# ACOUSTIC NONLINEARITIES IN ADHESIVE JOINTS

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## INTRODUCTION

Ultrasonic techniques have been used successfully to measure important bond parameters and to detect various defects in adhesive joints for about twenty years. Recent reviews of nondestructive testing of adhesively bonded structures can be found in the literature [1-3]. For direct strength assessment, the reliability of these techniques leaves much to be desired. Linear acoustic parameters are only indirectly correlated to material and bond strength, therefore we must rely on dubious empirical relations between the measured parameter (e.g., velocity or attenuation) and the sought strength parameter on a case-to-case basis. On the other hand, it is well known that failure of most materials and bonds is usually preceded by some kind of nonlinear mechanical behavior, well before appreciable plastic deformation occurs, i.e. within the range of nondestructive testing. This macroscopic nonlinearity is due to a number of different causes such as weakening of covalent bonds with increased atomic spacing, reduction in the number of these bonds, etc. It seems to be reasonable to assume that non-linear parameters measured at approximately 10-20% of the ultimate stress level are more directly correlated to mechanical strength than linear ones measured at negligibly low ultrasonic amplitudes:

Figure 1 shows an example of nonlinear stress-strain curves. Assuming odd symmetry, which is quite evident for shear loads considered in this study, the simplest possible nonlinear stress-strain relation is a third order extension of the first order, i.e. linear approximation:

$$\tau = \alpha\xi - \beta\xi^3. \qquad (1)$$

We can define a number of parameters to measure the nonlinearity of the material. For instance, the simplest definition seems to be the relative deviation from the linear behavior, i.e.

$$\eta = \frac{\alpha\xi - \tau(\xi)}{\alpha\xi} . \qquad (2)$$

In this case, the measured nonlinearity $\eta_m$ is proportional to the square of the measuring stress level $\tau_m$

$$\eta_m \simeq \frac{\beta}{\alpha^3} \tau_m^2, \qquad (3)$$

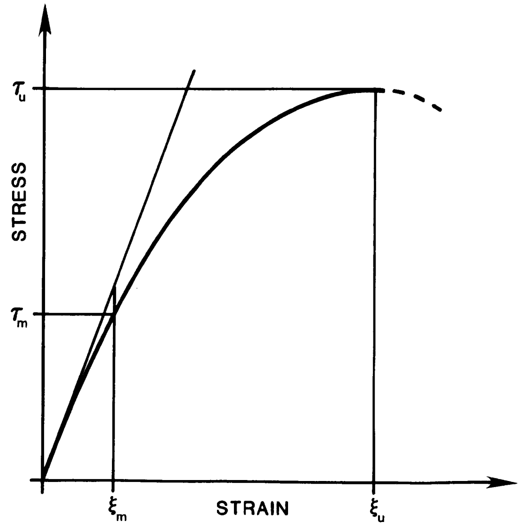


Fig. 1 Example of nonlinear stress-strain relationship.

and the mechanical strength can be expressed as the ultimate stress level

$$\tau_u = \frac{2}{3}\sqrt{\frac{\alpha^3}{3\beta}} = \frac{2}{3}\frac{\tau_m}{\sqrt{3\eta_m}} \qquad (4)$$

This basic approach was originally suggested by J. D. Achenbach, et al., for strength assessment in adhesive joints of negligible bond-line thickness [4,5]. In this study, we attempt to develop measuring techniques to investigate and hopefully verify the feasibility of this approach for the more practical case of adhesive joints with small, but finite bond-line thickness.

