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Theoretical model of adhesively bonded single lap joints with functionally graded adherends

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ABSTRACT

Adhesively bonded joints with functionally graded (FG) adherends are of practical significance since tailoring material composition through the adherend thickness can lead to more uniform shear or peeling stress distributions in the adherends and the adhesive layer near the edges of the joint. Stresses at the free edges of the adhesive layer have been found to be critical to the integrity of the joint. To this end, an analytical model is proposed for an adhesively bonded single lap joint with FG adherends. In this model, the adhesive layer is modeled as a three parameter, elastic foundation, allowing for different peel stress values at the two adherend-adhesive interfaces. Closed-form expressions for interface stresses and internal forces in the adherends are obtained. The model is validated by its agreement with finite element analysis simulations. This model shows that the peel stresses are critical at the left edge of the upper adherend-adhesive interface and at the right edge of the lower adherend–adhesive interface, suggesting that the joint is vulnerable to delaminations along the upper adherend-adhesive interface at the left edge and along the lower adherend-adhesive interface at the right edge. Parametric studies reveal the effects of adhesive thickness, adhesive stiffness, and FGM configuration on the stresses within the single lap joint. Results show that stress concentrations can be reduced near the edges of the joint by increasing the thickness of the adhesive layer, reducing the Young's modulus of the adhesive layer, and/or configuring the FG adherends so that the stiffer material is nearest the adhesive layer.

1. Introduction

Adhesively bonded joints are commonly used structural connections due to their effectiveness and ease-of-use with a variety of materials. Single and double lap joints have been successfully used with metal and non-metal materials, including traditional composite materials. Adhesively bonded joints have also found their use in the experimental determination of the mechanical properties of adhesive materials. However, these joints, when loaded in tension, are subject to significant stress concentrations near the edges of the bonded region. This can lead to premature failure of the joint due to debonding along the adhesive-adherend interfaces. The analysis of adhesively bonded joints has been completed by a number of researchers both recently and historically. Many of these studies have centered on analytical models that mathematically treat the adhesively layer as an elastic foundation. For example, Goland and Reissner [1] modeled the adhesive layer in a single lap joint as continuously distributed shear and vertical springs, where no interaction is assumed between the two. In this way, the expression of the stress-deformation relationship in the adhesive layer is identical to a Winkler type of foundation with two stiffness parameters [9,10]. More sophisticated elastic foundation models have also been proposed, including the Filonenko-Borodich approach [11] (which accounts for some degree of interaction between the individual spring elements), the Hetényi approach [12,13] (which also accounts for interaction between the individual spring elements), the Pasternak approach [14] (which assumes that there are shear interactions between the individual spring elements), and the "generalized" approach [15] (which assumes that the moment response is proportional to the angle of rotation of the foundation surface).

Goland and Reissner's model and many of its descendents [2–8] are therefore referred to as two-parameter, elastic foundation (2-PEF) models in this study. All of these models suffer from the same mathematical flaw: they only satisfy six boundary conditions while there are eight boundary conditions available. One notable issue that results from this flaw is that the zero shear stress conditions at the free edges of the adhesive layer are not satisfied in these 2-PEF models.

Many of the existing adhesive joint analyses have focused on joints with isotropic or traditional composite adherends. Single lap joints with functionally graded (FG) adherends, however, have

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not been as widely considered. Like traditional laminate composites, functionally graded materials (FGM) seek to combine the advantageous properties of multiple constituent materials to form an enhanced final product with tailorable properties. The concept of structural gradients across engineering materials was first introduced for composite materials [16] and polymeric materials [17] in 1972, while interest in the design, fabrication, and analysis of FGM developed in earnest in the 1980s [18]. FGM can be comprised of constituent materials having different mechanical properties, sizes, and/or shapes, which can be either uniformly or non-uniformly distributed throughout the material. Interestingly, a number of natural (biological) materials have graded structures, including bones, teeth, bamboo, and shells [18]. In part, these structures arise in nature in order to reduce stress concentrations and provide for uniform distributions of stress [18–20]. In this same way, engineered FGM offer a distinct advantage over traditional composites in that their mechanical properties vary continuously across one or more dimensions of the material, thereby avoiding the stress concentrations seen at the lamina interfaces in traditional composites [21–23] – which is desirable with respect to both mechanical and thermal loading [24–27]. Furthermore, adhesively bonded joints with functionally graded (FG) adherends are of practical significance [27,28] since tailoring or grading material composition through the adherend thickness can lead to more uniform shear and peeling stress distributions in the adhesive layer and along the adherend-adhesive interfaces.

