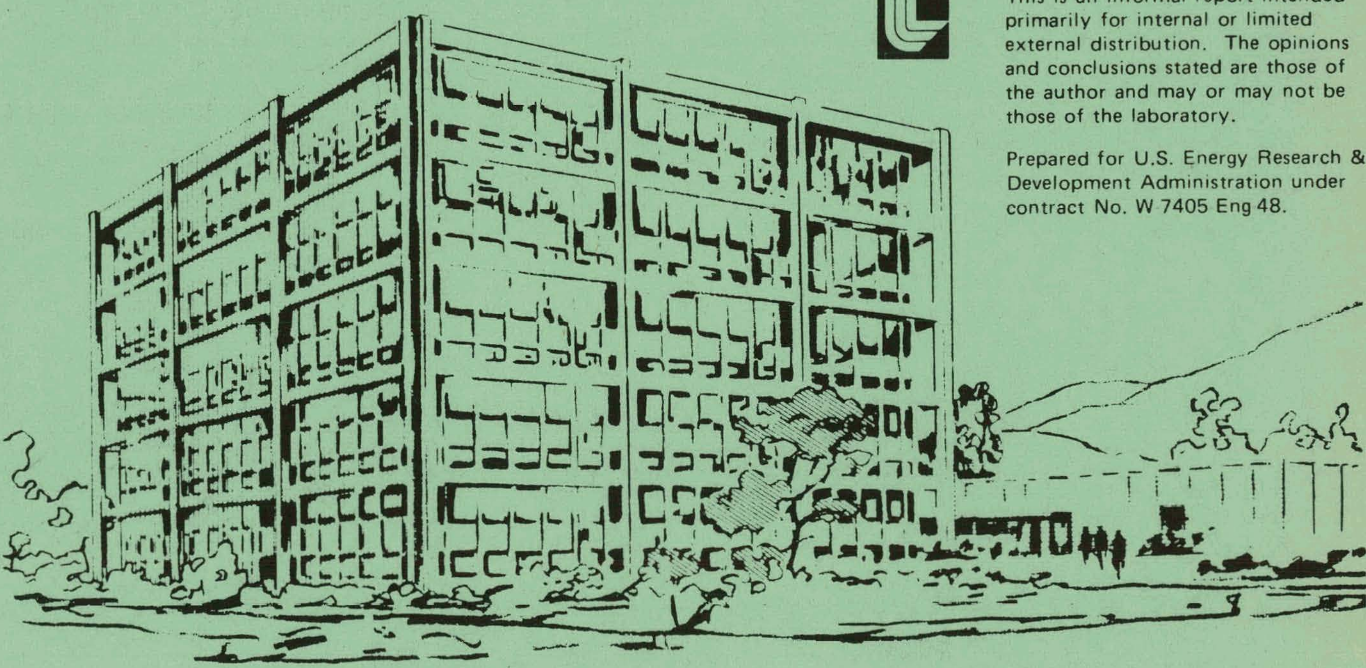

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On a Philosophy for Nondestructive Testing of Fiber Composites

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ABSTRACT

A discussion of a nondestructive testing philosophy for fiber composites is presented. The position is taken that the nondestructive test indications must be quantitatively correlated to the required engineering performance properties of the composite article. The currently unknown defect structure in many fiber composites is discussed with respect to nondestructive testing. A few examples from the literature of the above described quantitative nondestructive testing of fiber composites are presented from the fields of acoustic emission and ultrasonics.

INTRODUCTION

All engineering structures are designed to meet certain requirements in terms of load, deflection, lifetime, etc. When he designs the structure, the designer assumes certain values for the strength, modulus, fatigue life, etc. of the material. These values are based on certain mechanical tests that were performed on the material type that is to be used in the design or on actual prototypes in cases where theoretical design is not adequate. If the designer does not make mistakes, if the structure is fabricated to the designed geometry, and if the flaw or defect structure (includes types, sizes, orientations, locations and number) in the manufactured article is the same (or less detrimental) as in the specimens used in the mechanical tests, then the actual engineering structure should meet all necessary service requirements without an unexpected failure.

