BASELINE VALUES FOR NON-DESTRUCTIVE STRUCTURAL EVALUATION OF GLASS REINFORCED COMPOSITES

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ABSTRACT

Ultrasonic readings taken from glass reinforced plastic can be related to the elastic modulus, and hence the strength of the material. Research results dating back to the 1960's have shown that stressing fiberglass reinforced plastics (FRP) has resulted in decreasing the modulus of the material – thus reducing its strength. In service, the stresses applied to FRP have the same effect. Two approaches are proposed for monitoring the condition of structural composites – one is to use a baseline developed from specimens of new FRP combined with theoretical work and the other is to use the results of ultrasonic readings taken from the new structure to be monitored and to use this as the baseline. This paper describes both how both approaches can be used.

1. INTRODUCTION

Reliable performance of composites in structural applications, especially where remaining service life prediction is sought after, requires non-destructive methods that can verify structural properties including mechanical strength. Through the development of reliable non-destructive methods, regular evaluations can be completed to monitor condition. Such a system permits owners to avoid costly consequences (such as premature repair and replacement, confined space entry, environmental cleanup and lost opportunity) and capitalize on repeatable and reproducible information to manage repair and replacement scopes within budget cycles.

This paper describes developments in ultrasonic non-destructive evaluation of glass reinforced composites that have generally been made using open-mold methods and laminate thickness of 6mm and greater. Emphasis is on monitoring the condition of composites structures in service, using technology that is readily available at this writing. The purpose of this paper is to investigate and describe an objective methodology for determining baseline values for use in monitoring changes occurring to composite structures in service.

It is intended that this paper will interest those directly involved with manufacturing, engineering, quality assurance and testing of composite materials.

1.1 Basic Ultrasonic Testing Principles

The first patent application regarding use of ultrasound for testing materials was made in 1940 by Dr. Floyd Firestone at the University of Michigan. This first patent, and most subsequent work using ultrasound identified that invisible inhomogeneities within materials could be detected. For most of the 74 years since the first patent application, the focus of ultrasonic testing has been on metals. In the case of ultrasound, a pressure pulse is applied to material and inhomogeneities are detected when a feature blocks some of the path – features that are parallel to the path direction are generally not detected.

Use of fiber reinforced polymer composites for structural applications has been pursued since the 1930's, and has seen significant changes in the polymers and fibers available. With the growth of commercial aircraft starting in the 1960's, many investigations were conducted into use of ultrasound to detect flaws and defects in composites. Because many fiber reinforced composites are made in layers, interfaces between layers often interrupt the path of the pressure pulses and show as features or possible defects for most ultrasonic techniques. Ultrasound is the most common non-destructive technology used for composite materials.

Ultrasonic pulses can be applied to materials in three main modes:

- pulse-echo, where the pulse is applied to the surface by the same transducer that receives reflected energy from within the material,
- thru-transmission, where the pulse is applied to one surface by one transducer and the pulses that pass through the material are received by a transducer placed on the opposite surface, and
- pitch-catch, where the pulse is applied to the surface by one transducer and another transducer on the same surface receives reflected energy within the material.

Ultrasonic pulses can range in frequency from 100,000 Hertz (0.1 MHz) to beyond 20 MHz. When used with glass reinforced composite materials, signal losses in the material increase with frequency, making the highest reasonable frequency 1.0 MHz. Work completed for this paper uses a nominal ultrasound frequency of 500 kHz. Work done by the author has found attenuation values ranging from 0.3 to 2.0 decibels (dB)/mm (7.62 to 50.8 dB/in).

In ultrasonic testing, an energy pulse is applied to the face of a material by an actuator, or transducer. These pulses have a short wavelength which translates into a wave frequency in the range listed above. Ultrasound uses two primary modes to travel through a material – longitudinal and transverse waves. This paper limits itself to discussion of longitudinal waves and fiberglass reinforced polymers.

