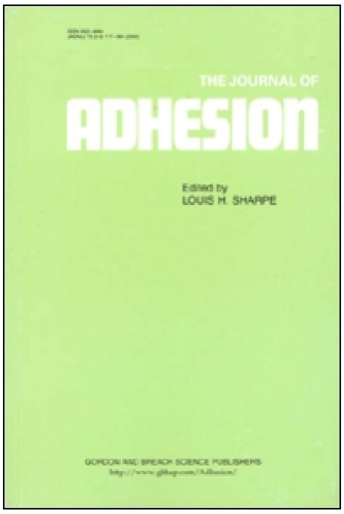

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Acousto-ultrasonic (AU) Technique for Assuring Adhesive Bond Quality

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This paper examines the feasibility of using the Acousto-Ultrasonics (AU), nondestructive technique, for assuring the quality of adhesively bonded sheet-metal used for automobiles. Kissing bonds or regions lacking adhesive were easily identified by this technique. A bond quality (BQ) model is introduced that takes into account the mixed mode failure. Destructive testing results showing fairly consistent correlation of BQ values with the breaking strength of the adhesive joint failing in mixed mode failure are presented.

KEY WORDS NDT; SWF; acousto-ultrasonic; adhesion; bond quality; mixed-mode failure

INTRODUCTION

A perfect bonding in an adhesive joint can never exist. The major parameters that affect the bond strength includes bond line thickness, surface roughness, chemical conditions, adhesive type, environmental conditions and aging effects. The boundary layers have different physical and chemical properties from their parent bulk material. Since boundary layers are present and are part of the joint, they will influence its behavior. The major limitation of the usage of adhesives in structural applications is the inability of present techniques and methods to determine the quality of the bond and to predict its performance and the durability of the structure.

A nondestructive evaluation (NDE) method needs to be developed that can be used to evaluate the bond quality so as to ensure that the structural performance of the bonded joint meets the desired design and service requirements. Alex Vary and co-workers[1] developed a technique, *viz.*, the acousto-ultrasonic (AU) method, which is a hybrid of acoustic emission (AE) and ultrasonics. Recent studies [2–12] reveal that there is a correlation between stress wave propagation characteristics determined by AU and the mechanical properties of the material.

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The AU technique involves inducing an ultrasonic signal into a specimen and its subsequent detection and analysis using AE methods. One of the major advantages of this technique is that it gives an integrated effect of overall flaw/damage present in the structure. The propagating stress wave interacts with the micro-structure and flaws present along the bond line between the two transducers as well as with the adhesive. The received signal can be analyzed to evaluate the damage or the condition of the bonded joint. A schematic diagram of the set-up is shown in Figure 1. The analysis of the received signal produces a stress wave factor (SWF) which can be related experimentally to the "lap shear strength" of an adhesive joint.

An alternative approach to analyze the signal was developed by the Materials Response Group at Virginia Tech.[4-7] This approach takes the digitized time-

