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Stress-function variational method for interfacial stress analysis of adhesively bonded joints

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ABSTRACT

High interfacial stresses at the free edges of adherends are responsible for the debonding failure of adhesively bonded joints (ABJs). In this paper, a general stress-function variational method is formulated to determinate the interfacial shear and normal (peeling) stresses in ABJs in high accuracy. By extending authors' prior work in stress analysis of bonded joints (Wu and Jenson, 2011), all the planar stress components in the adherends and adhesive layer of an ABJ are expressed in terms of four unknown interfacial stress functions, which are introduced at the upper and lower surfaces of the adhesive layer. A set of governing ordinary differential equations (ODEs) of the four interfacial stress functions is obtained via minimizing the complimentary strain energy of the ABJ, which is further solved by using eigenfunctions. The obtained semi-analytic stress field can satisfy all the traction boundary conditions (BCs) of the ABJ, especially the stress continuity across the bonding lines and the shear-free condition at the ends of adherends and adhesive layer. As an example, the stress field in an adhesively single-sided strap joint is determined by the present method, whose numerical accuracy and reliability are validated by finite element method (FEM) and compared to existing models in the literature. Parameter studies are performed to examine the dependencies of the interfacial stresses of the exemplified ABJ upon the geometries, moduli and temperature change of the adherends and adhesive layer, respectively. The present method is applicable for scaling analysis of joint strength, optimal design of ABJs, etc.

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1. Introduction

The history of joining technology is as old as our human being itself beginning with building hunting and cultivating tools through binding sharp stones to wood sticks, while use of advanced adhesive bonding techniques in manufacturing modern aircraft structures started only around 30–40 years ago (Davis and Bond, 1999; Higgins, 2000; Park et al., 2010). To date, adhesively bonded metallic joints have been structured in commercial aircrafts with the advent of Airbus A300 (Racker, 2004). Joining technology has also been extended for use in broader primary structures in aerospace, ground vehicles, and other mechanical systems and civil infrastructures. Fig. 1 illustrates several typical adhesively bonded joints (ABJs). By comparison with traditional mechanically fastened bolted, riveted and welded joints, ABJs bear several advantages such as simplified structural design and fabrication, reduced joining space and joint weight, enhanced fatigue tolerance and structural durability, suppression of noises and material wear, and so on (Tomblin and Davies, 2004).

In addition, joining technology also plays a crucial role in microelectronics packaging since 1970s, where thermomechanical stresses have been the leading factor dominating the structural failure and function degradation and have become one of technical concerns (Chen and Nelson, 1979; Suhir, 1989; Eischen et al., 1990; Ru, 2002; Suo, 2003). Accurate prediction of the interfacial thermomechanical stresses in bonded thermostats (chips) is fundamental to understanding the failure mechanism and damage evolution in microelectronic devices subjected to combined mechanical, thermal and electrical loads (Suo, 2003). More recently, flexible electronics based on smart deposition of stiffer silicon micro units onto compliant polymeric substrates become more and more popular, which demands new understanding of their mechanical durability that highly depends on the interfacial stresses near the free edges of the stiff silicon islands (Lu et al., 2007; Kim and Rogers, 2008; Suo, 2012; Sun, 2013). Rapidly expanding utilization of adhesive joining technology in broad engineering sectors also presents new technological challenges to designers, structural analysts and materials scientists such as wise selection of adhesives, accurate strength and durability analysis under various loading and environmental conditions, reliable characterization of structural failure mechanisms, and so on. Among these, accurate stress analysis and rational identification of the failure mechanism and relevant criteria are considered to be crucial.

Substantial progress has been made in theoretical prediction of interfacial stresses in ABJs subjected to either mechanical or

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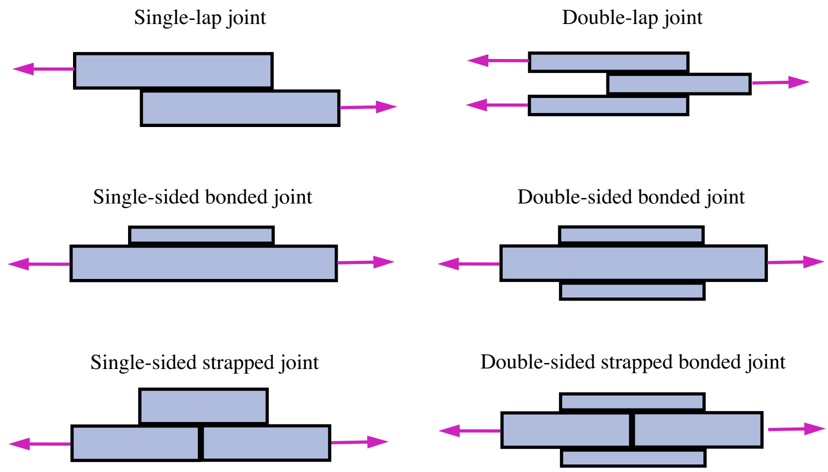

Fig. 1. Typical adhesively bonded joints.