Currently, the most common use of longitudinal waves in FRP is in thickness measurement of new FRP structures. Thickness measurements are usually made by following this process:

1. A reference standard is used which duplicates the material to be measured with a known thickness so that the transit time of the reflected signal can be used to determine the sonic velocity through the reference standard
2. It is assumed that the sonic velocity through the material to be measured is the same as the reference standard.

3. The transit time of ultrasonic pulses applied to the material is converted into thickness.

Thickness testing does not use any other information contained in the returned ultrasound signal.

As for metal structures, flaws such as voids, porosity and planar defects that interrupt the path of the ultrasonic wave through a fiber reinforced composite will appear in an ultrasonic A-Scan and can often be analyzed by a skilled analyst. This principle is used for evaluating composites in some applications, aerospace in particular.

Propagation of sound waves through a medium is affected by changes along the wave path. Examples of these changes could be foreign objects, gaps or bubbles, changes in the crystal structure of the material, and others. In the case of fiber reinforced composite materials, the structure of the material always includes some (and sometimes all) of these changes along any wave path. These generally show as attenuation of any signal that passes through the material as well as visible indications on the test instrument. For glass reinforced composites, normal variations that occur because of materials and processes used would often be cause for rejection using the criteria that have been adopted for metals.

1.2 Summary of Earlier Investigations into Ultrasound with Fiber Reinforced Composites

In the early 1960's, use of ultrasonic testing (UT) was already showing reliable results for finding flaws in metallic structures. One of the desirable attributes of this technique is that reliable data could be generated if only one side of the material under investigation was accessible. This meant that in addition to finding flaws or defects, the same techniques could be used to produce thickness records of reasonable accuracy. At the same time, use of composite materials such as glass reinforced thermoset plastics was being explored for a number of structural and corrosion-resistant applications. Starting in the mid 1960's, researchers started to examine uses of ultrasound with these fiber-reinforced composite materials.

Vary[1] applied ultrasonic pulses to composites and received the responses using acousto-ultrasonic devices, thus mixing the principles of ultrasound with acoustic emission testing. This process is known as "acousto-ultrasonic" because the forces applied to the specimen are from ultrasonic pulses, whereas for acoustic emission, the forces applied to the composite are from mechanical loads applied, such as pressures and weights. In both cases, the responses are received in real time by acoustical equipment. This work showed correlation between the attenuation of the signal transmitted through the full thickness of a laminate – across its layers - and its tensile strength parallel to its layers. This technique is the subject of two American Society for Testing and Materials (ASTM) standards – ASTM E 1495 Standard Guide for Acousto-Ultrasonic Assessment of Composite, Laminates and Bonded Joints[2] (ASTM E 1495) and ASTM E 1736 Standard Practice for Acousto-Ultrasonic Assessment of Filament Wound Pressure Vessels[3] (ASTM E 1736).

Several researchers[1,4,5] have reported experimental results showing good correlation between the elastic modulus of FRP and acousto-ultrasonic results. This includes correlation of changes in strength that has occurred from applied stresses and chemical permeation with changes in ultrasonic response of the FRP. These early researchers have successfully shown that acousto-ultrasonic methods can be used to determine changes in condition of composite laminates. With the appropriate criteria, this information can be used to determine whether a composite laminate is suitable for the loads to be applied in service conditions.

It is important to note at this stage that the correlation does not mean that the value of the elastic modulus can be determined directly from the acousto-ultrasonic data. To determine the actual modulus it is necessary to know the modulus value corresponding to an acousto-ultrasonic value at one point along the curve.

A method to employ these techniques is also described in ASTM E 1736[2]. In this Standard Practice, it is recommended that initial readings be taken from the vessel to be monitored after calibration to a reference standard and before it is put into service. After the unit has been in service for some time, the results of the initial readings are then compared to readings taken after the unit has been in service. Changes that have occurred in the modulus of the composite from corrosion, decay or mechanical loads will appear as changes in the results of the scan. While there is relationship between acousto-ultrasonic results and the presence of detectable defects such as voids or delaminations and porosity, it is not certain that these defects are the cause of strength changes. Furthermore, it is generally required that reference standards be available for each feature and condition that requires detection.