Although the 2-PEF model provides acceptable results for adhesively bonded joints with isotropic or traditional composite material adherends, it is not ideal for joints with FG adherends. This is because of the unique features of the stress distributions within the adhesive layer in joints with FG adherends. According to numerical analysis based on finite element analysis (FEA) [27,28], the peel stress peaks at the left free edge of the upper adherend–adhesive interface and at the right free edge of the lower adherend–adhesive interface in an adhesively bonded joint with FG adherends. This suggests that peel stresses along these two interfaces are significantly different. The existing 2-PEF model assumes that this peel stress is a constant through the whole thickness and therefore cannot capture this feature. For this reason, most existing studies on adhesively bonded joints with FG adherends are based on numerical simulation using FEA [27,28]. The only relevant analytical solution available in the literature [29] is based on Goland and Reissner's 2-PEF model.

To address this gap, this study aims to develop an analytical solution for adhesively bonded single lap joints with FG adherends which can capture the difference of the peel stresses along two adherend/adhesive interfaces. To this end, a three-parameter, elastic foundation (3-PEF) model [30] is adopted to simulate the behavior of the adhesive, which allows two different peel stresses along the two interfaces. In addition, this new model can satisfy all boundary conditions, and therefore, eliminate the fundamental flaw in existing 2-PEF models. The adhesive joint considered herein is symmetric and is comprised of two FG adherends. FEA is used to verify the analytical model, and parametric studies are carried out to analyze the effects of various parameters on the stresses within the adhesive joint.

2. Theory

2.1. Adhesive joint with FG adherends

Consider a typical adhesively bonded single lap joint in which the two FG adherends are attached by a thin layer of adhesive in the overlap region, as shown in Fig. 1. The coordinate system is chosen such that the positive *x*-direction corresponds to the axial

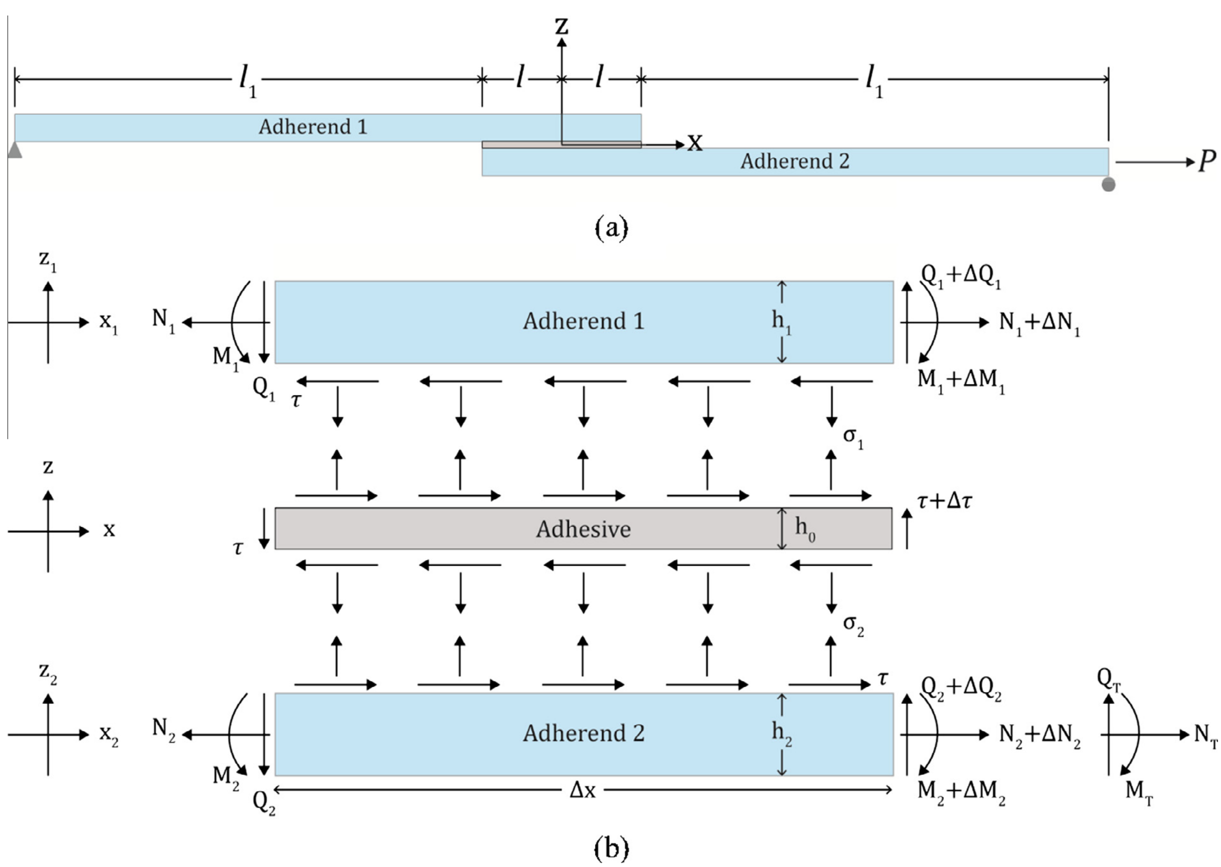

Fig. 1. (a) Overall schematic of the adhesively bonded single lap joint considered in this study, and (b) Free body diagram of the overlap region in the joint.