Designer mistakes should be exposed and corrected as a result of prototype testing to failure. Further, it is not normally a difficult task to see that the structure has been fabricated to the designed geometry. The key question has to do with flaws or defects in the finished structure. This question is particularly important for fiber composites where, during the structural fabrication procedure, fiber with a given flaw structure is combined during a manufacturing process with a matrix with another given flaw structure. The result is a composite article which then has a flaw structure that can be pictured as having three components: (1) that associated with the fibers; (2) that associated with the matrix; and (3) that which is inherently created by the manufacturing process (e.g., damage to fibers, mis-aligned fibers, resin rich or poor regions, uncured or overcured regions, etc.).

Because it has been recognized that flaw structures always exist in a finished composite article, various approaches have been used to assure the user that the resulting flaw structure is less severe than in the composite upon which the designer's assumed properties were based. One possible approach to try to control the problems of flaw structure is to set strict specifications on the acceptance of the raw fiber and matrix materials, and on the manufacturing process. A further step in the sophistication of attempts to control the results of the flaw structure is to randomly select a certain percentage of the finished composite articles and to test them to failure under the design conditions. It is presumed that if all material and fabrication specifications are met, and if each failure of the randomly selected articles is above design levels, then the rest of the composite articles will perform as expected.

A further sophistication is to proof test each composite article to or above design levels. The weakness of this approach as well as all the other schemes listed above is that no quantitative information is obtained on the defect structure of the composite that will allow one to state definitely whether or not the composite article will survive its designed lifetime or if in fact it will fail the next time it is loaded to the design level. Another approach is to apply certain anomaly detection and location techniques to the composite article and then hypothesize that as long as the anomaly structure (type, location, size, number, and orientation) is below a certain arbitrarily defined level, then the composite article will survive its intended lifetime at design loads. The problem with this approach is that often the anomalies that are detected do not control the failure of the composite article, but instead, the failure is controlled by some unknown or undetected defect structure. This situation is not like most metal structures where we know the basic defect we are looking for is a crack, and once this defect structure has been determined by nondestructive tests, then using the accepted and experimentally based ideas of fracture mechanics, the expected performance of the metal article under use conditions can be calculated.

Since the above mentioned approaches to control the results of defects in fiber composites have difficulties associated with them, various ideal nondestructive tests (NDT) have been proposed. We suggest that the ideal NDT (i.e., one which does not impair the usefulness of the composite article) is one that has the following characteristic for <u>each</u> composite article. The required engineering performance properties (e.g., strength, fatigue life, etc.) should be quantitatively related to the defect structure determined by NDT of the composite article. We will refer to this ideal test as a quantitative NDT technique. (For a general discussion of quantitative NDT see Ref. [1].) This relation may be either a direct experimentally based relationship determined by doing destructive testing after nondestructively measuring the flaw structure of a subset of the composite items, or may be based on an analytical calculation (using an experimentally verified theory) that relates the nondestructively determined flaw structure to the required engineering design properties.

The next sections of this paper discuss in more detail some of the above ideas, after which some specific research work is examined that meets the standards of the above defined ideal NDT.

UNKNOWN FLAW STRUCTURES IN COMPOSITES

As alluded to in the Introduction of this paper, one of the main difficulties in NDT of composites is that it has not yet been established what some of the key flaws are for which they must be inspected. This situation is illustrated by the following example. A series of macroscopically identical composite laminates can be fabricated and then inspected with all the possible applicable conventional NDT techniques. The first surprising result when these laminates are tested to failure is that often the failure is not controlled by the anomalies that are discovered during the NDT testing.[2,3] Secondly, if macroscopically identical laminates without detected anomalies are tested to failure, there is often a wide variation in the experimental failure stresses.[2,3] Thus, the conclusion seems to be that there is a significant defect structure present in composite articles, but we do not know what the defect structure is or how to nondestructively characterize it.

Because of this unknown defect structure, NDT of composite articles is often an inspection of workmanship rather than assessment of whether defects are present which will prevent the composite article from exhibiting its required engineering properties. Since we do not know this defect structure or how it grows to result in macroscopic failure of the composite article, it is not any easy task to develop a quantitative NDT technique for composites. Thus, we believe it is <u>extremely important</u> that combined studies of composite microfailure mechanisms <u>and</u> of corresponding NDT inspection capabilities (to inspect for the "real" defects which initially exist and grow during the failure process) be undertaken. In fact, without such a combined study, it may be difficult to study microfailure mechanisms in composites because one would be unable to characterize the severity of the growing defects. This latter situation would be equivalent to studying fracture in metals without being able to keep track of the crack sizes. A fruitful study procedure may be to quantitatively measure a certain defect structure in several specimens, and then destructively test these specimens and attempt to correlate the measured defect severity with the failure stresses.