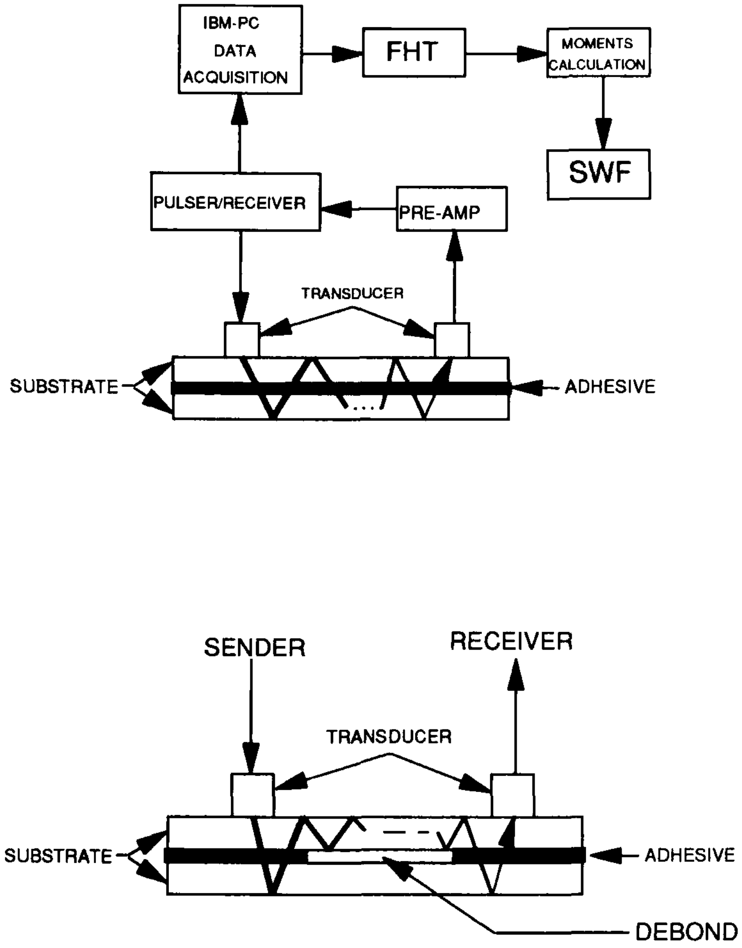


FIGURE 1 Schematic diagram of AU set-up for adhesively bonded joint.

voltage signal from the data acquisition system and converts it into an amplitude-frequency spectrum by means of a Hartley's transform algorithm.[13,14]

Various statistical moments of the frequency spectrum are then calculated and defined as various SWF values. These SWF values are then examined for an empirical correlation with the strength of the structure. Consider the frequency spectrum to be a plane figure, closed on the frequency axis. The location parameter of the spectrum is given by the centroid of the figure. The area of this figure can suitably represent the scale parameter of the distribution. Thus, the 0th moment of the plane figure, M_0, is

$$M_0 = \int_{-\infty}^{\infty} S(f)\, df \tag{1.0}$$

where,

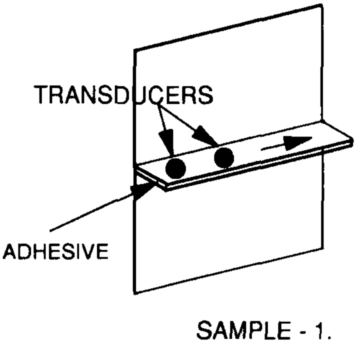
$S(f)$ = power spectral density.
f = frequency
M_0 = zeroth moment of the frequency distribution.

The zeroth moment of the signal is the area under the spectral density distribution and is indicative of the total energy content of the received signal.[15,16] It indicates the ability of the material to transfer stress/strain energy. The SWF(M_0) value is a measure of stress wave energy transmission. The SWF(M_0) values provide a way to rate the efficiency with which dynamic strain energy transfer takes place in the material. If the material exhibits high SWF(M_0) values, the material has better transmission of dynamic stress or a better load redistribution capability and hence will have higher strength. Conversely, low SWF(M_0) values indicate places where dynamic strain energy is likely to concentrate and promote fracture. Along the bond line, regions with low values of SWF(M_0) indicate regions for the possible origin of failure. Studies have shown that these moments are affected by the damage/flaws present in the structure in a particular manner, such that they can be located and characterized. Stiffler *et al.*[17] have shown that a decrease in SWF values calculated by the moments method correlates well with the reduction of stiffness of graphite-epoxy specimens subjected to fatigue tests. Dos Reis *et al.*[18] have shown that higher values of SWF correspond to higher values of peel strength of rubber bonded to steel.

EXPERIMENTAL

The samples were adhesively bonded plates, each having a different geometrical configuration as shown in Figure 2. The sheet metal plates were 11.0 inches in length and 0.05 inches thick. The overlap length of the bond was 1.0 inches, in each case.