## JOINT VERSUS BOND PARAMETERS

One of the major problems we must face throughout this study is the considerable difference between overall joint parameters measured by destructive techniques and the corresponding localized bond parameters determined by ultrasonic means. The principal source of these differences is the usually quite complex, uneven stress distribution in the bonded region. Figure 2 shows the shear stress distribution in a lap joint during tensile-shear experiment (for the sake of simplicity, the also present normal stress is neglected). The strain in the sample is measured by optical or mechanical means at the center of the overlap where the actual stress is much smaller than anywhere else. The stress is not measured directly, but rather calculated as the average value from the tensile force (F) and the total overlap area (A). Consequently, the initial slope of the stress-strain curve as measured on the joint ($\alpha^{joint}$) turns out to be much higher than the shear modulus of the adhesive material ($\alpha^{bond}$). On the other hand, failure usually occurs at the edges where there is high stress concentration, therefore the ultimate shear stress of the joint ($\tau_u^{joint}$) is considerably lower than the corresponding bond strength ($\tau_u^{bond}$) (Fig. 3). Figure 4 shows the experimental stress-strain curve of an FM300K lap joint. The dashed line represents the nonlinear model of Eq. (1) for the same principal parameters, i.e. for the same initial slope and ultimate stress. The agreement is rather poor in the upper half of the stress range, but a much more serious discrepancy can be found if we compare the initial slope, $\alpha^{joint}$ = 695 ksi, to the shear velocity of the adhesive, $\alpha^{bond}$ = 170 ksi,

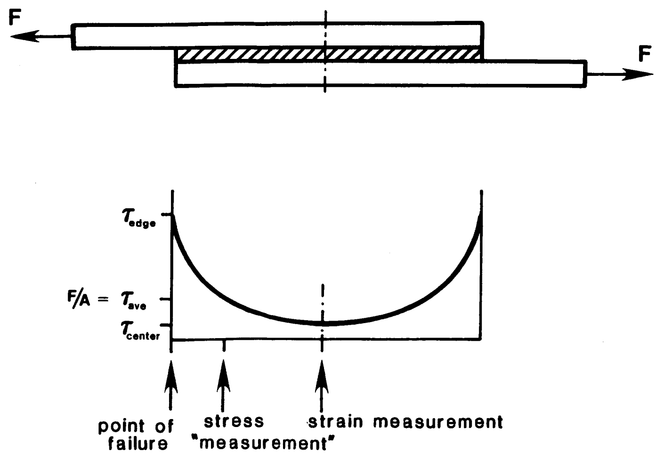

Fig. 2  Shear stress distribution in a tensile-shear specimen.

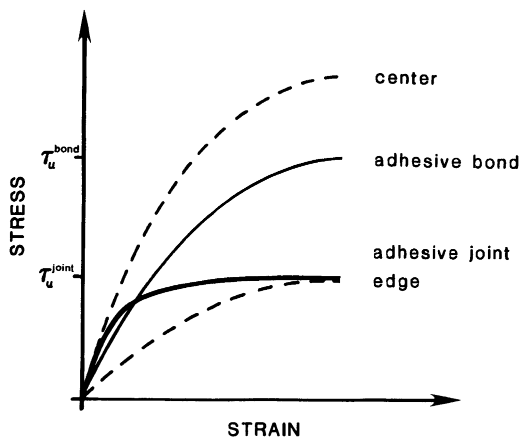

Fig. 3  Stress-strain curves of the adhesive bond and joint.

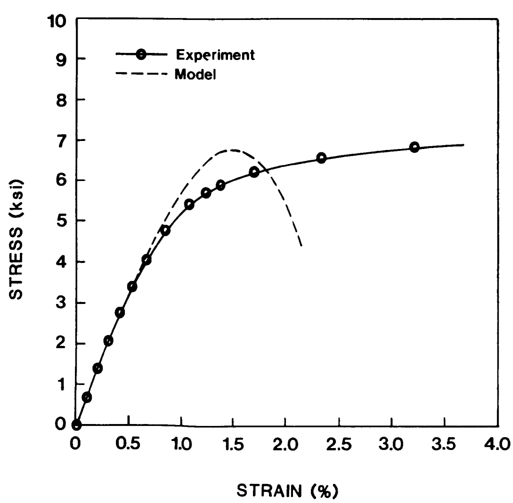

Fig. 4  Nonlinear stress-strain curve in an FM300K lap joint.

as determined from ultrasonic velocity measurement. This example clearly shows that neither linear nor nonlinear properties of the adhesive bond can be directly evaluated from elastic measurements on the joint without taking into consideration the actual stress distribution in the bonded region.