The solution of this unknown defect problem would probably do two things which would enhance the use of composites. First, knowledge of this flaw structure may result in the ability to lessen the severity of these flaws by different processing or fabrication techniques. Second, knowledge of this flaw structure and an associated quantitative NDT technique would allow one to separate the composite articles which do not possess the required engineering properties. Thus, it would not be necessary to follow the current practice of conservatively designing around the relatively high coefficient of variation of composites. By way of comparison, this same large coefficient of variation would often be present in macroscopically identical metallic structures if it were not for the theory of fracture mechanics and NDT crack detection capabilities.

DEFECTS AND THEIR QUANTITATIVE MEASUREMENT

A typical composite article has a very extensive anomaly structure. By this term we mean all deviations from the normal, regular, or ideal pattern of the condition of the article. The smaller the scale on which the structure is inspected, the greater will be the detected anomaly structure. We will call the subset of the anomaly structure which limits the intended use of the composite article the defect structure. It is only this defect structure which interests us because it affects the engineering properties of the article with respect to its intended use. The main task of quantitative NDT is to measure this defect structure and then to use these results to determine the expected or predicted engineering performance of the article. When the predicted performance has been determined, a decision can be made as to whether or not the article should be put in service; and if it is put into service, for how long and what possible subsequent NDT inspection intervals should be.

We have required our NDT to be quantitative. That means for a composite article that is, for example, required to survive a given load, the NDT will predict a strength of X newtons for the composite article. With a qualitative NDT, it is not possible to make a prediction of the actual strength of a part; instead, a rather arbitrary standard is set up to define a "good" vs a "bad" part. Thus, a qualitative NDT can actually result in the classification "good" of a part with insufficient strength while rejecting an article with sufficient strength. Most often the error is the latter case since designers, realizing the limitations of qualitative NDT, tend to be overconservative in their designs. Both of these mistakes in predicting the performance of a composite can be costly.

Shown in Fig. 1 are the steps we propose in the development of a quantitative NDT for a composite article or specimens. Step 1 is the application of appropriate NDT to the composite article. Step 2 is the establishment of a correlation between the recorded NDT observations and the quantified defect structure. This step may require an independent measurement of the defect structure. Step 3 is the establishment of a correlation between the required engineering performance properties and the quantified defect structure. Often, this step requires destructive evaluation of the composite articles with the quantified defect structure. This relationship could also be determined from theoretical considerations upon development of the required experimentally verified theoretical model. Step 4 uses the two correlations established to obtain a direct correlation between NDT measurements and required engineering performance. After this step, appropriate acceptance and rejection criteria can be established. It should be noted that it may be possible to skip step 2 and still develop a successful quantitative NDT. But the use of such an approach would be limited to a specific composite article and would be a fortunate development except for NDT techniques such as acoustic emission.

EXAMPLES OF QUANTITATIVE NDT FOR FIBER COMPOSITES

A relatively thorough search of the literature has revealed few examples of the ideal quantitative NDT we have proposed for fiber composites. Of the seven different examples we found, only two refer to actual useful composite structures, and only one of these is an actual production NDT application. The other cases refer to what would be better termed composite test specimens. In this search we have not included those references where artificial macroscopic anomalies, which might occur during processing and fabrication, were introduced into composite articles which were then inspected by NDT methods and then destructively tested. The reason we have not included these results is that these artificial anomalies as often as not did not control the failure of the part when it was destructively tested and in fact there were weak parts that failed below design levels in these tests due to natural but unknown defects (see, for example, Ref. [4]).

The first two examples use the NDT technique called acoustic emission. The first example is work by Green, et al. [5] in 1962, and the second is work by Jessen, et al. [6] in 1975 (see Figs. 2 and 3). In both cases, an experimental correlation was obtained between the acoustic emission generated during a proof test of a filament wound fiber/epoxy rocket motor case and the burst pressure of the rocket motor case. The early work is for actual production. The more recent work is for pre-production samples. In both of these cases the actual defect structure is not determined.