Ultrasonic pulses are introduced into the specimen through a broadband transducer, Panametrics Model V133 (2.25 Mhz/0.25" diameter, right angled microdot). The couplant used was Sonotrace-30. A Panametrics Model 5052-AU



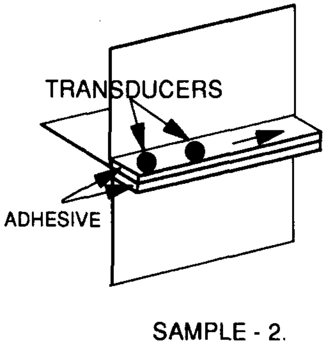


FIGURE 2 Schematic of transducer placement for samples 1 and 2.

pulser/receive unit was used to generate and receive the ultrasonic signal. The receiving transducer was the same type as the transmitter. The received signal was fed into the pre-amplifier and then to the amplifier with gains being set for each individual sample.

A transducer holder was designed and fabricated. The holder kept the transducers exactly 1.0 inch apart, center to center. A weight was applied to the transducer holder at the center, to maintain a constant and even pressure on both the transducers. An optimal weight was selected by trial which gave reproducible results while keeping the other parameters constant.

Readings were taken with the transducers maintained 1.0″ apart by the transducer fixture and the successive readings were taken by moving the whole assembly 0.5″ at a time along the entire bond-line length. The data acquisition board (PCDAS) operating in an XT type computer was manufactured by General Research Corporation. It provides sampling rates from 156 Khz to 20 Mhz in transient mode. Sampling rates of 40, 80 and 160 Mhz are available in the time equivalent sampling mode. A sampling rate of 20 Mhz was used for these tests.

After a group of signals is saved, the signals are input to a Fortran program developed at Virginia Tech.[19] This program uses a Hartley's transform algorithm[13,14] to do the analysis in the frequency domain. Various statistical moments of the frequency spectrum as defined in the previous section are calculated for each application. The parameter that was considered here, and that provided encouraging results for empirical correlation to strength, was the zeroth moment. This parameter provides a means of quantifying the energy content of the received signal and thereby rating the efficiency of the dynamic strain/stress transfer between the transducers.

Samples were cut 1 inch wide perpendicular to the bond line to form ten sub-samples of each specimen. These sub-samples will be referred to alphabetically in increasing order, from the left edge of the bond line. Sub-samples were 1.0 inches wide, 3.0 inches in length from the overlap edge and had a grip length of 1.0 inch. An MTS 880 series hydraulic testing machine was used to run the destructive tests. The sub-samples were pulled apart by uniaxial tensile load, at a constant head speed of 0.02 inches/minute in stroke control mode. Relative grading of the bond strength was done by comparing the breaking loads.

RESULTS AND DISCUSSION

The SWF values were calculated by taking the zeroth moment (M_0) of the frequency spectrum as discussed previously. The M_0 value provides a measure of the total energy content of the received signal and a means to rate the efficiency of transmission of stress/strain energy in the bond. *A priori,* one would expect that the higher the value of SWF, the better the transmission of stress/strain energy, the better the load re-distribution and hence, the better the bond quality.

Both the samples had mixed mode failure, *i.e.* they displayed areas of both adhesive and cohesive failure. In regions lacking adhesive, the ultrasonic signal travels through only one plate resulting in high values of SWF as shown in Figure 1. Thus, it is possible to obtain a high value of SWF in a region where there is absolutely no adhesive. Hence, one must be careful when interpreting regions where the SWF is high—does a large value of SWF mean better bond quality or simply that no adhesive is present? Regions having a kissing bond also have high SWF values, although the bond strength is zero. The segregation of debonded regions must be done first, and only then the SWF values in bonded regions may be compared to grade relatively the bond strength.

BQ model

An empirical model is proposed to show correlation of SWF with strength of the bonded specimens having mixed mode failure due to the presence of kissing or weak bonds. This model relates the attenuation of the energy content of the received signal to the bond quality.

$$\mathrm{SWF} = l_0 e^{-K_c A_c} \qquad (2.0)$$

where,

SWF = Stress wave factor (M_0).
l_0 = Energy content of the signal input in the sample.
K_c = Attenuation constant per unit area.
A_c = Fraction of the area failing in cohesive mode.