thermomechanical loads since the pioneering works by Volkersen (1938) and Goland and Reissner (1944) within the framework of linear elasticity. Yet, limitations still exist in these pioneering joint models and many follow-ups that were mainly induced by their oversimplified assumptions. For instance, the peak shear stresses predicted by Volkersen's and Goland and Reissner's models appear at the adherend ends, which obviously violates the shear-free condition at the free-ends; stress variation across the adhesive layer is assumed very small and ignored, which cannot be held near the adherend ends as to be discussed in this study, etc. In order to enhance the accuracy of stress analysis of ABJs, quite a few modern joint models have been proposed in the last three decades. To mention a few, Delale et al. (1981) formulated an ABJ model, in which the adherends were treated as flexural *Euler–Bernoulli* beams and the deformation of the adhesive layer was ignored due to the small layer thickness. This model was generalized by the authors for stress analysis of all kinds of ABJs. Yet, the shear stress predicted by this model does not satisfy the shear-free condition at the adherend ends; the predicted interfacial stresses are overshot in a large region close to the adherend ends by comparison with those predicted by refined finite element analysis (FEA). Chen and Cheng (1983) further formulated an ABJ model where the stress field in the adherends was expressed in terms of two unknown normal stresses according to two-dimensional (2D) elasticity. These two unknown stress functions were determined by solving a set of two coupled 2nd order ordinary differential equations (ODEs) that were derived by evoking the theorem of minimum complementary strain energy of the joint. Though the stress variation across the adhesive layer was ignored, the stress field gained by this model can satisfy all the traction boundary conditions (BCs). Besides, this model predicted the reasonable location of the peak interfacial shear stress, which was located at a distance of $\sim$20% the adherend thickness from the adherend ends as validated quantitatively by FEA (Mortensen and Thomsen, 2002; Lee and Kim, 2005; Diaz et al., 2009). Furthermore, Tsai et al. (2004) furthered the classic studies by Volkersen (1938) and Goland and Reissner (1944) to adopt a linearly varying shear deformation across the adhesive layer, which can recover the classic Volkersen's and Goland and Reissner's models at the limiting cases. Lee and Kim (2005) considered the adhesively bonded single/double lap joints with the adhesive layers modeled as distributed linearly elastic springs. In addition, there are also a few layerwise models developed recently for stress analysis of ABJs. Hadj-Ahmed et al. (2001) formulated a layerwise model called M4-4N (multi-particle model of multi-layered material with five kinetic fields per layer for an N-layer laminate) for stress analysis of ABJs. In this model, the multi-layers of an ABJ were modeled as a stack of Reissner plates coupled through the interlaminar normal and shear stresses, and the governing equations were obtained via minimization of the strain energy of the ABJ. Diaz et al. (2009) also proposed an improved layerwise ABJ model, in which the ABJ was modeled as a stack of Reissner–Mindlin plates. A set of eight governing ODEs was obtained via evoking the constitutive laws and solved to satisfy the traction BCs. This ABJ model can be well validated by FEM for free-edge interfacial stress prediction. Moreover, Yousefsani and Tahani (2013a,b) recently provided another version of the layerwise ABJ models. In their models, the displacements of artificially divided sub-layers of an ABJ were treated as field variables, and a set of governing ODEs was obtained by evoking the theorem of the minimum potential energy of the joint. For accurate interfacial stress prediction, 18 artificial sub-layers were used in their numerical examples. More detailed survey of the historical developments and comparative studies of several important analytical models for the stress analysis of ABJs and composite joints can be found in the recent review articles by da Silva et al. (2009a,b). Some more recent works include the displacement method (Zhao et al., 2011) for stress analysis of ABJs and stress function method (Kumar and Scanlan, 2013) for stress analysis of adhesively bonded tubular joints with graded interface stiffness, etc. Yet, compared to the perfect theoretical formulation of cracking in layered elastic materials (Suo and Hutchinson, 1990; Hutchinson and Suo, 1992; Yu and Hutchinson, 2001, 2003; Wu and Dzenis, 2002; Wu et al., 2002, 2003), further theoretical refinements are still needed for accurate and efficient stress analysis of ABJs.

Without a doubt, the adhesive layers play a crucial role in all the theoretical modeling of ABJs in the literature, which function to link the adherends of mismatching displacements and physically dominate the structural durability and failure process of ABJs. Yet, mismatch of the material properties between the adherends and adhesive layers has not been rigorously treated or has been oversimplified in most existing models of ABJs though some thermosetting adhesive systems may carry the mechanical properties close to some special adherends made of plastics. In fact, the generalized Hooke's law of the adhesive layers, the shear-free condition at adherend ends, and the stress continuity across the bonding lines of ABJs are normally not satisfied in most literature models of ABJs due to various technical compromises and oversimplifications in modeling. Besides, quite a few misunderstandings still exist in some of the literature models that were mainly induced by oversimplified model assumptions. For instance, some researchers incorrectly claimed that the maximum interfacial shear and normal stresses predicted by their theoretical models

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