The remaining examples use the NDT technique called ultrasonics. The first two examples concern void content as the defect structure. In both cases a correlation between ultrasonic attenuation and the void content was obtained. Then a correlation between void content and interlaminar shear was obtained. These correlations were used to obtain a correlation between the attenuation and the interlaminar shear strength as in the sequence outlined in Fig. 1. Hand [7] in 1965 reported this successful work for filament wound glass/epoxy, and Stone, et al. [8] in 1975 reported successful results for carbon fiber reinforced plastic (see Figs. 4 and 5). These results are not for composite articles but for composite specimens. But they do show that such techniques have high promise of success in actual production composite articles if these articles fail due to interlaminar shear stresses.

The next two examples again did not determine the actual defect structure but instead obtained a direct correlation between ultrasonic measurements and certain mechanical properties. The work by Hastings, et al [3] in 1973 obtained results for boron/epoxy specimens rather than actual production composite articles. One correlation obtained was between the ultrasonic modulus (as calculated from ultrasonic velocity measurements) and the tensile modulus (see Fig. 6). The other correlation obtained was between the ultrasonic modulus and tensile strength (see Fig. 7). Hence, for these simple tensile specimens, measurement of the ultrasonic velocity would allow prediction of the tensile modulus and the tensile strength.

The last example by Padilla et al. [9] in 1975 concerned a correlation between the tensile strength of strands of graphite reinforced aluminum and the integrated voltage of the signal picked up by a receiver transducer from an ultrasonic pulse from a transmitting transducer (see Fig. 8). Again, these results are for a simple specimen rather than a composite production article.

CONCLUSIONS

1. Fiber composites often fail due to an unknown defect structure.

2. Research should be undertaken that combines studies to determine the unknown defect structure of composites and nondestructive tests that will measure this defect structure.

3. Quantitative nondestructive tests which will allow predictions of engineering performance properties are required for fiber composites.

4. Currently, there are almost no quantitative nondestructive tests for fiber composite articles.

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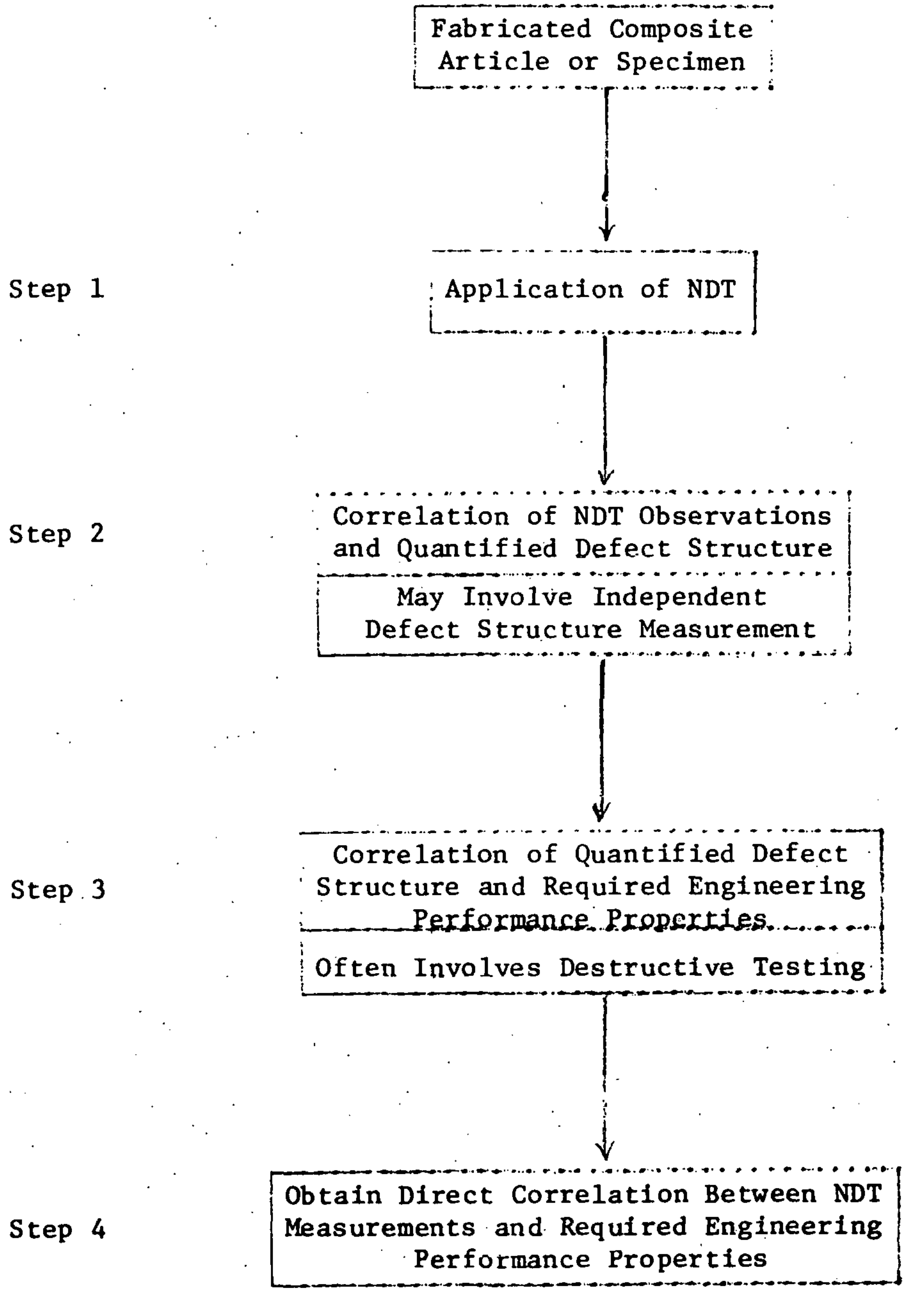