As an example, Fig. 5 shows the normal and shear stress distributions in a shear-tensile lap joint specimen after Goland, et al. [6]. 3/8" thick aluminum plates were bonded over 1" length with a 300 μm thick FM300K adhesive layer. Numerical values are also listed for three particular points of interest: at center, 1/3" off center, and at the edge. For later use, we should notice that the maximum shear stress occurs at the edge and its value can be calculated from the normal and shear stresses as follows [7]:

$$\tau_M \approx \sqrt{\tau_3^2 + \frac{\sigma_3^2}{4}} \approx 3\tau_{ave}. \tag{5}$$

EXPERIMENTAL TECHNIQUE AND RESULTS

The schematic diagram of our experimental arrangement is shown in Fig. 6. Based on the nonlinear model of Eq. (1), we can expect considerable nonlinearity at acceptably low measuring levels. For instance,

$$\eta_m = \frac{4}{27} \frac{\tau_m{}^2}{\tau_u{}^2} \sim 1\% \text{ at } \tau_m = 0.25\tau_u. \tag{6}$$

Since nonlinear effects add up as the sound propagates in the nonlinear medium, 1% relative nonlinearity could be quite easy to measure in larger samples, but it presents a serious problem in a thin layer of a few wavelength. In order to increase the accuracy of conventional acousto-elastic

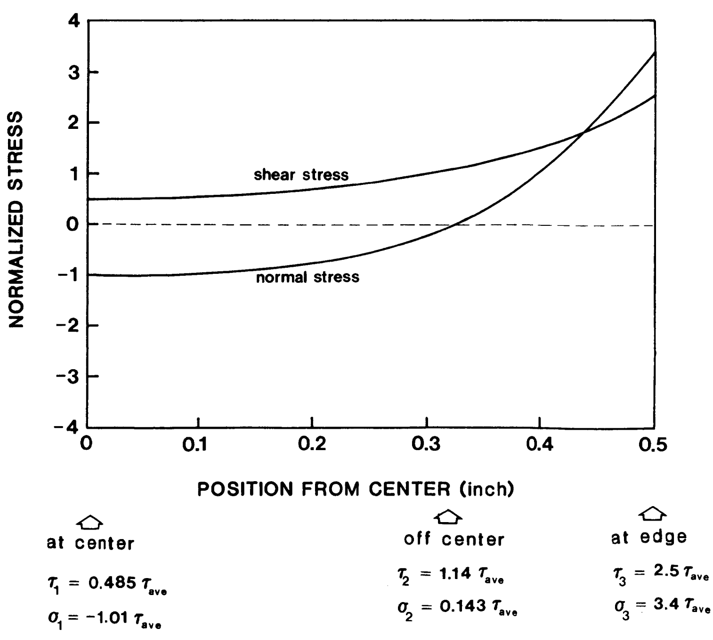


Fig. 5 Normal and shear stress distribution in a shear-tensile lap joint specimen.

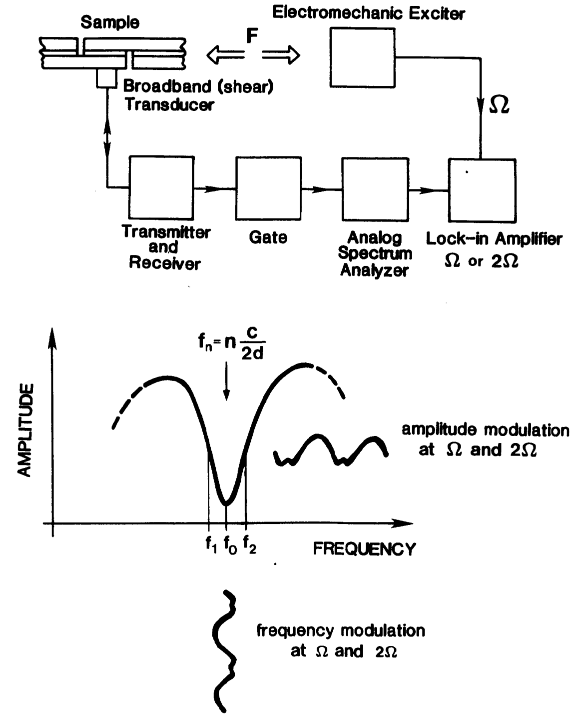


Fig. 6 Schematic diagram of the acousto-elastic measurement.

measurements, we introduced dynamic excitation combined with frequency- and phase-sensitive detection. A broadband shear transducer is used to interrogate the bond-line at normal incidence. Sharp minima in the frequency spectrum of the interface reflection offer simple means to monitor the sound velocity in the adhesive layer as a function of external stress.

