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QUANTITATIVE ULTRASONIC EVALUATION OF ENGINEERING PROPERTIES IN METALS, COMPOSITES, AND CERAMICS

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ENGINEERING PROPERTIES IN METALS, COMPOSITES, AND CERAMICS

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INTRODUCTION

Reliable performance of advanced, high-strength materials in critical applications depends on assuring that each part placed in service satisfies the conditions assumed in design and life prediction analyses. Reliability assurance requires the availability of nondestructive evaluation (NDE) techniques not only for defect detection but also for verification of mechanical strength and associated properties. Advanced NDE techniques are needed to confirm that metallic, composite, or ceramic parts will not fail under design loads due to inadequate or degraded mechanical strength. This calls for NDE techniques that are sensitive to variations in microstructure, extrinsic properties, and dispersed flaw populations that govern the ultimate mechanical performance of a structure.

In its most general context, nondestructive evaluation is a branch of materials science that is concerned with all aspects of the uniformity, quality, and serviceability of materials and structures. Therefore, NDE should not be defined solely by the current emphasis on the detection of overt flaws (Sharpe, 1976). Certainly, it is necessary to employ NDE technology to characterize discrete flaws according to their location, size, orientation, and nature. This leads to improved assessment of the potential criticality of individual flaws. Concurrently, it is necessary to develop NDE techniques for characterizing various inherent material properties. In this case, the emphasis is on evaluation of microstructural and morphological factors that ultimately govern mechanical strength and dynamic performance. As illustrated in Figure 1, a holistic approach combines nondestructive characterization of defects and also material environments in which the defects reside. This leads to improved accuracy in predicting structural integrity and life upon exposure to service conditions, particularly in the presence of discrete flaws.

The specification of flaw criticality and prediction of safe life depend on the assumption of a realistic set of extrinsic properties and conditions, such as those listed in Figure 2. Fracture and life prediction analysis models invariably presuppose flaw development and propagation in materials with well established moduli, ultimate strengths, fracture toughnesses, and fatigue and creep properties. It is within the province and capability of NDE technology to verify whether or not a structural part possesses the properties assumed in design analysis (Vary, 1980a). There are numerous NDE techniques that can be used for material properties characterization (e.g., radiometric, electromagnetic, ultrasonic) (McMaster, 1959; Green, 1973; Krautkramer, 1977; Hayward, 1978). Many of these are complementary and can be used to extend or corroborate measurements by other methods.

This paper focuses on ultrasonic techniques that have demonstrated potential for materials characterization. These techniques rely on physical acoustic properties of materials and the interaction of elastic stress waves with morphological factors in the ultrasonic regime (Mason, 1958; Kolsky, 1963; Kolsky, 1973). All the material properties and conditions listed in Figure 2 are amenable to ultrasonic evaluation to differing degrees (Vary, 1978a; 1980a). The speed of wave propagation and energy loss by interaction with material microstructure and geometrical factors underlie ultrasonic determination of material properties.

MATERIAL STRENGTH MEASUREMENTS

Ultrasonic materials characterization may be divided into two major categories. The first category pertains to measurements that are related to material strengths, e.g., elastic moduli, tensile strength, and fracture toughness. The second category pertains to morphology and material conditions that govern strength and performance, e.g., microstructure, void content, residual stress, fatigue damage. In this and the next section, we will take up these two categories in sequence. Selected illustrative cases will be given in an overview of the capabilities of ultrasonics for materials characterization.

Elastic Moduli. - Measurement of elastic moduli are fundamental to understanding and predicting material behavior, e.g., bending moments, thermal expansion, strain under load, etc. Since they are related to interatomic forces, elastic moduli indicate maximum attainable strengths. Elastic moduli also appear in equations for strain energy release rate and are related to stress wave propagation properties associated with impact shock, crack growth, fracture, etc.

As a class, brittle materials are particularly amenable to ultrasonic determination of elastic moduli. This is typified by ceramics where velocity measurements are necessary for determining elastic moduli since other methods produce either poor or no results. Moreover, moduli of brittle solids are easier to determine than either their fracture surface energy or strain energy release rate. This is because ceramics and similar brittle solids have small strains to fracture in mechanical tests (Wachtman, 1974).