It is assumed that no attentuation of the energy content of the received signal takes place in the region failing in an adhesive mode or regions lacking in adhesive. In these regions, the signal passes through only the top substrate and hence it is safe to assume that the attenuation in the metal substrate is negligible as compared with the attenuation of the energy content of the signal passing through both the substrates as well as the bulk adhesive material. The attenuation of the energy takes place only in the regions failing in a cohesive mode. This simplified assumption holds for the type of adhesively bonded joint under consideration.

$$l_0 = \mathrm{SWF}_a \tag{3.0}$$

The value of SWF_a tends to the value of the energy content of the signal input to the sample (l_0). The SWF_a value is the energy content of the received signal passing only through the substrate between the two transducers. This value can be found by taking readings over a debonded region or on a single substrate. It is reasonable to assume l_0 is nearly equal to SWF_a as the attenuation of the energy content in the metal substrate is comparatively low.

The bond quality (BQ) is directly proportional to A_c and inversely proportional to K_c. The larger the regions failing in a cohesive mode, the better is the bond quality and hence the larger is the breaking load. The larger the value of K_c, the more the attenuation of the energy content of the signal, the weaker is the bond quality and correspondingly the breaking load is also less.

$$\mathrm{BQ} = C\frac{A_c}{K_c} \tag{4.0}$$

where,

BQ = Bond quality.
C = Constant.
A_c = Fraction of the area failing in cohesive mode.
K_c = Attenuation constant per unit area.

The value of K_c depends on the properties of the interface, which in turn depends on the surface treatment, surface roughness and surface condition of the substrate. It also depends on the curing cycle of the bonding process and the type of adhesive used. The final form of the BQ model is arrived at on substituting in the above (4.0) equation the value of K_c from the previous (2.0) equation.

$$\mathrm{BQ} = \frac{-\alpha^2}{\log\left(\dfrac{\mathrm{SWF}}{\mathrm{SWF}_a}\right)} \tag{5.0}$$

where,

BQ = Bond quality
α = ratio of the cohesive failure area to the total area, expressed in fractions. ($0 < \alpha < 1$)
SWF_a = Maximum value of SWF observed of a sample.
SWF = Stress wave factor (M_0)

The value of α is assessed visually after the destructive testing and then the "BQ" values are calculated. While this empirical relation obviously does not lead to a NDE technique, the concept will be shown to indicate that possible correlations can be found between bond strength and SWF values. The "BQ" model is only for mixed mode failure and hence the BQ value is undefined for $\alpha = 1$, when the failure is totally cohesive in nature and also for $\alpha = 0$, when there is no adhesive present in the region. Hence, α must always be taken in the range, $0 < \alpha < 1$. The BQ values generated by this equation are then correlated empirically with the breaking load of the bond. Further work should be performed to determine how this or a related technique might be made truly nondestructive. The results of this

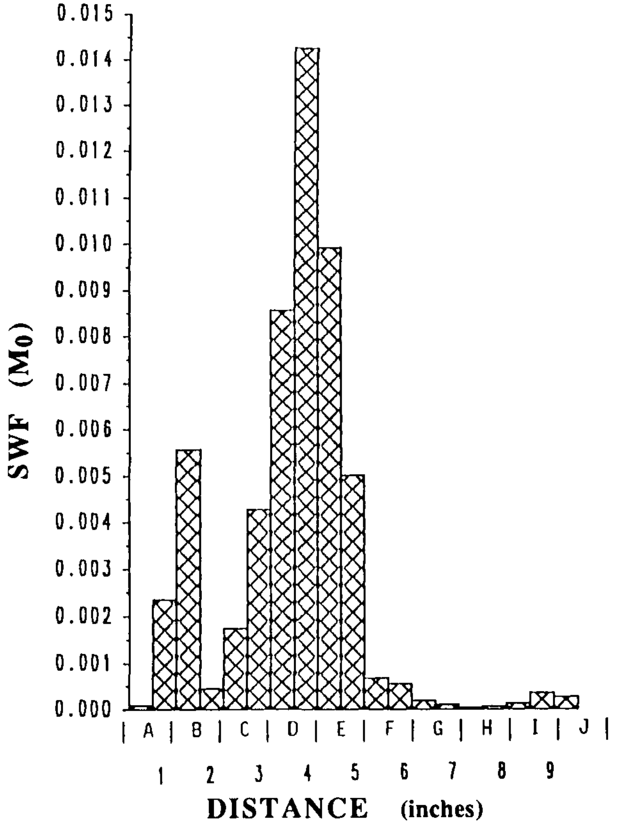


FIGURE 3 Bar chart of SWF values *vs* distance for sample-1.

