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Effect of vibration fatigue on modal properties of single lap adhesive joints

Yu Du*, Lu Shi

School of Automotive Engineering, Dalian University of Technology, Dalian, China

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ABSTRACT

As most existing studies focus on developing models and theories describing the static strength of adhesive joints as a function of the fatigue loading, there is a lack of understanding on how the fatigue of the adhesive joint affects dynamic modal properties of the bonded structure. In applications such as automobile components, modal properties are critical in determining their dynamic performances. To investigate the relationship between modal properties of single lap joints (SLJs) and the cyclic-vibration-peel loading, this study first carries out vibration fatigue tests and subsequent modal response measurements using steel–aluminum SLJ specimens. It is experimentally demonstrated that modal frequencies of the SLJ structure tend to decrease with increasing vibration fatigue cycles. Furthermore, it is also shown that this trend is related to the fatigue characteristics of the adhesive layer. The fatigue degradation effects of Young's modulus and contact area between the adhesive and the adherends on modal frequencies are then investigated using a finite element model. Simulation results reveal that dramatic reductions in modulus and contact area values are required to result in the modal frequency shifting observed in experiments, which may not be always realistic. Although the findings in this study are informative, more research effort is needed to further identify the critical reason(s) for the experimental trend of decreasing modal frequencies with increasing vibration fatigue cycles.

1. Introduction

Adhesively bonded structural joints have been widely used in aeronautics, aerospace, automobile, semiconductor, and civil structures, benefiting mainly from their high fatigue strength in comparison with other mechanical fastening technology, such as welding and riveting [1]. Adhesively bonded joints also present many other advantages like design flexibility and simplicity of fabrication. Nevertheless, fatigue damage is still an important design consideration in most structural applications of adhesive joints, especially when the fatigue damage is introduced by vibration loads that may weaken the joint strength and affect the dynamic modal properties of the bonded structure [2].

The fatigue damage, or in a more general term defect, of adhesive joints is often studied in terms of the fatigue crack growth (FCG) rate of a defect as a function of loading conditions and states. In many studies, the fatigue crack growth rate (FCGR) is described with the Paris law that relates the FCGR with the amplitude of the energy release rate and the mode-ratio [3]. As the Paris law provides more of a data correlation scheme rather than a predictive capability for the relation between the damage extent and the constitutive properties of the adhesive joint [4], its reliability highly depends on the simulation as well as the experimental techniques. In simulating the fatigue driven delamination growth in laminated composites, Muñoz et al. investigated the robustness and efficiency of a numerical method to accurately reproduce the linear portion of the Paris plot that describes the rate of the crack growth length per cycle as a function of the applied strain energy release rate [5]. Based on experimental mode I and mix-mode I+II fatigue characterization of composite bonded joints, Fernández et al. evaluated the performance of different data reduction schemes to obtain the energy release rate in the FCGR using double cantilever beam (DCB) and single leg bending (SLB) specimens [6,7]. They concluded that the compliance based beam method is more reliable and efficient than the classical crack monitoring based method in determining the strain energy release rate as a function of crack length.

To simulate the crack growth with the increase of load cycles, the Paris law is often used together with the cohesive zone model (CZM) as the CZM is capable of combining a strength-based failure criterion to predict the damage initiation and a fracture mechanics-based criterion to determine the damage propagation. In the CZM, the fatigue damage is usually represented by defining a damage variable whose value depends on the loading conditions and the adhesive properties [3,4,8–12]. For example, Khoramishad et al. introduced a maximum principal strain based damage variable

* Corresponding author.
E-mail address: yudu@dlut.edu.cn (Y. Du).

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calculation method to predict the crack evolution and fatigue life of single lap joints (SLJs) under fixed load-ratio fatigue loading [8]. Later, they extended this method to cases of variable load-ratio and variable amplitude fatigue loading [9,10]. In Ref. [13], by degrading the elastic modulus and yield stress of the adhesive material through a damage variable, the experimental backface strain data at different fatigue cycles obtained from SLJ specimens were reasonably simulated using the finite element (FE) method.

It may be noticed that the existing discussions on the fatigue characteristics of adhesive structures in the open literature are predominantly in terms of static or quasi-static performance criteria (e.g., residue strength after certain fatigue cycles) or loading conditions (e.g., cyclic fatigue test under a couple of Hertz). In contrast, there has been much less research effort focusing on investigating the relationship between the fatigue damage of the adhesive joints and the dynamic properties of the bonded structures. In many applications, the dynamic properties, such as the modal frequency and the modal shape, are critical in determining and understanding the dynamic mechanical responses (e.g., noise and vibration performances) of the structure [14].

