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Nonlinear ultrasonic evaluation of the fatigue damage of adhesive joints

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ABSTRACT

An experimental method based on the nonlinear ultrasonic technique is presented to evaluate fatigue damage of an adhesive joint. In this paper, specimens made from AZ31 magnesium–aluminum alloy bonded through an epoxy layer are subjected to a fatigue load. The ultrasonic harmonics generated due to damage within the adhesive layer are measured; and the acoustic nonlinearity parameter (ANP) based on the fundamental and second harmonics is determined. The results show that the normalized ANP increases with the fatigue cycles. Furthermore, a theoretical model with different interfacial compression and tension stiffness is proposed to interpret the generation of second harmonics.

1. Introduction

Adhesive joints are widely used in various industrial applications, such as safety-critical structures in the aerospace and automotive industries. Adhesively bonded structural components usually provide many advantages over conventional mechanical fasteners. Among these advantages are lower structural weight, lower fabrication cost, and improved damage tolerance [1,2]. For example, advances in aerospace technology have been made possible through the use of lightweight materials and weight-saving structural designs. Joints, in particular, have been and continue to be areas in which weight can be trimmed from an airframe through the use of novel attachment techniques.

With the increasing use of adhesive bonded structures, corresponding methods for evaluation and testing of the structural integrity and quality of bonded joints have been widely investigated and developed for the purpose of structural health monitoring [3–5]. Non-destructive characterization for quality control and remaining life prediction has been a key enabling technology for the effective use of adhesive joints. Conventional linear ultrasonic techniques can detect flaws such as delamination, cracks, and voids in the adhesive joints. However, more important to the bond quality is the adhesive strength. Although in principle, strength cannot be measured non-destructively, the slight nonlinearity in the material may indicate material degradation or the onset of failure [6]. Furthermore, microstructural variations due to aging may also cause change in the third order elastic constants, which are related to the acoustic nonlinear parameter (ANP) of the polymer adhesive.

It has been observed that higher harmonics of the fundamental frequency are generated when a harmonic ultrasonic wave propagates through a nonlinear material [7]. It is proposed that the material degradation creates nonlinearity which can be detected in the wave propagation characteristics [8,9]. Several theories have been developed to model this nonlinear effect. For example, Achenbach and Parikh [10] presented their theoretical investigation to obtain information on the adhesive bond strength from ultrasonic test results. Using the postulate that failure of the adhesive bond is preceded by nonlinear behavior at the interface, they obtained a nonlinear parameter that correlates to joint strength. Based on a microscopic description of the nonlinear interface binding force, a quantitative method was presented by Pangraz and Arnold [11]. Tang et al. [12] measured the onset of nonlinearity in adhesive bonds by subjecting to static loads simultaneously with the ultrasonic testing. The degradation of the adhesive bond was induced by cyclic fatigue loading. The deterioration due to cyclic fatigue is identified by the reduction of the linear portion of the stress–strain curve without any change in slope in the linear range. Furthermore, Delsanto et al. [13,14] developed a spring model to simulate the ultrasonic wave propagation in non-classical (hysteretic) nonlinear media. Vanaverbeke et al. [15] proposed a multiscale model for the two-dimensional (2D) nonlinear wave propagation in a locally microdamaged medium, and presented numerical simulations in view of nondestructive testing applications. An et al. [16] developed a rigorous nonlinear spring model under the normal incidence of both longitudinal and SH waves. The numerical simulations show the accuracy and applicability of their model for a

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thin layer between two solids under the condition of small ratio of thickness to wavelength.

In the meanwhile, ultrasonic guided waves have been used to analyze adhesive or diffusion bonded joints. For example, Nagy and Adler [17] studied guided waves in adhesive layers between two half-spaces, demonstrating that the resulting dispersion curves are relatively insensitive to the properties of the adhesive layer. Rohklin and Wang [18] examined Lamb waves in lap–shear joints, including the development of an analytical spring model. Rose et al. [19] developed dispersion curves for titanium diffusion bonds and examined frequency shifts and spectral peak-to-peak ratios of different bonded states. Lowe and Cawley [20] analyzed the sensitivity of adhesive bond properties on guided waves using a three-layered model. Heller et al. [21] combined laser ultrasonic techniques with the 2D fast Fourier transform (FFT) to characterize adhesive bond properties. Seifried et al. [22] used analytical and computational models to develop a quantitative understanding of the propagation of guided Lamb waves in multi-layered, adhesive bonded components.

In this paper, the ANP is used to characterize the degradation of an adhesive joint made from epoxy resin between two aluminum plates. Ultrasonic through-transmission tests were conducted on samples cured under various conditions. The magnitude of the second order harmonic was measured and the corresponding ANP was evaluated. These experimentally measured ANPs, as functions of degradation, are then used to quantitatively characterize the condition of the adhesive bond. A fairly good correlation between the fatigue cycle and the ANP is observed. Furthermore, the experimentally observed second harmonic generation is interpreted by developing an analytical model. The results show that the ANP can be used as a good indicator of the adhesive strength for adhesive joints.