model, discussed below, show that a definite correlation exists between the SWF values generated by AU and the bond strength of a specimen with mixed mode failure due to the presence of kissing bonds.

Sample-1

Sample-1 has no adhesive present in the region between 3.5 inches and 4.5 inches from the left edge of the bond length. A bar chart of SWF value *vs* distance for sample-1 is shown in Figure 3. The value of SWF is very high, as expected, in this region. A bar chart of BQ values of sample-1 is plotted in Figure 4. Sub-samples G and F have the highest BQ values and the breaking load for sub-samples G and F was also maximum, as expected, Figure 5. Samples A and B do not follow the same trend as the other samples because they were damaged during preparation for mechanical testing. Samples E had no adhesive present and hence the BQ model cannot be applied. A linear regression curve fit between the BQ values and the breaking load is shown in Figure 6 (correlation coefficient = 0.7089). The BQ values for samples A, B and E are not included in this curve. The model for

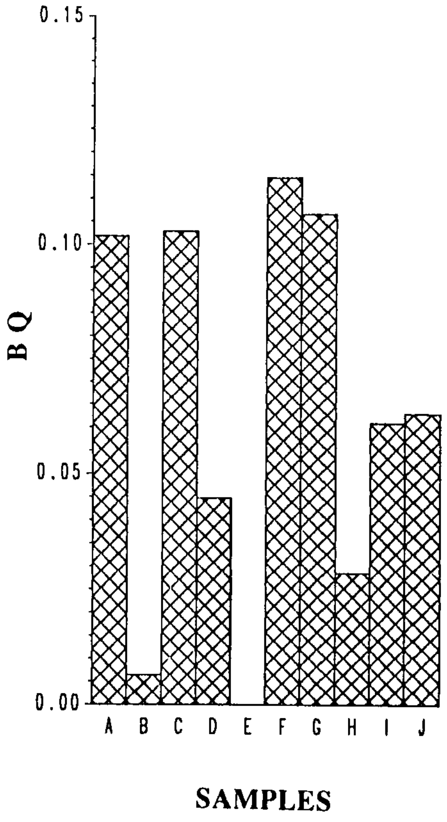


FIGURE 4 Bar chart of BQ values *vs* sub-samples for sample-1.

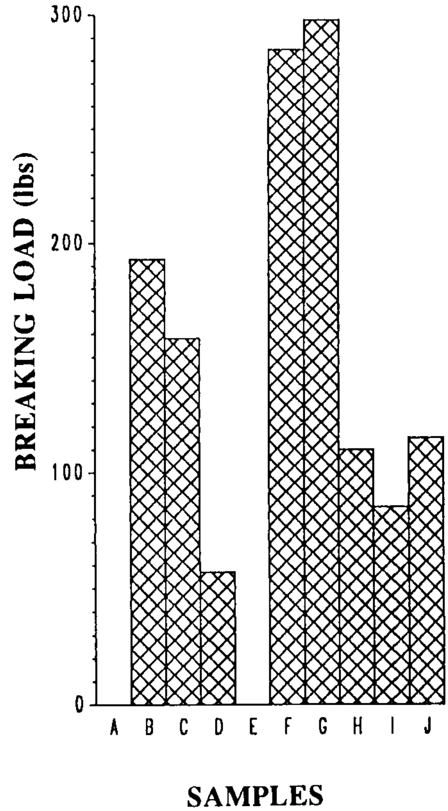


FIGURE 5 Bar chart of breaking load *vs* sub-samples for sample-1.