Figure 1. Schematic of Development of a Quantitative NDT for a Composite Article.

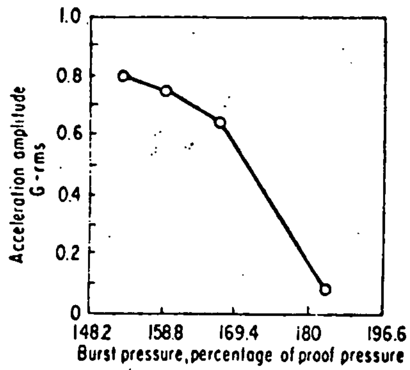

Fig. 2. Acoustic emission acceleration amplitude vs burst pressure for the glass/epoxy composite rocket chamber from Fig. 11 of Ref. [5].

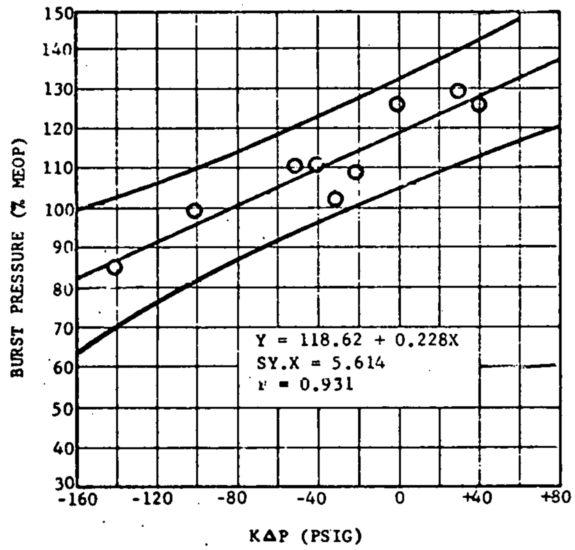

Fig. 3. Burst pressure as a percentage of operating pressure vs KΔP, Fig. 8 from Ref. [6]. KΔP is a pressure difference defined from the acoustic emission data taken on the Kevlar/epoxy composite rocket chamber.

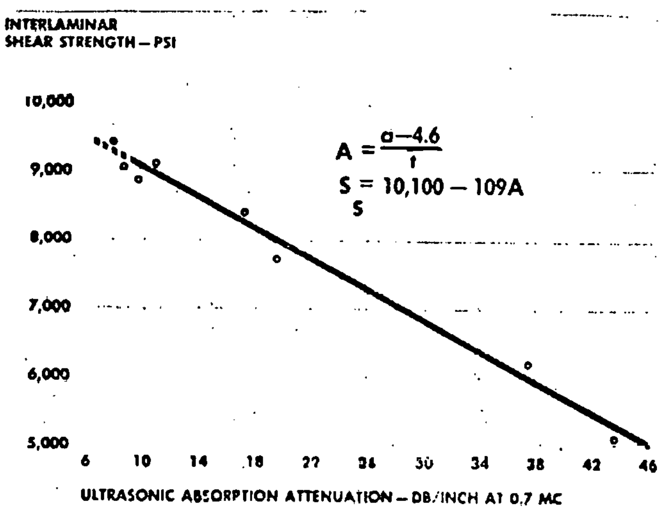

Fig. 4. Interlaminar shear strength vs ultrasonic attenuation for glass/epoxy filament wound specimens from Fig. 5 of Ref. [7].