Kreher, et al. (1977) demonstrated the relation of longitudinal and transverse velocities to elastic moduli of porous ceramics. Working with brittle graphites and sintered tungsten billets, Lockyer and Proudfoot (1967) obtained excellent linear relations between longitudinal modulus and destructively determined tensile moduli. Similar correlations were obtained by Proudfoot (1970) for a number of fiber reinforced composites. Schultz (1971) reported strong correlations among flexural modulus, flexural strength, and ultrasonic velocity for fiber composites. Good agreement between theory and experimental data relative to the ultrasonic moduli and strength were reported by Smith (1972) for carbon fibers and their composites.

In the case of anisotropic materials, ultrasonic measurements of various moduli can be an adjunct to strength analyses and theory (Smith, 1972). Given an unknown sample, anisotropy, symmetry, homogeneity, degree of misorientation, and similar morphological factors having a bearing on modulus and hence strength variations can be determined ultrasonic velocity measurements.

Tensile and Shear Strengths. - Magnitudes of elastic constants are related directly to strengths for some classes of brittle materials. Because the tensile modulus may be determined from longitudinal and transverse velocities, ultrasonics can form the basis for correlations with the tensile strengths of materials such as concrete, cast iron, ceramics, and some composites.

The tensile strength of cast iron may be deduced from longitudinal velocity and Brinell hardness measurements (Felix, 1963; Krautkramer, 1977). Thus, by combining two independent nondestructive measurements on a finished article, an important strength property may be verified better than by either method alone.

In fiber composite laminates, both velocity and attenuation appear important in measuring shear strength. Hayford, et al. (1977) demonstrated a dependence of through transmission attenuation on interlaminar shear strength. Vary and Bowles (1977) found a relation among interlaminar shear strength, attenuation, and velocity. The effect of fiber orientations on elastic properties of fiber composites has been studied by Zurbrick (1973). Velocity was measured parallel to the lamina. Good correlations were obtained between destructively measured tensile strengths and the ultrasonic modulus for materials ranging from glass/epoxy to boron/aluminum fiber composites.

Toughness and Yield Strength. - Ultrasonic measurements relating to yield strength and fracture resistance of structural materials have long been of high interest. There are strong incentives for ultrasonic toughness tests. One of the major cost drivers in using fracture controlled materials in aircraft is the requirement to verify toughness levels of materials at receiving inspection and also after any processing that may adversely affect fracture toughness.

The feasibility of ultrasonic measurement of plane strain fracture toughness has been demonstrated for two maraging steels and a titanium alloy (Vary, 1978b). Empirical correlations were found among ultrasonic attenuation factors, fracture toughness, and yield strength. The correlations are indicated in Figures 3 and 4. It appears that the essential measurements for deducing both fracture roughness and yield strength can be made by purely ultrasonic methods, once calibration curves have been established for a given (polycrystalline) material (Vary, 1979a).

Hardness and Gradients. - Nondestructive measurement of hardness in metals is now routinely accomplished by microindentation methods. Ultrasonic methods for the same purpose have been studied as a key to rapid, on-line product verification. For example, existing ultrasonic velocity correlations with hardness can form the basis for sorting malleable cast iron parts (Tamburelli and Quaroni, 1975).

Treatments of steel, such as hardening, annealing, quenching, and cold working, will produce a definite change in velocity. Both velocity and attenuation are generally reduced by hardening, quenching, or tempering, e.g., the attenuation coefficient varies inversely with hardness in some steels. Apparently, either velocity or attenuation measurements can correlate with the effects of various heat treatments (Papadakis, 1970; Krautkramer, 1977).

Recent studies have focused on hardness gradients associated with surface treatments. Flambard and Lambert (1976) describe two ultrasonic velocity methods for measurement of the depth of the case hardened layer in steel. Ultrasonic surface waves appear promising in the measurement of variations with depth of properties such as density, case hardening, mechanical deformation, and gas diffusion effects in metals. Hardness gradients in quench hardened steel have been shown to correlate with the frequency dispersion of surface waves (Tittmann, et al., 1973; 1974).