mixed mode failure relating BQ generated by the AU technique and the breaking strength shows an encouraging result. The scattering of a few data points may be attributed to the erroneous values of α assessed visually. The error in α can be minimized by calculating its value with the help of imaging techniques. The BQ value is found to be related fairly well to the strength of the adhesive bond. The BQ value corresponding to the minimum acceptable bond strength can be evaluated for a given geometry and type of adhesive and then used for an accept/reject NDT system.†

Sample-2

Sample-2 is a three-layered joint. A bar chart of its SWF values is shown in Figure 7. There is no adhesive present between the second and third plate around

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† For a given adhesively bonded joint type, it is feasible to find the limits of SWF values for which the joint has the minimum acceptable strength with the help of the BQ model although, initially, we need to break the samples for the BQ model.

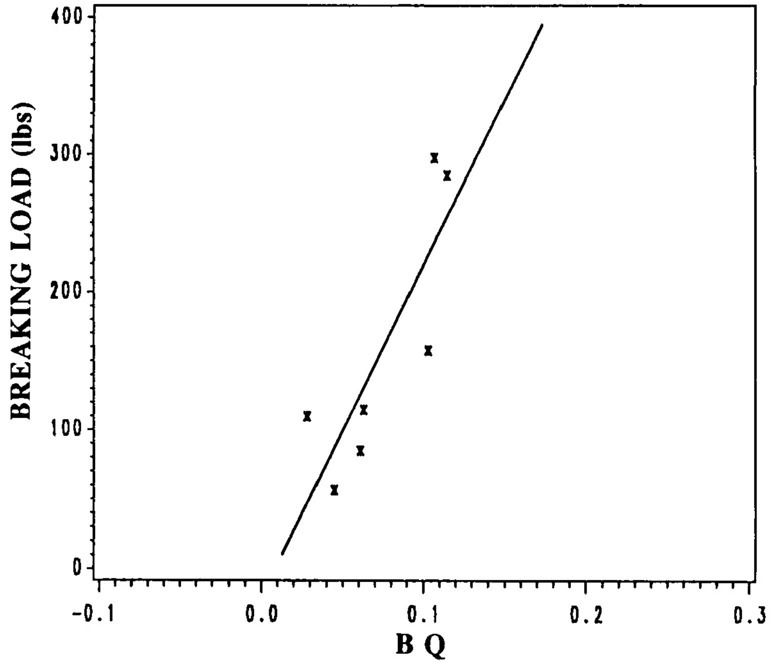

FIGURE 6 Graph of breaking load *vs* BQ values for sample-1 (correlation coefficient = 0.7089).

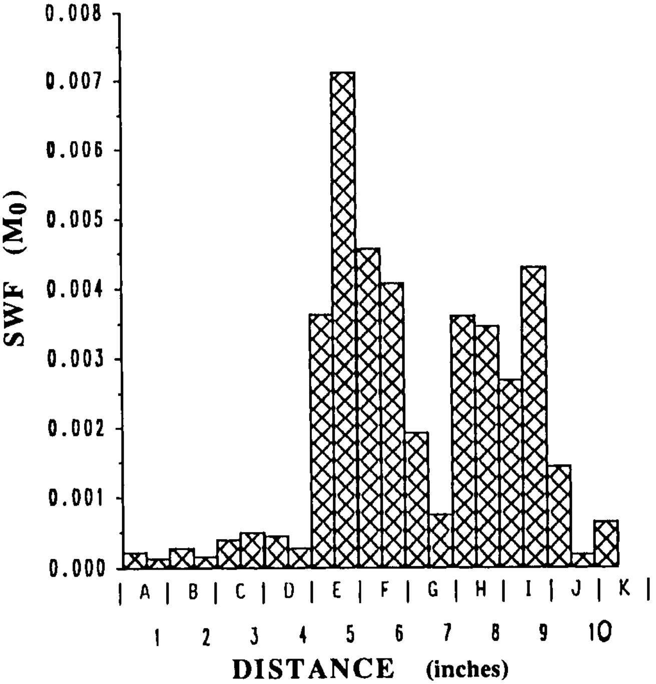

FIGURE 7 Bar chart of SWF values *vs* distance for sample-2.