2. Experimental procedure

As shown in Fig. 1, the test sample is an overlap joint of two aluminum plates bonded together by an adhesive layer. The adhesive is a kind of bisphenol epoxy resin with epoxy value of 0.441 mol/100 g. The aluminum plate is made of AZ31 magnesium–aluminum alloy, with the yielding stress 199 MPa, elastic modulus 46 GPa, Poisson's ratio 0.27 and density 1770 kg/m^3. As illustrated in Fig. 1, the bonded area of the specimen is 30 mm × 24 mm. The adhesive (bondline) thickness is generally less than 1 mm and the adherend's thickness is about 6.5 mm. The aluminum plates were anodized and primed prior to application of the adhesive. The joints were then put into a temperature/pressure oven for curing. They were firstly cured for two hours with a temperature of 80 °C, and then cured for another two hours with a temperature of 160 °C. All samples used in this study were prepared under the same conditions.

A schematic diagram for the experimental setup is shown in Fig. 2. The transmitting transducer was driven by a tone burst signal of 6 cycles at 5 MHz. The receiving transducer was used to

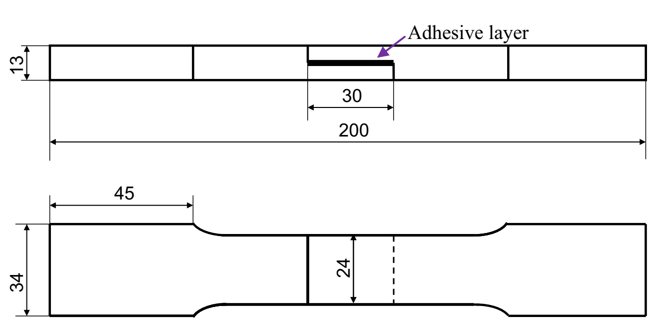

Fig. 1. Dimension of two aluminum plates bonded through an adhesive layer (unit: mm). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

detect the fundamental and second harmonics of longitudinal ultrasonic waves passing through the adhesive joint. The central frequencies of transmitting and receiving transducers are, respectively, 5 MHz and 10 MHz. The tone burst signal was generated by Ritec SNAP-0.25-7-G2 nonlinear measurement system with the high-power gated amplifier. Before driving the transmitting transducer, the high voltage signal passed through a 50 Ω termination, an attenuator and a set of low-pass filter so that the transient behavior and high frequency component from the amplifier were suppressed. This nonlinear measurement system can provide a more monochromatic ultrasonic sine wave signal with higher quality, and this will decrease the acoustic nonlinearity from the signal considerably.

Although the multi-reflection can take place between the upper/lower surface and interface in the experimental samples, the reflected waves reach the Receiver about 0.6 μs later than the last cycle of the waves passing through the adhesive joint reach the Receiver. So there is no multi-reflective influence in the received signal. A typical longitudinal wave signal acquired is shown in Fig. 3. (One should notice that 9.0 μs shown in this figure, which is owing to the setting of the oscilloscope, is NOT the flight time of the wave.) The sampling rate of the oscilloscope is 1.25 GS/s. The signal of an entire length consists of a transient part at the beginning, a steady state portion, and finally the turnoff ringing at the end. To make sure that only the steady-state part of the tone burst signal was used, a Hanning window was applied to the acquired time-domain signal for Fast Fourier Transform (FFT). Therefore, only the data points within the steady-state part were selected and then transformed to the frequency domain where the amplitudes of the fundamental and higher order harmonics of the detected waves become visible. Fig. 4 shows the amplitudes of the fundamental (A_1) and second (A_2) harmonics in the frequency domain, respectively.

3. Experimental results

During the experimental measurements, ten samples were selected to be fatigued. The fatigue loading is parallel to the adhesive layer, as shown in Fig. 2. The maximum load for five of the samples was 2.5 kN; and the maximum load for another five was 3.0 kN. The fatigue tests were interrupted to perform the nonlinear ultrasonic measurements at different numbers of fatigue cycles.

Following Refs. [23,24], the ANP of the adhesive is defined by

$$\beta = \frac{8A_2}{A_1^2 h k^2} \tag{1}$$

where A_1 is the amplitude of the fundamental harmonic wave; A_2 is the amplitude of the second harmonic wave; h is the propagation distance; and k is the wave number. For longitudinal waves with a fixed frequency and a fixed transmitting distance, the ANP, β, is only proportional to A_2/A_1^2. Therefore, in this measurement, we use, for convenience, a relative ANP defined as

$$\beta' = \frac{A_2}{A_1^2} \tag{2}$$

Because there will be some level of variability associated with the initial microstructure of each specimen, the measured ANPs will be normalized by the value (β'_0) measured in each undamaged specimen before any mechanical load is applied. This normalization procedure removes some of the variability associated with the initial microstructures of each specimen, enables a direct comparison of the acoustic nonlinearity evolution of all the specimens tested, and normalizes the nonlinearity associated with the transmitting piezoelectric transducers. The evolution of the normalized ANP, β'/β'_0, as a function of the normalized fatigue life is shown in Fig. 5(a) for specimens 1–5 with the maximum load of 2.5 kN. Here, the fatigue