Lamina Bond Strengths. - The use of adhesively bonded structures and laminated composites is increasing in aerospace and other structures where high strength to weight ratios are mandatory. Relations among velocity, attenuation, and strength factors in bonded and laminar structures are being explored in efforts to evolve ultrasonic methods for predicting inter- and intralaminar and adhesive bond strengths. The approaches include: (i) metal-to-metal adhesive bond strengths from ultrasonic resonance measurements, (ii) fiber reinforced composite laminate strengths from elastic moduli determined by velocity measurements.

Evaluation of metal-to-metal adhesive bond strength may be based on resonant frequency in the adhesive layer (Schliekelmann, 1972). Assessments of composite laminate and adhesive bond strengths are also being explored by means of frequency spectrum analysis of pulse echoes returned from bond interfaces (Lloyd, 1974; Alers, et al., 1977; Flynn, 1977).

An acoustic stimulation method for fiber composite strength evaluation has produced correlations with interlaminar shear and tensile strengths for fiber composite laminates. Stimulated acoustic emission signals are analyzed to determine a "stress wave factor" (Vary and Bowles, 1979). This factor is a function of attenuation, velocity, and resonance in composite laminates. The method produces a numerical value that can rank specimen laminates according to ultimate strength irrespective of fiber orientation, Figure 5 (Vary and Lark, (1979). When combined with velocity measurements, the stress wave factor can be used for estimating interlaminar shear strength of fiber composite laminates, Figure 6 (Vary and Bowles, 1977).

MORPHOLOGY MEASUREMENTS

Grain size distribution, metallurgical phases, interstitals, anisotropies, etc. contribute to material morphology and form the basis for property measurements by ultrasonic waves. In addition to revealing morphology, ultrasonic wave interactions can also indicate material condition variations due to residual stresses, fatigue damage, cold work, thermal shock, creep, etc.

Microstructure, Grain Size. - The effects of microstructure can be a impediment to effective flaw detection by ultrasonics. The detection of very small critical flaws in many metals is hampered by "grain noise" or backscatter which can mask flaw indications. From the perspective of materials characterizations, this "noise" can be useful since it reveals much about material morphology, when analyzed. Backscatter signals are, for example, useful for determining the cleanliness of steel (i.e., degree of freedom from nonmetallic inclusions) (Schlengermann, 1974).

Predictions of material behavior can be based on microstructural features as disclosed by attenuation, ultrasonic spectroscopy, ultrasonic microscopy, and acoustic emission. Inferences of material properties and behavior have long been made by spectro-chemical, metallographic, and other methods that reveal material morphology. Ultrasonics is a nondestructive approach to this same purpose, e.g., Fay (1976) reported the use of an ultrasonic backscatter method for determining grain size in steel as an effective substitute for metallography while eliminating the need for specimen preparation by polishing, etc.

Systematic studies of the relation of grain size to attenuation coefficients have produced a number of empirical grain scattering formulas and tabulations of scattering constants. Papadakis (1964b; 1965a) has developed extensive tabulations of scattering constants for cubic and polycrystalline solids. In addition to attenuation correlations, variations of velocity with grain size have also been found (Papadakis 1970; 1968).

Attenuation and velocity can be empirically related to microstructural changes that attend heat treatment and transformations in various steels (Papadakis, 1964a; 1965b; Noranha, et al., 1973). Acoustic emission methods provide an in situ approach to studying microstructural transformation phenomena (Speich and Schwoeble, 1975). The application of attenuation and velocity measurements to a variety of austenitic steels produced strong correlations with factors such as grain size, precipitates, alloy content, and columnar structuring (Murray, 1969; Juva and Haarvisto, 1977).

While the major portion of quantitative evaluations of microstructure have heretofore utilized velocity and attenuation measurements, some recent work has illustrated the utility of ultrasonic microscopy (Szilard and Scruton, 1974; Kessler, 1974). Microstructure in amorphous as well as polycrystalline materials has been qualitatively characterized with ultrasonic spectroscopy (Gericke, 1970; Brown, 1973).

Density, Porosity, Voids. - The evaluation of ceramic materials of current technological importance presents special demands. Micron-size voids and inclusions can constitute serious flaws in these ceramics. Micron-size flaws may be rather uniformly distributed throughout the bulk of a ceramic article and thus affect bulk properties. Ultrasonic methods can be used to determine these bulk property variations due to microporosity, inclusions, etc.