Figure 7 shows the results of static measurements on an FM300K lap joint at the center. The apparent velocity change (including the actual change in velocity and a small change in layer thickness as well) seems to be more or

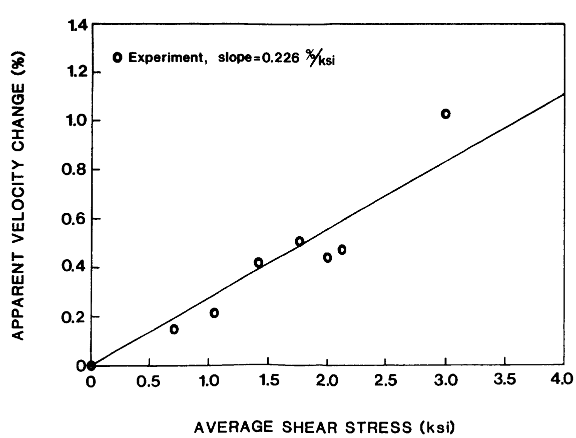


Fig. 7 Velocity change versus external stress in an FM300K adhesive layer (static measurement).

less proportional to the external stress, but the scatter of the data is unacceptably high. Much better results were achieved by using a fatigue machine operating at $\Omega = 10$ Hz to load the sample. In this case, the spectrum analyzer was used as a selective receiver tuned to $f_1$ and $f_2$ frequencies, below and above the resonance minimum. The amplitude modulation at these frequencies then was measured by a lock-in-amplifier synchronized to the electromechanical exciter. The sought frequency modulation was calculated from the measured amplitudes and the calibrated slopes of the resonance curve, and the two values were averaged with proper phase to increase accuracy. Figure 8 shows the results of a dynamic measurement at both the center of the lap joint and 1/3" off center. The slope of the velocity change versus shear stress curve turns out to be 2.28 $10^{-3}$ $ksi^{-1}$, basically the same as the one obtained by static measurement, but the scatter of the data is much smaller. Because of symmetry considerations, this effect must be due to the normal stress in the layer. This conclusion is also confirmed by the much smaller slope of the opposite sign found at off center, which is in good agreement with our expectations based on Fig. 5.

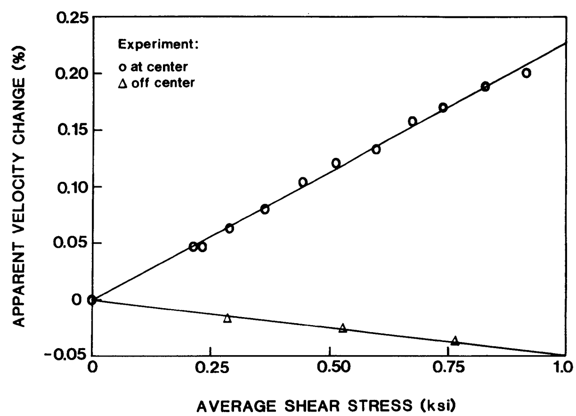


Fig. 8 Velocity change versus external stress in an FM300K adhesive layer (dynamic measurement, first harmonic).

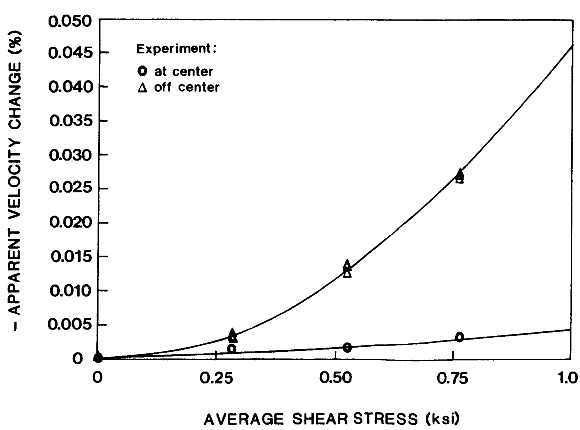


Fig. 9 Velocity change versus external stress in an FM300K adhesive layer (dynamic measurement, second harmonic).