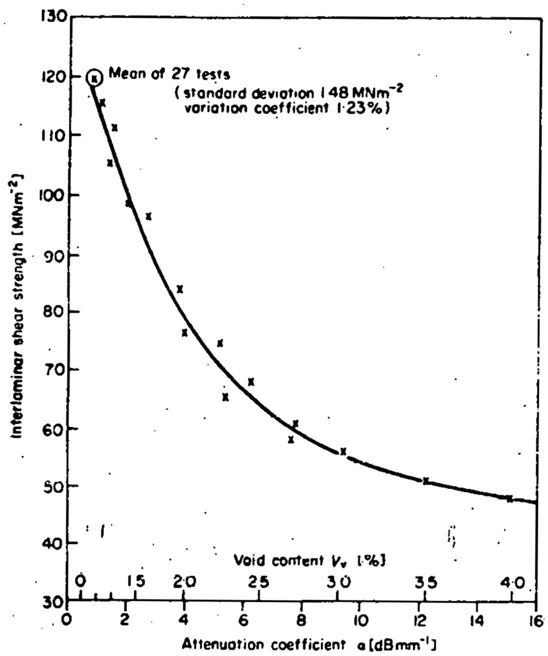

Fig. 5. Interlaminar shear strength vs ultrasonic attenuation coefficient and void content for graphite/epoxy composite specimens from Fig. 12 of Ref. [8].

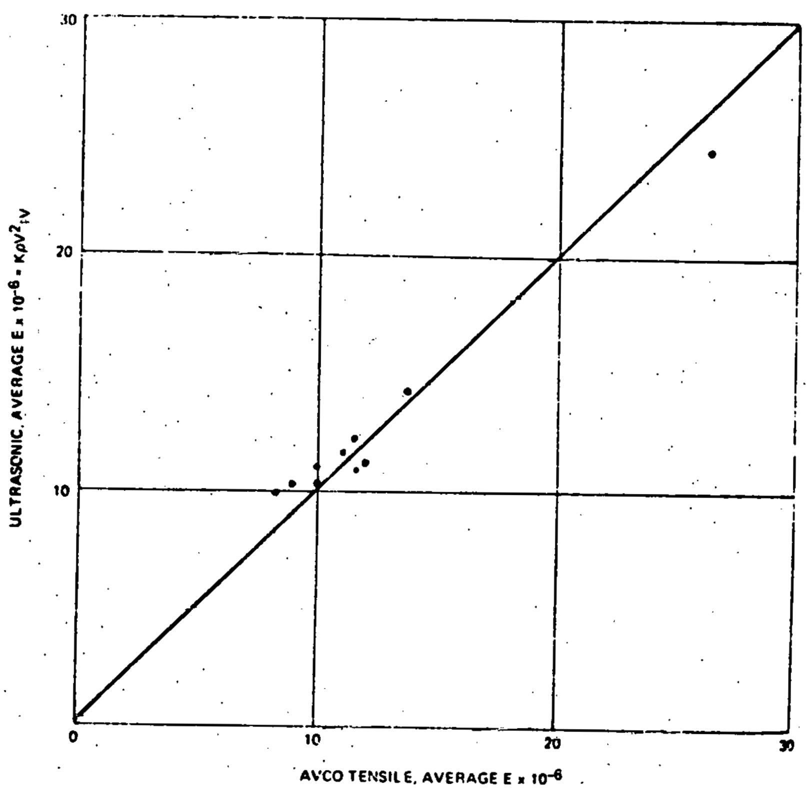

Fig. 6. Tensile modulus vs average ultrasonic modulus for boron/epoxy composite specimens from Fig. 6 of Ref. [3].