High frequency ultrasonic methods have the potential for verifying low density, porosity, and similar microstructural deficiencies in very fine grained sintered and reaction-bonded ceramics. Density variations in sintered products are of interest and particularly amenable to ultrasonic assessment. Goldschmidt, et al., (1977) have found that for porous sintered materials velocity will increase with density because the tensile modulus changes more rapidly than density itself. An inverse relation of velocity to density cannot be assumed because in these materials the tensile modulus itself is a function of density. It is also necessary to consider anisotropies due to pore shape. Furthermore, in evaluating the strength of porous ceramics, Kreher, et al., (1977) found that velocity will differ with the aspect ratio of elongated voids.

Microvoids in fiber composites, when exceeding a few percent, are known to be serious strength-reducing factors depending on their size, shape, and distribution. Correlations among ultrasonic attenuation, microvoid content, and fiber composite interlaminar shear strength have been demonstrated (Martin, 1977). Using through transmission methods, it was shown that increased attenuation corresponded to greater void content and lower interlaminar shear strength (Stone and Clarke, 1975; Jones and Stone, 1976).

Stress, Process Condition. - Residual stresses in structures burdened with heavy duty service can pose hazards unless controlled, e.g., railway tracks, train wheels, landing gear (Egle and Bray, 1975). The magnitudes of residual stresses can be deduced from ultrasonic velocity measurements. Velocity measurements using shear waves polarized in two mutually perpendicular directions form the basis of the birefringence method for residual stress determination (Hsu, 1974; Hsu and Sackse, 1975).

In an ultrasonic method suggested by Williams and Lee (1977), thermal acoustic stimulation is used to infer near surface residual stress states. Longitudinal velocity changes associated with variations in bulk stress have also been proposed for indicating stress states (Noronha, et al., 1973; Takahashi, et al., 1978). Indeed, velocity change with stress has found a practical application in determining bolt tightness (Heyman, 1977). An ultrasonic bolt stress monitor has an advantage over the torque wrench in being insensitive to the effects of friction under the bolt head.

Velocity measurements during sintering of ceramics can serve to follow the process of pore formation (Malecki, 1977). Distinct velocity changes observed during the process of polymer hardening can be utilized for process control (Zacharias, 1970; Malecki, 1977). Controlling the melting process and phase formation in metallurgy can be accomplished by monitoring changes in ultrasonic velocity or acoustic emission and stopping the process at a critical stage, e.g., during martensite formation (Speich and Fisher, 1972).

Damage, Degradation. - Composites are as a class highly susceptible to damage and degradation (Stone, 1978). Strength loss in fiber reinforced plastics can follow moisture ingress, for example. Hydrothermal aging (combined effects of high moisutre and temperature) of graphite fiber composites has produced strength lowering that was detected by velocity variations (Kaeble and Dynes, 1977a; 1977b; Meron, et al., 1977). Velocity variations correlated with interlaminar shear strength degradation.

Early detection of cyclic fatigue damage in metals has been the object of ultrasonic studies. Green (1973b) suggested the simultaneous use of ultrasonic attenuation and acoustic emission testing for fatigue damage detection and monitoring. Surface wave velocity measurements appear promising for detection and prediction of imminent fatigue failure (Martin and Tsang, 1970); Rasmussen, 1962). Schultz (1971) proposed a variation of acoustic stimulation for indicating fatigue damage in fiber composites.

Dislocation movements and collisions, especially in high strength materials, are revealed through acoustic emission monitoring. Acoustic emission studies near yield have indicated that emission activity is proportional to creep-strain. The work thus far suggests a potential for acoustic characterization of creep damage effects (Liptai, et al., 1971).

INDUSTRIAL APPLICATIONS

Most of the previously described ultrasonic materials characterization methods are, at present, neither widely applied nor widely accepted in commerce and industry. Adaptation to practical uses on actual parts is still emerging from the laboratory. There are relatively few exceptions to this in the case of structural materials, although rather sophisticated equipment is currently used for overt defect detection. It should be noted, however, that other NDE techniques are being used for certain types of property measurements: eddy current for sorting metal parts, verifying hardness; X-ray diffraction for residual stress determination; radiometry for density and void content measurement; and so forth (McMaster, 1959; Haward, 1978; Sharpe, et al., 1975).