1.3 Property Changes in Structural Composites

Many users of structural composites can report where the structural capacity of the composite has reduced while it has been in service. There have been numerous investigations into this phenomenon[6,7,8], including proposed models of the causes of these changes. It is beyond the scope of this paper to identify or categorize these changes or models.

Many of the works identified above were successful in identifying that changes also resulted in reduced strength or elastic modulus of the material. Reduction in structural capacity has not been universally associated with any change in defects that are normally detected by ultrasonic methods, such as voids, delaminations or porosity within the composites. It is most common for defects and discontinuities to be widely dispersed and not identified as discrete flaws.

Figure 1 shows the results from tests of samples removed from a glass reinforced tank on two (2) occasions. The tank had been in service storing a corrosive liquid. The results shown are for the measured thickness of the tank shell and the results of destructive testing. The results of the tests are shown as percentages as given by equation (1) below. Clearly the new values would be 100%

$$Percentage\ of\ Original = \frac{Current\ Measurement}{Original\ Measurement}\ x\ 100\% \qquad (1)$$

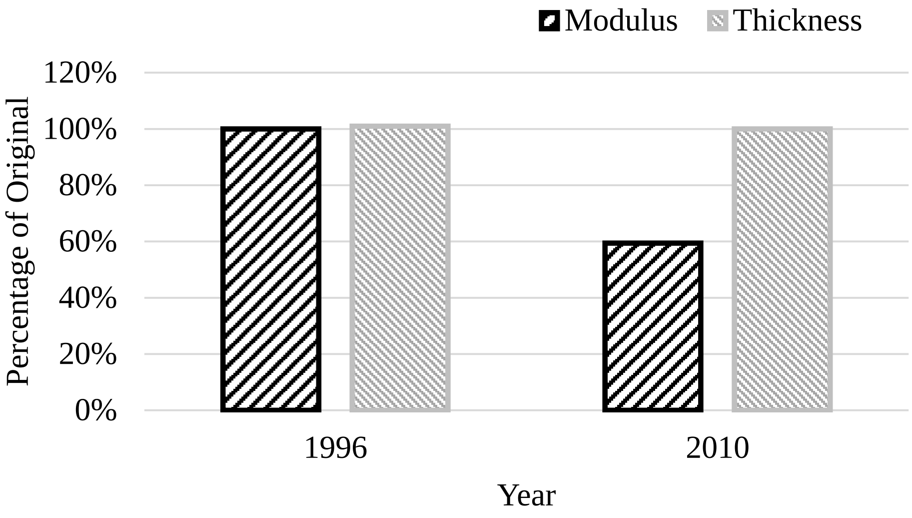


Figure 1. Destructive Test Results from Samples Removed from Glass Fiber Reinforced Tank Shell

From Figure 1, it can be seen that during fourteen (14) years of service, the thickness of the laminate did not change appreciably but the modulus reduced by 40%. At some point in this decline, it is likely that the composite will no longer be able to support the required loads.

1.4 Determining Changes to Composites

Reliable performance of composites in structural applications, especially where life prediction is desired, requires non-destructive methods that can verify structural properties including mechanical strength. With availability of reliable non-destructive methods, regular evaluations can be completed to monitor condition.

At this writing, for industrial and civil applications there is not a generally accepted non-destructive methodology to determine whether a composite structure being put into service meets the design requirements. Furthermore, for composite structures that have been in service for some time, relevant non-destructive data is rarely available from the new structure, which prevents comparisons related to changes that have occurred and thus the current suitability for service.

First, consider a parallel situation where a steel structure is to be evaluated. For steel, structural capacity is generally related directly to thickness. In this case, the original thickness is documented, say on a drawing or specification. Conventional non-destructive methods can be used to reliably determine the current thickness of the steel. It is reasonable to use the original documented thickness as the starting thickness, even if the actual thickness was different. From the starting thickness, the rate of thickness change can be determined and life prediction of the structure can be estimated, even when measurements might not be available.