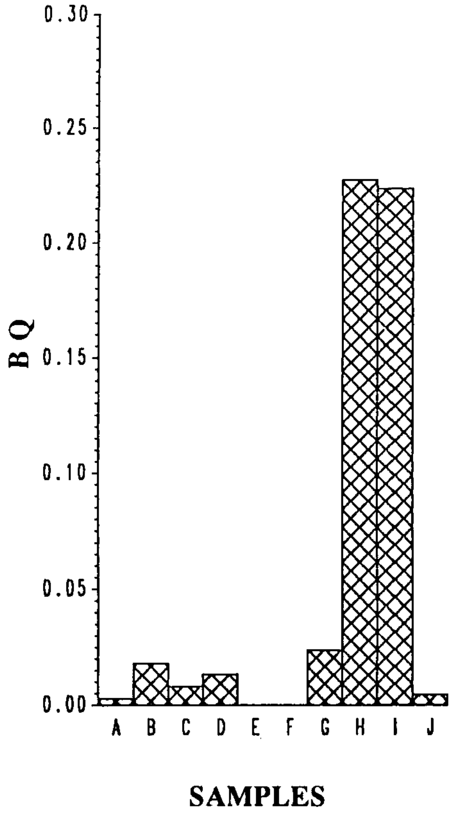

FIGURE 8 Bar chart of BQ values *vs* sub-samples for sample-2.

5.0 inches from the left edge of the bond length. Accordingly, the SWF value is very high in this region. The BQ values are plotted in Figure 8. Sub-samples H and I have the highest BQ values and, as expected, the breaking load is maximum, *viz.*, 396 and 326 lbs as shown in Figure 9. Sub-samples E and F have no adhesive present and hence the BQ values for E and F are undefined for the model and hence ignored. A linear regression curve fit for BQ values and breaking load is shown in Figure 10 (correlation coefficient = 0.805). The scatter of a few data points may also be attributed to errors involved in the measurement of α, *i.e.* the percentage of area of cohesive failure, assessed visually. The trend is upwards as expected, *i.e.* the larger the BQ value, the higher the breaking load, as shown in Figure 10.

The AU data were collected again at a few random locations before performing the destructive testing. The AU signal was fairly reproducible at these locations. The slight changes in the signal that were recorded may have been caused by the variation of the couplant. Thermography and ultrasonic *c*-scan were also done on these samples.

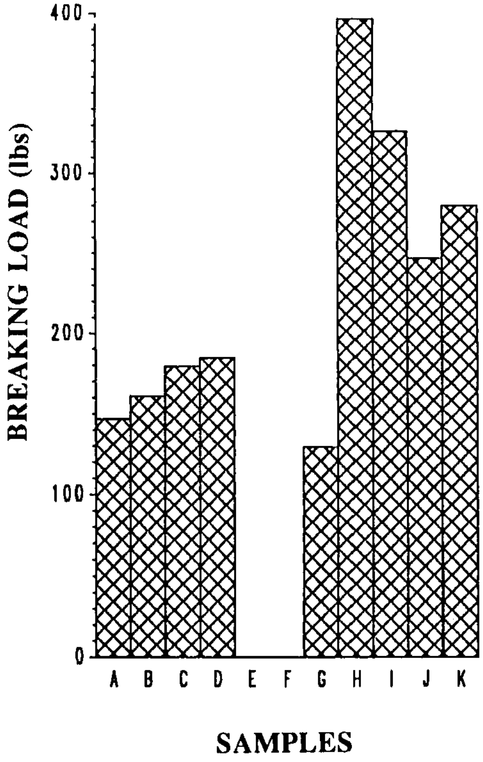

FIGURE 9 Bar chart of breaking load *vs* sub-samples for sample-2.