Papadakis (1976) has reviewed some examples of industrial adaptations of ultrasonic materials characterization measurements in industry. Probably the most frequent use of ultrasound is for velocity measurements of nonstructural materials as in monitoring and feedback control of pipeline flow, chemical reactions, food processing, etc. (Zacharias, 1970). However, acoustic emission monitoring of large structures is becoming commonplace (Spanner, 1974). Resonance testing is standard in verifying the integrity of adhesively bonded structures (Schliekelmann, 1972); Norriss, 1974); Leonard and Gardner, 1973). A recent application of attenuation has been in detecting and controlling morphological defects due to various types of macro- and microinclusions in heavy machinery, bearing materials, and parts made of carbon steels (St. John, 1978; Schlengermann, 1974; Cannella, et al., 1978).

An outstanding example of the successful application of computer automated ultrasonics to material strength verification in a production environment pertains to the fabrication of nodular cast iron parts for automotive and construction applications. In order to meet stringent safety criteria, this material must possess a specific microstructure with respect to the size, shape, and distribution of contained carbon, i.e., the carbon must be in the form of "spherical" nodules as opposed to flake graphite. Foundry procedures that have been established to guarantee the proper percentage of nodularity are not foolproof and must be supplemented by a nondestructive method of verification. This is accomplished by ultrasonic velocity measurements which correlate strongly both with tensile strength and degree of nodularity. The correlation is sufficiently well established so that computer automated velocity measurements on castings can confidently assure that the critical level of 80 percent nodularity or greater exists. More than 12 million castings have been tested satisfactority in this manner (Henderson, 1976).

TECHNOLOGY NEEDS

To realize universal application in practical situations, ultrasonic NDE must advance in several main areas: (i) theory development, (ii) instrumentation, (iii) system automation, (iv) standardization, and (v) coordination with design. These topics are discussed briefly in the following paragraphs.

It is significant that correlations of both attenuation and velocity with material strength properties exist. The classical elastic wave model does support the expectation velocity will relate to strength through elastic moduli (Green, 1973a; Schreiber, et al., 1973). However, current theory does not adequately account for the strong correlations of strength and toughness properties with attenuation. This lack will probably be remedied by more detailed studies of material behavior that are based on dynamic ultrasonic wave interaction models (Kolsky, 1973; Vary, 1979a; 1980b).

There is a need for ultrasonic probe systems that can readily adapt to the variety of material configurations and surface conditions encountered in real structures and components. Advanced and novel instrumentation approaches will be needed to accommodate the probe coupling, transduction, bandwidth, sensitivity, and other factors associated with measurement accuracy requirements. This will entail more attention than is currently being given to probe construction and performance evaluation (Bredael, 1977; Vary, 1980c).

The successful transfer of ultrasonic techniques to the field will require advanced electronic instrumentation in association with computers. The availability of microelectronics and high speed computers assures speedy performance of complex signal processing steps. This is needed to resolve the often subtle ultrasonic propagation variations that accompany significant change in material properties. Even for relatively simple velocity measurements, automation is necessary. More refined measurements will require use of computer implemented Fourier transforms, modulation analyses, signal deconvolution, etc. (Newhouse and Furgason, 1977).

Another area that merits advancement involves the creation of suitable reference standards. Ultrasonic reference blocks that have been available in the past have been found inadequate (Sushinski, et al., 1977). The requirements of ultrasonic materials characterization demand an extensive collection of precise calibration standards both for instrument calibration and for material property certification (Burley, 1977).

Naturally, the designer is concerned primarily with the various engineering factors that will guarantee the integrity of a structure. It is not always recognized that the inspectability of a structure is one of these factors. The appropriate approach would be to design all structures with inspectability as an objective. It should not be assumed that inspection difficulties will always vanish by the use of innovative NDE methods. Advancements in technique precision and sensitivity may require design accommodations to be effective. The incentive to make the necessary accommodations is clear; advancements in NDE technology may be useless if reasonable provisions for their application are omitted in structural design (Vary, 1979c).

Current and prospective NDE technology can meet the implied requirements only if it is an integral part of material development, testing, analysis, and component design and fabrication activities.

The interaction of principal activities is illustrated in Figure 7. Structural reliability and economical use of composites will require the close coordination of all the disciplines involved: materials development, materials processing, engineering design, testing, failure analysis, and nondestructive evaluation.