Now consider a typical situation as shown in the case illustrated in Figure 1, above, where thickness is not expected to change but the modulus does. In this case, non-destructive measurements similar to acousto-ultrasonic results described above are required to know the current relative modulus value. In order to create a prediction of the rate of modulus change, it will be necessary to have a starting value. For the purpose of this paper, the starting value, or “New” value, is the baseline value.

2. EXPERIMENTATION

The test work described here was performed to develop comparison between parameters calculated from ultrasonic readings and standard destructive test results for glass reinforced composite laminates.

2.1 Hypothesis

Ultrasonic data from a variety of glass reinforced composites can be used to establish a universal baseline parameter.

2.2 Experimental Method

To compare methods, samples of glass reinforced composites were produced, or removed from various structures, and tested both by the ultrasonic methods known as the UTComp® System and by using standard destructive tests to determine the modulus of the material. A total of thirty-six (36) samples were used. Thirty percent (30 %) of the samples were newly made, and the remaining seventy percent (70 %) had been in service for up to thirty (30) years.

The samples were constructed using open mold techniques and had varying reinforcement content. Twenty-five (25) samples were made using filament winding and ten (10) used contact molding. Each sample was approximately 300 mm x 300 mm in size. Sample thicknesses ranged from eight (8) mm (0.315 inch) to forty-eight (48) mm (1.890 inches). Most of the samples were from cylindrical shells where the material properties in the hoop direction were of most interest.

The samples used for these experiments were manufactured by twelve (12) different manufacturers using individual methods and practices. For the samples that were provided from structures exposed to corrosive substances, chemical attack and absorption was also different. It is expected that differences among samples from these factors also will introduce random variation.

The designation of the destructive test used is ASTM D 790[10].

2.2.1 Non-Destructive Tests

The ultrasonic readings were taken by following a written procedure. All readings were pulse-echo readings using a 0.5 MHz transducer with a vulcanized rubber delay line. For each sample, the average thickness was measured using a caliper and recorded. At least 30 readings were taken over the surface of each sample.

The ultrasonic readings were then processed through proprietary software to identify the opposite surface reflection and to calculate the value and total transit time of the reflected peak. Thickness was used to determine the average sonic velocity for the reading.

The results of all readings for a sample were averaged.

For each sample the following non-destructive parameters were calculated:

$$L = f(attenuation) \tag{2}$$

$$L_t = L \times thickness \tag{3}$$

$$L_{tt} = L \times transit\ time \tag{4}$$

$$V = 2 \times \frac{thickness}{transit\ time} \tag{5}$$

$$LV = L_t \times V \tag{6}$$

The values calculated using (2), (3), (4), (5) and (6) were tabulated by sample.

2.2.2 Destructive Tests

For each of the samples, the procedure outlined below was followed:

1. Ultrasonic data and thickness measurements were collected from the sample.
2. The sample was cut into test specimens in accordance with ASTM D 790.
3. Where the lamination sequence of the sample was unknown, a specimen was also cut for ignition loss analysis in accordance with ASTM D 2584[9] and reinforcement analysis.
4. A third-party test laboratory completed the ASTM D 790 and ASTM D 2584 (as applicable) testing and reported the results.
5. The third party laboratory returned the reinforcement from the ASTM D 2584 specimen as it was removed from the furnace.
6. The ASTM D 2584 residue was used to determine the lamination sequence.
7. The Design Flexural Modulus was modeled using lamination analysis as described in ASME RTP-1[11], Appendix M-3.
8. The flexural modulus result obtained from the ASTM D 790 test was normalized by dividing it by the design values from lamination analysis modeling and termed "Normalized Strength Percentage" as in equation (6).

$$\text{Normalized Strength Percentage} = \frac{ASTM\ D\ 790\ Modulus}{Design\ Flexural\ Modulus} \times 100\ \% \tag{7}$$

An example of the calculation process is shown below:

Table 1. Calculation Example

Design Flexural Modulus in GPa (Msi)	Thickness in mm (in)	ASTM D 790 Modulus in GPa (Msi)	Normalized Strength Percentage
15.36 (2.229)	48.03 (1.891)	9.25 (1.343)	60.2 %

3. RESULTS

3.1 Normalized Strength Percentage

The results of the normalized strength percentage calculations are presented in Figure 2. The data have been ordered from highest to lowest. Note that the values range from 43 % to 132 % of the calculated design value.