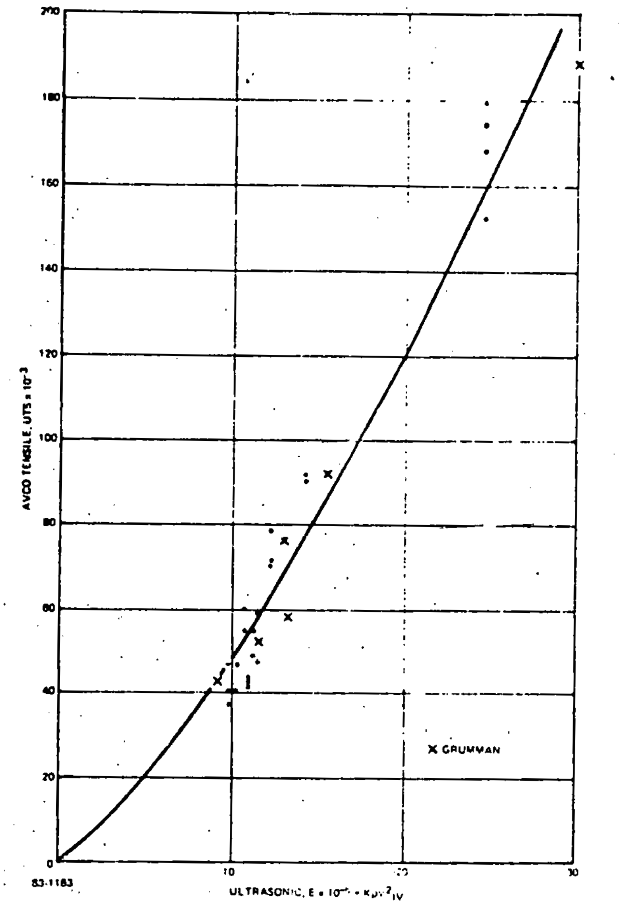

Fig. 7. Ultrasonic modulus vs tensile strength for boron/epoxy composite from Fig. 10 of Ref. [3].

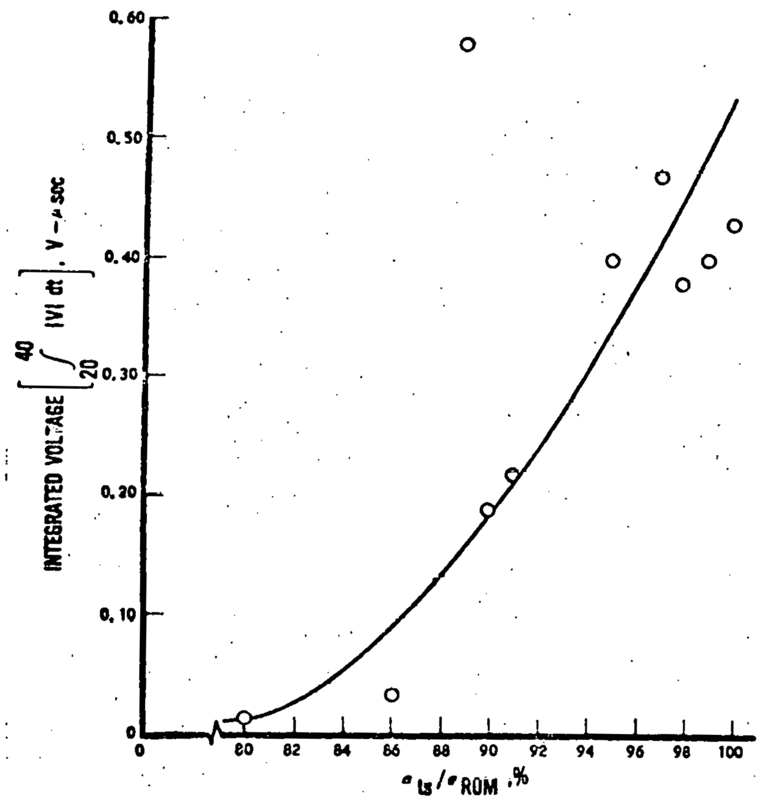

Fig. 8. Integrated voltage (of ultrasonic pulse received at 1.5 inches from transmitter transducer) vs tensile strength (as a percentage of rule of mixture) for composite strand of graphite reinforced aluminum from Fig. 20 of Ref. [9].

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