CONCLUDING REMARKS

This paper overviewed a potentially broad new area that involves research and application of ultrasonic techniques for characterizing structural material properties. The emphasis was on techniques that indicate quantitative ultrasonic correlations with material strength and morphology relevant to verifying the reliability of load bearing structures. It was seen that ultrasonic methods can go beyond merely searching for overt defects and become viable tools during crucial stages in materials development, fabrication, and use. Universal application to practical industrial situations awaits advancements in associated areas such as instrumentation, automation, standardization, and design. In the latter case, the emphasis would be on accommodations that permit nondestructive methods to be used to their fullest capability without compromising material processing, fabrication, and design objectives.

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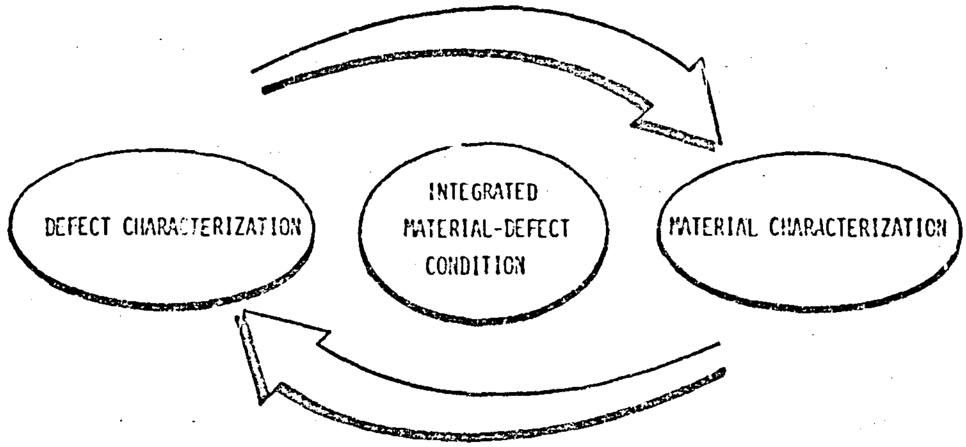

Fig. 1 Diagram illustrating the relation of defect and material characterization to defining the integrated effect of the material-defect state on structural integrity and life. A holistic approach combines nondestructive characterization of defects and also the material environments in which the defects reside.

PROPERTIES	CONDITIONS
TENSILE MODULUS	ANISOTROPY
SHEAR MODULUS	MICROSTRUCTURE
TENSILE STRENGTH	GRAIN SIZE
SHEAR STRENGTH	POROSITY, VOIDS
YIELD STRENGTH	PHASE COMPOSITION
BOND STRENGTH	HARDENING DEPTH
HARDNESS	RESIDUAL STRESS
IMPACT STRENGTH	HEAT TREATMENT
FRACTURE TOUGHNESS	FATIGUE DAMAGE

Fig. 2. Material properties and conditions that can be assessed by various nondestructive evaluation (NDE) techniques. This paper reviews prominent cases of ultrasonic techniques applied to material property and condition measurements.

