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On thermomechanical stress analysis of adhesively bonded composite joints in presence of an interfacial void

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ABSTRACT

This paper deals with analytical thermomechanical stress analysis of adhesively bonded composite joints in presence of a structural imperfection in the form of an interfacial void within the adhesive layer based on the full layerwise theory (FLWT). The joints are subjected to mechanical tension, uniform temperature change, or steady-state heat conduction. The proposed adhesive joint is divided into three distinct regions along its length and a large number of mathematical plies through its thickness. Three sets of fully coupled governing equilibrium equations are derived employing the principle of minimum total potential energy. The three-dimensional nonlinear interlaminar stress distributions along the bond-line in the interior region and near the edges are obtained. The results, showing fast convergence speed and quite agreement with the finite element method, reveal that the presence of such defect within the adhesive layer can increase the stress concentrations resulting in premature failure and debonding.

1. Introduction

Mechanical joining processes like riveting and bolting, although, are commonly used to tie single composite parts together, they increase the stress concentration around the intermediate component(s) causing local weakness, and impose significant added mass to the structure. From the cost and safety points of view, it is vital, indeed, to decrease both the stress concentration and mass as much as possible. In composite structures, one of the most common joining processes is adhesive bonding sometimes reinforced by some other mechanical joining methods. The loads transferred in adhesive bonding are well distributed on large interfaces decreasing high intensive stress concentrations. Furthermore, there is no considerable added mass, and the bonding strength is also high enough. However, different types of defects formed at the preparation steps, during or, after construction of adhesively bonded composite joints can extremely affect their functionality and even fail the joint. Unclearness of interfacial surfaces, chemical incompatibility of substrates and adhesive, high temperature and moisture, etc. are some of these defects.

Local lack of adhesive, in form of void, is a common physical defect decreasing the joint strength, lifetime, and reliability due to local increase of stress concentrations. Consequently, in an adhesively bonded composite joint exposed to a structural defect such as a void within the bonding region, the intensive violations of peel and shear stress components around the discontinuity in response to external loadings must be accurately determined.

Although, there is a wide spectrum of studies that have provided destructive and nondestructive experimental investigations on predicting the mechanical responses of joints like natural frequencies, vibration modes, fatigue and fracture loads, failure modes, and substrates deformations, there is no an available empirical approach to find the interlaminar stresses interior the bonding region. Therefore, introduction of well accepted, powerful methods to predict the interfacial stress field is irrefutable.

There are many works that have focused on this challenging problem, and presented some approaches to determine the distribution of interfacial stress components and estimate the joint strength. First attempts in this issue was a simple model presented by Volkersen [1] that considered only the shear stress in the adhesive layer and neglected the normal component of the interlaminar stress. This peel stress plays a significant role in the process that may cause bonding rupture and joint failure. Several modifications then were applied to this model considering the peel stress, large deformations of substrates, adhesive plasticity, etc., for different joint configurations by Goland and Reissner [2], Hart-Smith [3],

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and Bigwood and Crocombe [4]. Tsai et al. [5] improved the Volkeresen and Goland–Reissner models considering the linearly varying shear stress through the thickness of substrates and studied the effects of shear deformations on the shear stress distribution in the adhesive layer.

Although these simple models could not predict the complicated stress field particularly near the ends of bonding line as accurate as enough, they provided a concrete base for more recent studies. Apalak and Engin [6] provided a two-dimensional nonlinear-FEM based elastic–plastic analysis for single-lap joints subjected to bending moment, and showed that debonding starts from the endpoints of bonding region due to considerable stress and strain concentrations, and then extends along the mid-surface of the adhesive layer. Osnes and Andersen [7] investigated the effects of geometrical nonlinearity on the ultimate strength of composite single-lap joints using the FEM. They also compared their outcomes with the results of linear model and showed a significant discrepancy between them for a wide spectrum of endpoint deformations.

Based on the application of energy method and using the Timoshenko's beam theory, Selahi et al. [8] presented an analytical method considering the adhesive thickness effects to determine the peel and shear stress distributions within the bonding region adhesively bonded joints. They concluded that the bond-line endpoints experience great increase in peel and shear stress components, and that the shear stress variations through the adhesive thickness can be considerably significant. Using the finite element method and considering the geometrical nonlinearity, Magalhães et al. [9] demonstrated that there is considerable variations of peel and shear stress components through the thickness of adhesive in a linear elastic composite single-lap joint near the ends of the joint.