Figure 9 shows the second harmonic velocity change in the adhesive layer as a function of external stress. This nonlinearity parameter is expected to be strength related since we assumed that the effective elastic modulus, i.e. the slope of the nonlinear stress-strain curve, reduces with increased stress in both positive and negative cycles, i.e. two times in a full period of the dynamic load. The second harmonic velocity modulation seems to be mainly due to the shear stress component since the effect is much stronger off the center where the normal stress is negligible and the shear one is considerably higher than at the center. Naturally the measured nonlinearity is the combined effect of both normal and shear stresses, and separation of the different components is almost impossible, since superposition does not hold for this case. Therefore, our best chance is to carry out measurements under "pure" shear stress, which condition is more or less satisfied at the off-center position where the second order polynomial coefficient

$$B_2 = - \left. \frac{\Delta c^{(2)}/c}{\tau_{ave}^2} \right|_{\text{off center}} = 4.64 \times 10^{-4} \text{ ksi}^{-2} . \tag{7}$$

STRENGTH ASSESSMENT

In order to establish an approximate relationship between the measured nonlinearity parameter $B_2$ and the ultimate strength of the adhesive $\tau_u$, we assume that the measured sound velocity is proportional to the square-root of the effective shear modulus, i.e. the slope of the nonlinear stress-strain curve.

$$c = \sqrt{\frac{\mu}{\rho}} \tag{8}$$

Based on the earlier introduced nonlinear stress-strain model,

$$\mu \approx \frac{\partial \tau}{\partial \xi} \approx \alpha\left(1 - \frac{4}{9} \frac{\tau^2}{\tau_u^2}\right), \tag{9}$$

and the relative change in velocity can be written as follows:

$$\frac{\Delta c}{c} \approx - \frac{2}{9} \frac{\tau^2}{\tau_u^2} \tag{10}$$

In the case of $F = F_o \sin(\Omega t)$ harmonic excitation, the relative velocity modulation

$$\frac{\Delta c}{c} \approx - \frac{\tau^2}{9\tau_u^2} (1 - \cos(2\Omega t)) \tag{11}$$

has a DC and a double frequency AC component. From Eqs. (7) and (11), we get

$$B_2 \tau_{ave}^2 \approx \frac{\tau_2^2}{9\tau_u^2} , \tag{12}$$

where the actual shear stress $\tau = \tau_2$ can be expressed by $\tau_{ave}$ and the weighting factor

$$T_2 = \frac{\tau_2}{\tau_{ave}} \approx 1.14 \tag{13}$$

from Fig. 5. Finally, from Eqs. (12) and (13)

$$\tau_u = \frac{1}{3} \frac{T_2}{\sqrt{B_2}} \simeq 17.6 \text{ ksi.} \tag{14}$$

If we take into consideration the rather rough approximations used in our calculations, this nondestructive prediction turns out to be surprisingly close to the destructive result corrected for the stress concentration at the point of failure

$$\tau_u \approx \frac{\tau_M}{\tau_{ave}} \tau_u^{joint} = 20.6 \text{ ksi.} \tag{15}$$

CONCLUSIONS

A new nonlinear inspection method was introduced to study the feasibility of direct strength assessment from ultrasonic measurements. A dynamic acousto-elastic technique was shown to be sensitive enough to measure both first and second order nonlinearities at acceptable load levels of less than 15% of the ultimate strength. Possibly strength-related components of the measured nonlinearity were identifeid and separated from other, usually much stronger effects by harmonic (frequency) analysis. Comparison of destructive (joint) and nondestructive (bond) strength assessments must take into account the uneven stress distribution in the sample to obtain reasonable agreement. Further development of the suggested technique is necessary to increase its accuracy and make it more practical. Correlation between predicted and actually measured strength parameters must be verified on a large set of specimens.

ACKNOWLEDGEMENT

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