SUMMARY, CONCLUSIONS AND FUTURE WORK

Summary

An adhesive bond can fail in a cohesive mode or it can have an adhesive failure mode due to the presence of kissing bonds or lack of adhesive. Kissing bonds have adhesive present but it does not adhere to one or both of the substrates. An adhesive bond can also have a mixed mode failure where some regions fail in a cohesive mode and the rest in an adhesive mode. The SWF(M_0) values evaluated from the AU signal represent the energy content of the received signal. The higher the SWF value, the better is the efficiency of stress/strain energy transfer, the better is the load re-distribution and hence the better is the bond quality. On the other hand, although a debonded region or a region with kissing bonds has no bond strength, the SWF values are very high. In this latter case, the signal travels through the top plate only, without much attenuation of the energy content and hence the value of SWF is very high in these regions. An empirical bond quality, "BQ", model is proposed by the authors that fits the data for mixed mode failure. Results show close correlation of BQ values generated by the AU technique and the breaking load for samples failing in mixed mode. The bond quality (BQ) is

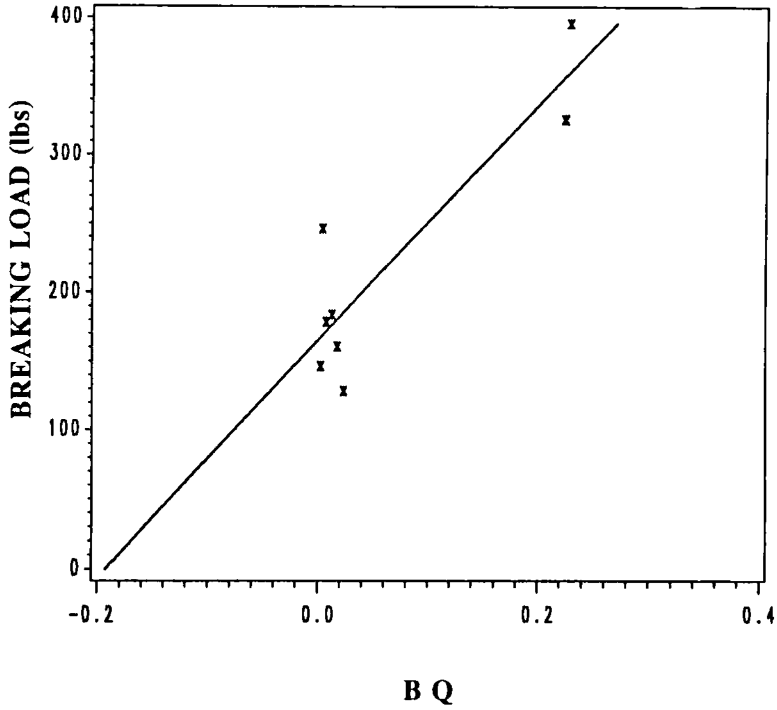

FIGURE 10 Graph of breaking load *vs* BQ values for sample-2 (correlation coefficient = 0.805).

related to the attenuation of the energy content of the received signal for mixed mode failure.

Conclusions

- AU can detect regions lacking in adhesive. Thermography and ultrasonic *c*-scan done on these samples complement and verify this result.
- AU can detect regions having kissing bonds. It can segregate good bonds from weak bonds which fail adhesively due to the presence of kissing bonds. The technique is sensitive to variations in the properties of the interface.
- The "BQ" model developed in this research can rank the quality of the bonds having mixed mode failure.
- The AU technique can assure the quality of an adhesively bonded joint.
- The AU technique requires access to only one side of the component and hence intricate, remote parts of, for example, an adhesively bonded automobile structure can be inspected by this method.

Future work

For the future, major work needs to be done in identifying different types of interface and bulk properties affecting the bond strength. The various mechanical properties and morphological conditions affecting the AU parameters also need to be identified. It is likely that surface roughness and cleanliness would also have an effect on the AU signal. The variations of such properties should be related to the AU parameter variation with the help of pattern recognition methods. "Training samples" containing known states can be used for pattern recognition, as has been successfully done for ultrasonic characterization of welding defects.[20,21] The AU parameter generated and the bond shear strength, however, can be related only after properly understanding the different properties and their effects on the bond quality as well as the AU signal.

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