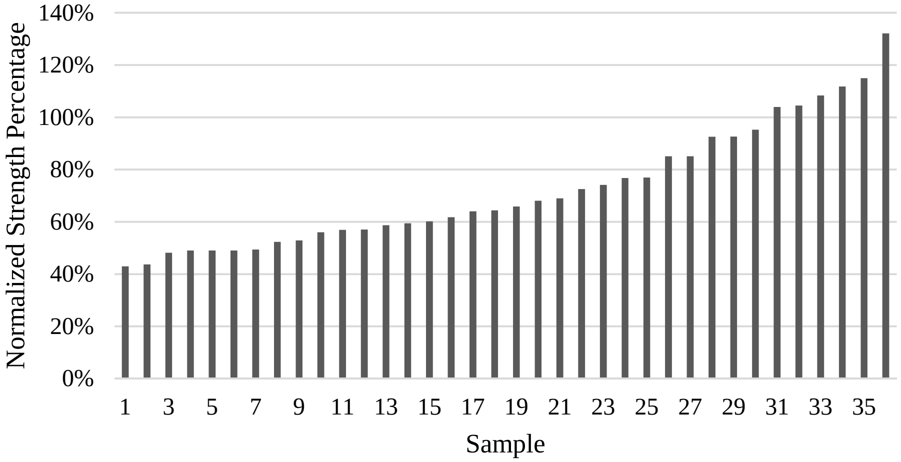
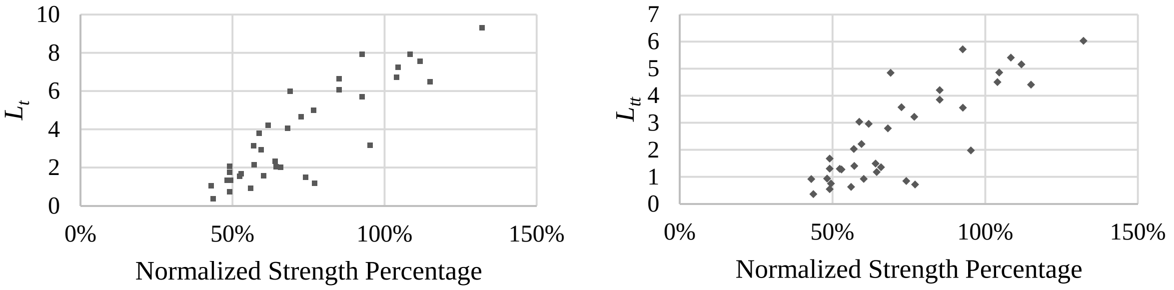


Figure 2. Normalized Strength Percentage Results

3.2 Non-Destructive Parameters

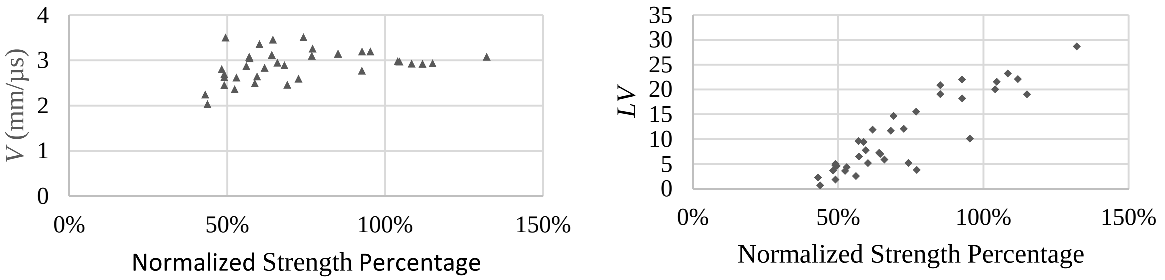
For all readings taken from each sample, the reflection of the applied pulse from the opposite surface was selected. Where the opposite surface reflection could not be identified, the reading was discarded.