Currently, some analytical models have been developed to capture the dynamic characteristics of the adhesively bonded joints. Saito and Tani [15], He and Rao [16,17], Renton and Vinson [18] and Yadagiri et al. [19] used analytical equations to predict the static and dynamic properties of adhesive joints. Kaya et al. analyzed the natural frequencies and modal shapes of adhesively bonded joints using a two-dimensional FE model [20]. Their results showed that, as the adhesive layer thickness increased, the natural frequencies of the structure decreased slightly. With numerical examples, He and Oyadiji [21] and He [22] investigated the influence of adhesive parameters on the natural frequencies and modal shapes of the single lap jointed cantilever beams. Their results indicated that the natural frequencies of the adhesive joints increased significantly as Young's modulus of the adhesive increases, while maintained nearly the same with various Poisson's ratios. In addition, Ko et al. [23], Reddy [24], Lin and Ko [25] used FE models to predict the free vibration behavior of bonded composite plates. Ingole and Chatterjee [26] proposed an analytical model to study the coupled transverse and longitudinal vibrations of SLJ structures. Their results demonstrated that the fundamental frequency of a SLJ beam with the free–free boundary condition was sensitive to the ratio of the joint overlap length to the overall length of the beam. In Ref. [27], Guyott and Cawley predicted the natural frequencies of the longitudinal modes of an adhesive joint using the receptance analysis and validated the predictions with the ultrasonic spectroscopy measured data. The results indicated that it was possible to calculate the thickness and modulus of the adhesive layer from measurements of the resonant frequencies of the joint.

Compared to the predictions of modal properties of adhesively bonded joints, there is even less discussion regarding the fatigue behavior of bonded joints under non-static loads and its effects on the dynamic characteristics of bonded structures. One article authored by Casas-Rodriguez et al. investigated the behavior and impact-fatigue life of adhesive joints exposed to low-velocity impact loading [28]. The results indicated that a vibration loading was much more detrimental compared to the standard static or quasi-static fatigue loading. Aiming at structures (e.g., aircraft and automobile components) experiencing irregular and dynamic fatigue loading, in a more recent study, Pang et al. used the CZM incorporated with a damage factor to describe the gradual decrease in the maximum shear strength of steel–aluminum SLJ specimens with increasing dynamic loading cycles [2]. In their model, the damage factor was calibrated against the experimental fatigue data due to a cyclic-vibration-peel (CVP) loading which drove the SLJ specimens to vibrate as cantilever beams close to one of their modal frequencies.

Continuing the work of Ref. [2], the objective of the current study is to investigate the effects of vibration fatigue on modal properties of single lap joints and attempt to identify the relationship between the fatigue damage in the adhesive layer and the modal properties of the jointed structure. For this purpose, the modal frequencies of steel–aluminum SLJ specimens were measured experimentally at different CVP fatigue cycles. It was observed that the modal frequencies tended to decrease as the CVP fatigue cycle increased. A FE simulation model was then developed in ABAQUS® /standard (Dassault Systems Simulia Corp., Providence, RI, USA) to predict the modal properties of the SLJ specimen. Based on the classical beam theory, it is assumed that the changes in modal properties of SLJ specimens are associated with the stiffness of the adhesive layer that is accordingly determined by the material Young's modulus and the contact area between the adhesive and the adherends. Using the FE model, different damage schemes were proposed to investigate the contributing reasons for the modal frequency shifting as a function of the CVP fatigue cycles.

2. Experimental study

To investigate the variations in modal frequencies of the adhesively bonded joints under CVP loading, two experimental steps were followed. First, the test specimens were subjected to vibration excitations with controlled cycle counts; and second, the first three modal frequencies of the adhesive structure at various fatigue cycles were obtained through an impact hammer test.

2.1. Material property and specimen preparation

The geometry of SLJ specimens under investigation is shown in Fig. 1. The specimens were prepared following the requirements stated in ASTM D1002-10 [29] with slightly different dimensions. The adherends were cut from 2.0 mm thick sheets of 7075 T76 aluminum alloy and 1.5 mm thick sheets of Cr. D steel using a wire-electrode cutting machine. These two dissimilar substrates of different materials were used to simulate the cases that are typically used in the auto industry. Typical mechanical properties of the two adherend materials used in this study are listed in Table 1.

Before joining, the surfaces of the substrates were prepared following instructions specified in ASTM D1002-10. First the overlap surfaces of both adherends were polished and degreased with water-proof abrasive paper and acetone to remove surface oxide layers and greasy dirt. Then a calibrated spacer was used to control the thickness of the adhesive layer at 0.15 mm. As required, curing of the specimens was carried out in a heating chamber for 1 h at 60 °C. AV138/HV998 (Araldites® AV138/HV998, Huntsman Advanced Materials, The Woodlands, Texas, USA) was chosen as

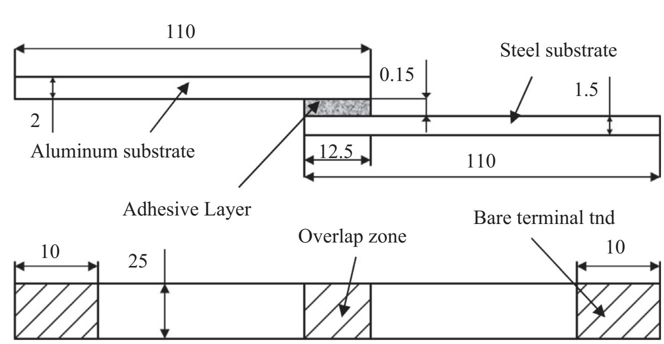

Fig. 1. Geometry of the single lap joint specimen (dimension unit in mm).