Rao et al. [10] demonstrated through a finite element analysis based on three-dimensional elasticity theory that the study of the mechanical response of composite laminated joints needs a three-dimensional stress analysis approach, and two-dimensional approaches may result in inaccurate outcomes. Moreover, Diaz Diaz et al. [11] demonstrated that it is an unrealistic assumption to suppose the interfacial stress distributions in relatively thick bonded joints to be constant through the thickness. Similar conclusions were drawn within recent analytical investigations on the stress analysis of thick adhesively bonded composite single- and double-lap joints undergoing mechanical loadings reported by Yousefsani and Tahani [12–14]. They presented an analytical approach based on the FLWT in order to accurately predict the three-dimensional nonlinear interlaminar stress distributions along the length and through the thickness of the adhesive layer and particularly near the bonding endpoint where the edge effects cause the three-dimensional stress state. Using the same approach, they also showed in other studies [15–17] that the thermal loadings such as uniform temperature changes as well as steady-state one-dimensional heat conduction can cause complex stress variations near the edges, through the joint and adhesive thicknesses, and near the interfaces of dissimilar materials (and even near common faces of laminas with different stacking sequences) in adhesively bonded joints.

Intensive increase in the stress values near the endpoints of bonding lines may be responsible to bonding separation. In this field, Panigrahi and Pradhan [18] studied the adhesive failure as well as delamination damage in adhesively bonded composite joints based on a three-dimensional nonlinear finite element analysis. They showed that the out-of-plane stress components are greatest on the interfaces of the adherend and adhesive layer. In addition, the adhesion failure starts at the edges of the bonding region, where the stress singularities cause significant increase in the values of interlaminar stresses.

Several works also have performed to study the influences of discontinuities such as voids and cracks on the stress distributions in bonding region as well as effects of their initiation/growth on the joint global failure. Edde and Verreman [19] presented a stress analysis approach based on the beam theory for clamped lap shear joints in presence of crack. To study how the cracks affect the stress distribution in the adhesive layer of a lap shear joint, Cheuk and Tong [20] provided a nonlinear finite element analysis. They also presented an analytical solution for cracked joint and estimated the failure loads based on the maximum stress criteria. In another study, Cheuk et al. [21] introduced an analytical method to find out how crack propagation can occur within the adhesively bonded double-lap joints subjected to fatigue loading.

Gonzalez Murillo et al. [22] studied the correlation between the geometry and strength of adhesively bonded composite lap joints using empirical investigations and finite element analysis. They reported that fracture occurs due to crack propagation at free endpoints of the bonding region.

Choupani [23] studied the stress fields and stress intensity factor for cracks embedded in adhesively bonded double-lap joints based on the finite element method. He carried out this research for several types of adhesives and joint configurations as well as different crack length, and found that adhesives with less modulus, substrates with less stiffness, and lower tapering angles result in stronger double-lap joints. Using the concept of vectorial J-integral in fracture analysis of cracked adhesively bonded joints, Chen et al. [24] presented a failure criterion to study the crack initiation and propagation. On the analysis of mechanical behavior of adhesively bonded joints in presence of an interfacial crack and void, Chadegani and Batra [25] presented an analytical approach based on the first-order shear deformation plate theory. They reported that presence of a void of a plausible length does not considerably aggravate the joint capacity for load bearing.

In present research, thermomechanical stress analysis of adhesively bonded composite joints in the presence of an interfacial void within the adhesive layer is studied based on the FLWT. The joints undergo mechanical tension, uniform temperature change, or steady-state one-dimensional heat conduction. The joint configuration is partitioned into three distinct regions along its length and a large number of mathematical plies through its thickness. Three sets of fully coupled three-dimensional governing equilibrium equations are derived based on the principle of minimum total potential energy, and then analytically solved introducing the state space variables. The three-dimensional nonlinear interlaminar peel and shear stress distributions within the bonding region and near the edges of the void are investigated.

2. Mathematical representation and formulations

Due to simplifications made in assumption of the displacement field as continuous functions of the thickness, the equivalent single-layer (ESL) theories give the interlaminar stress components discontinuous at the interfaces of dissimilar thin layers. This is while, according to the static equilibrium, these stresses continuously vary through the thickness of laminated structures. Moreover, for the analysis of thick laminated structures, it is needed to apply a powerful method that takes the thickness effects into account and gives the three-dimensional stress field and predicts the intensively high peel and shear stress components existing around the edges.

The interfacial stress components are varying rigorously near the endpoints of the bonding lines due to a phenomenon known as the edge effect. As well as the endpoints, the common interfaces of dissimilar materials in multi-layered structures are potential regions for intensive increase in the amount of interfacial stress values. Different thermomechanical properties of dissimilar