The values listed in equations were calculated and averaged for the sample. The values of L_t, L_{tt}, V, and LV were then plotted with the corresponding normalized strength percentage as shown in Figure 3 (a) to (d), below. The scatter of the data points is believed to be largely due to random variation introduced by differences among samples as discussed above.



L_t vs Normalized Strength Percentage

L_{tt} vs Normalized Strength Percentage



(c) V vs Normalized Strength Percentage

(d) LV vs Normalized Strength Percentage

Figure 3. Non-Destructive Parameters Plotted Against Destructive Test Results

Correlation coefficient and R-squared values for linear regression between the normalized strength percentage and the calculated values were calculated and are shown in Table 2.

Table 2. Correlations with Normalized Strength Percentage

	Non-Destructive Parameter and Equation Number			
	L_t (3)	L_{tt} (4)	V (5)	LV (6)
Correlation Coefficient	0.871	0.827	0.365	0.898
R-squared	0.759	0.6833	0.133	0.806

From Table 2, the best correlation and linear regression results correspond with the LV value determined by equation 6. These data are shown in Figure 3(d). Calculation of this value requires the magnitude and transit time of the opposite surface reflection from the ultrasonic readings as well as the thickness of the composite. If the thickness of the composite is unknown, the parameter L_{tt} is the alternative, although with lower correlation.

3.3 Sonic Velocity Considerations

Figure 3(c) shows the data where sonic velocity was calculated according to equation (5). The correlation coefficient for this data (Table 2) shows poor correlation with Strength Percentage. As well, correlation between sonic velocity and L_{tt}, which does not include knowledge of material thickness, was poor at 0.365. This discussion shows that sonic velocity cannot be used as an indicator of composite strength in the applications considered here and it cannot be modelled using the ultrasonic parameters discussed here.

From examination of the data in Figure 3(c), it appears that sonic velocity may converge to a narrower range at higher Strength Percentage. From this, at best, one can only be expected to provide a possible range of thickness.

3.4 Baseline Calculation

The intent of this paper is to identify values that could be used as Baseline, or starting, values for composites being evaluated for mechanical strength. The results described above show that two (2) parameters calculated from ultrasonic readings can be used to determine the strength of a glass reinforced composite as a percentage of the value determined from lamination analysis. From the data that was considered in this paper, solving the linear regression curves for the value that produces 100% will yield the baseline values.

For the two (2) parameters selected above, the Baseline values are shown in Table 3. For composites where the original parameters are unknown, assuming that the original strength was 100% of the calculated value would allow use of these values to determine the starting point. The ratio of current values to the baseline value can be used with the conversion curve shown in Figure 5 to provide the Strength Percentage.

Note in Figure 5 that the slope of the curve changes where the strength percentage is about 45 %. This is done to take the strength percentage to 0 % when the parameter is 0. At this point, the change in slope is not supported by data, since no samples tested in this paper have Normalized Strength Percentage less than 43 %.