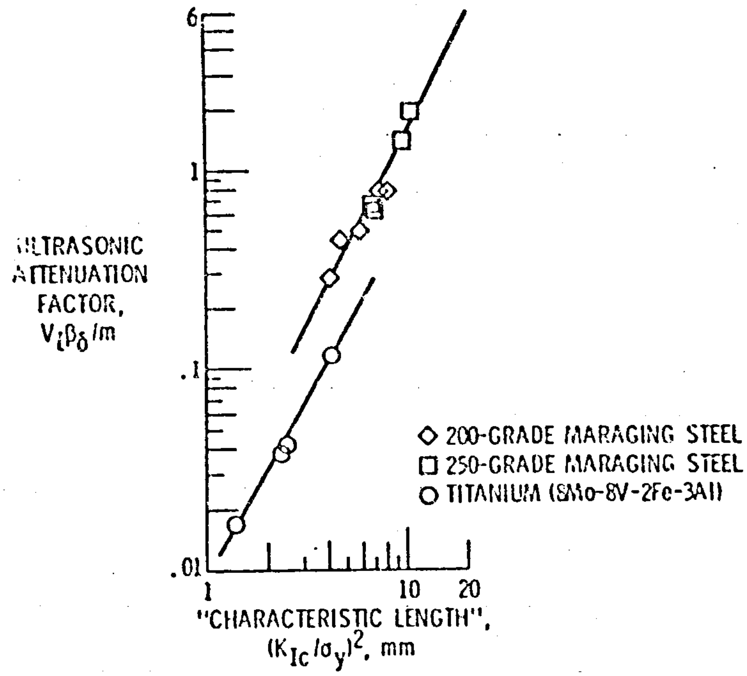

Fig. 3. Correlation of ultrasonic attenuation factor $V_l\beta_\delta/m$ with fracture toughness "characteristic length" factor $(K_{Ic}/\sigma_y)^2$ for two maraging steels and a titanium alloy, from Vary (1979a).

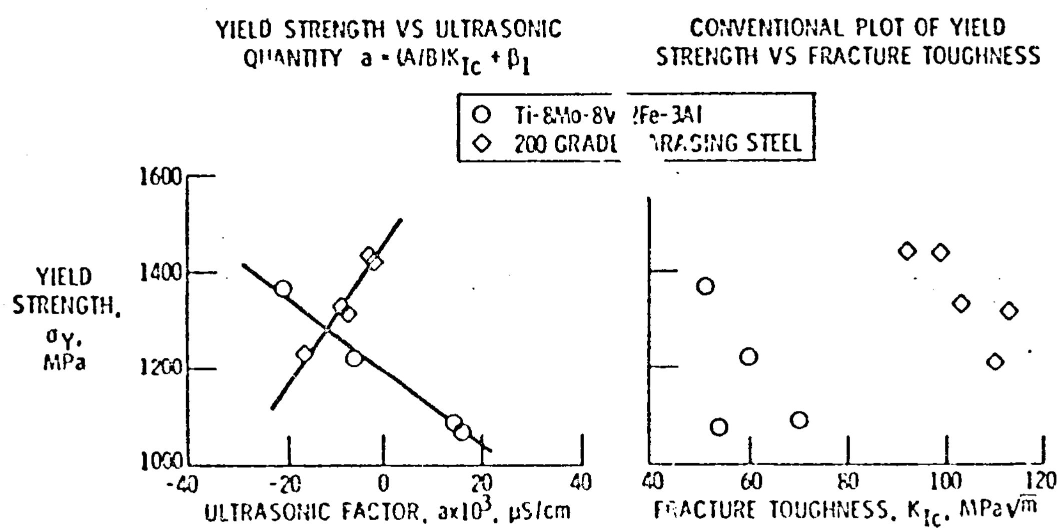

Fig. 4. Correlation of yield strength with fracture toughness. The lefthand graph combines the ultrasonic factor β_1 with plane strain fracture toughness K_{Ic} in the quantity a as defined above the figure, from Vary (1979a)

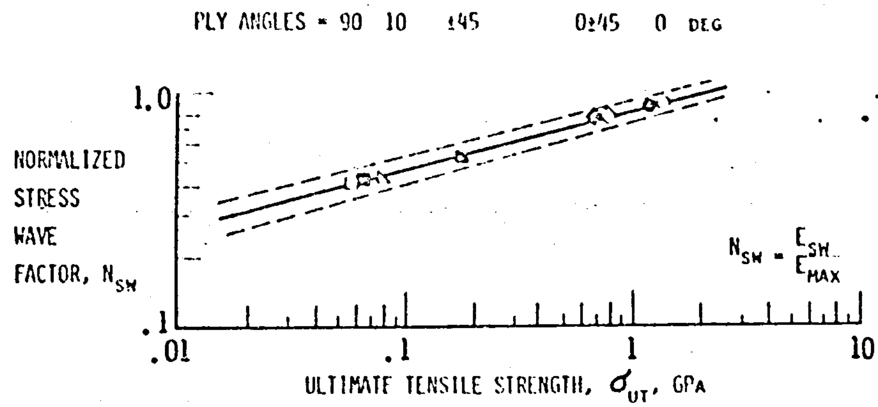

Fig. 5. Stress wave factor compared with ultimate tensile strength for graphite/epoxy fiber composite. The ultrasonic stress wave factor E_{SW} is a measure of efficiency of strain energy dissipation. The ply angles given are relative to the tensile loading axis, from Vary and Lark (1979).