Table 3. Baseline Values

Parameter	Baseline Value
L_{tt}	4.2606
LV	19.085

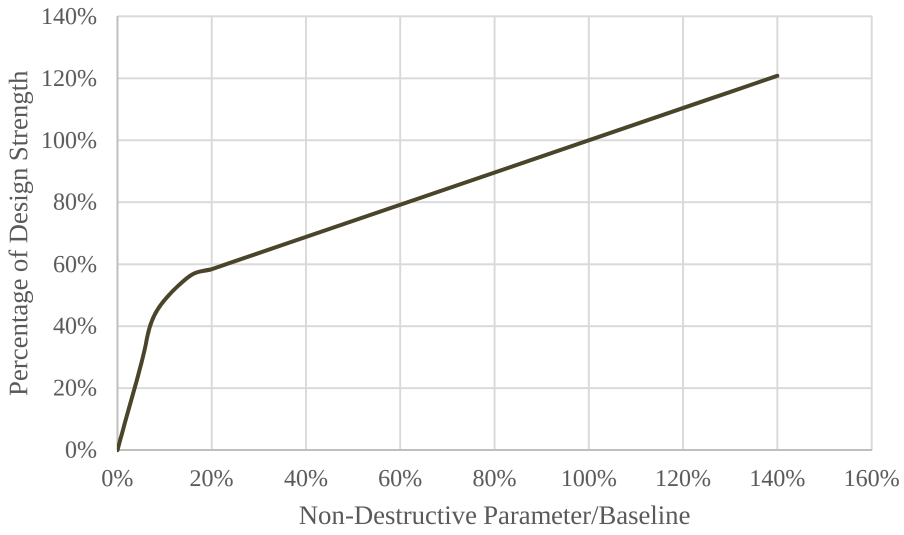


Figure 4. Conversion Curve

In the case where ultrasonic readings can be taken from a composite before it is put into service, the results of the readings can be used with the baseline values above and Figure 4 to provide the starting point value for future evaluations.

4. DISCUSSION

This paper has shown that non-destructive ultrasonic methods are available that show strong correlation with the actual bulk elastic modulus of a wide range of glass fiber reinforced composites. Some authors[6,8] have shown that the reduction in bulk modulus appears to occur at the reinforcement–to-matrix interface, inferring that this modulus reduction is independent of the type of fiber reinforcement. Damage of these interfaces has been produced in the laboratory by several means, including absorption of liquids and mechanical stresses – the same conditions that many structural composites must accommodate.

In practical application, the strain at failure is relatively constant for a composite. Reductions in bulk modulus will see the strain increase at a constant stress – therefore showing reduced strength. Thus, as the bulk modulus declines due to various environmental and loading conditions, the strain within the composite will increase. Failure will occur when the strain has increased to the failure level without any change in the load or application conditions.

These ultrasonic methods can be applied to composite structures for the purpose of monitoring changes in the bulk modulus of the material. When the Strength Percentage is determined for an as-built composite – or LV or L_{tt} are determined directly from the as-built structure – then changes in the bulk modulus can be determined from ultrasonic readings. Over time, the changes in bulk modulus can then be incorporated into risk assessment to determine whether the resulting strains are acceptable and to project remaining service life.

This is almost identical in outcome to thickness testing of metallic structures for the same purpose. In this case, the elastic modulus remains constant but the stress level increases due to reduction in area.

Most composite structures in use at this writing did not have the new Strength Percentage, *LV* or L_{tt} determined when they were new. As such, they do not have a known starting point from which to determine the rate of change or to make projections. In these cases, use of the baseline values listed in Table 3 will allow initial risk assessment to be conducted. Because the testing is non-destructive, the risk assessment can be updated frequently with minimal effect on the structure.

A further item to discuss is that the parameters calculated did not require explicit calibration standards. Only the samples provided were used with no outside reference standards. As well, different ultrasonic equipment – flaw detectors and transducers - were used for some of the samples. This makes it possible to use ultrasonic methods for strength evaluation of existing composite structures without access to calibration standards.

The work for this paper was conducted on a wide variety of composites made using open-mold methods with epoxy vinyl ester matrices and glass reinforcements. Further work is recommended to:

- Verify these results with other constituent materials and construction methods, and
- Refine the understanding of manufacturing and exposure effects.

5. CONCLUSIONS

The following conclusions are drawn.

- Ultrasonic readings provide reliable information about the current strength of glass reinforced plastics.
- Changes in composite strength determined using ultrasonic methods can be used for life prediction.
- Composite strength values can be provided without using calibration standards.
- Sonic velocity does not provide reliable correlation with composite strength.
- The calculation methods used in this paper can be applied to any open-mold composite.

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