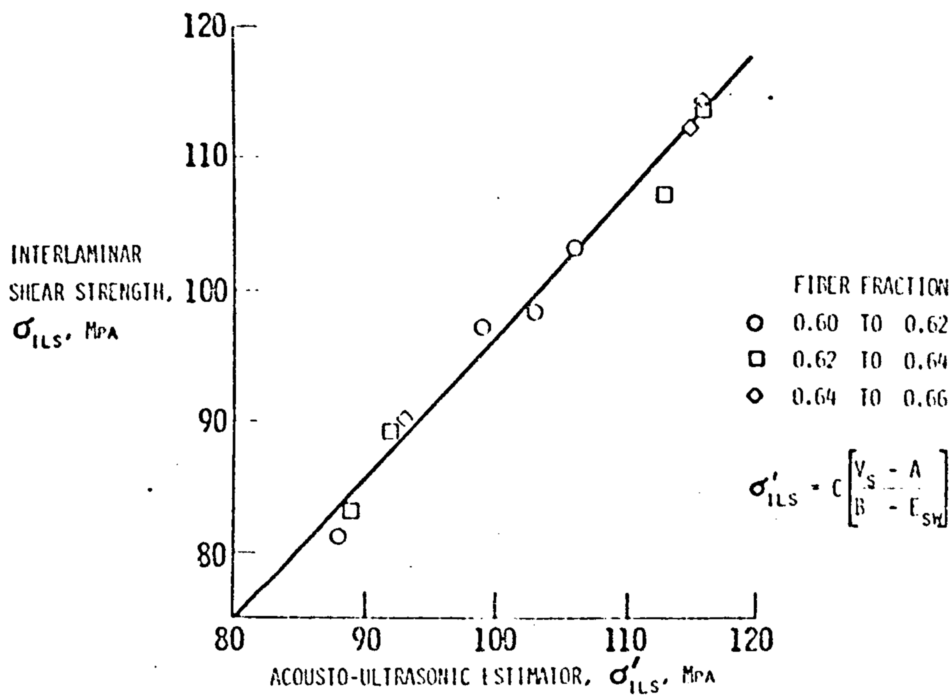

Fig. 6. Correlation of graphite/polyimide fiber composite interlaminar shear strength with acousto-ultrasonic estimates. The estimator is derived from stress wave factor and velocity measurements, E_{SW} and V_S, respectively, from Vary and Bowles (1977).

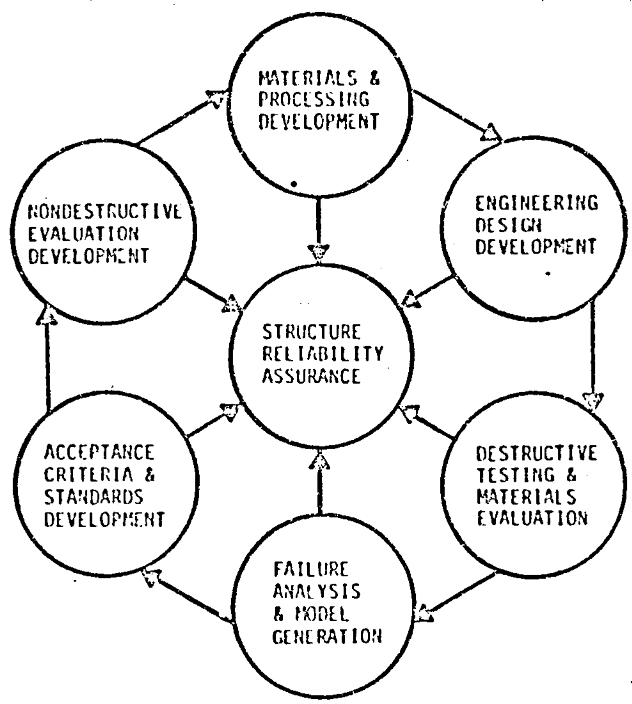

Fig. 7. Interaction of principal activities related to structural reliability assurance. Diagram illustrates the strategic importance of each of the activities not only as they contribute to structural reliability assurance but also as they pertain to each other. The clockwise cycle indicates how each activity forms a link in the reliability assurance chain.

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