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Functionally graded adhesives for composite joints

Scott E. Stapleton [a], Anthony M. Waas [a,*], Steven M. Arnold [b]

[a] Department of Aerospace Engineering, University of Michigan, Ann Arbor, MI 48105, USA
[b] Life Prediction Branch, NASA Glenn Research Center, Cleveland, OH 44135, USA

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ABSTRACT

Adhesives with functionally graded material properties are being considered for use in adhesively bonded joints to reduce the peel stress concentrations located near adherend discontinuities. Several practical concerns impede the actual use of such adhesives. These include increased manufacturing complications, alterations to the grading due to adhesive flow during manufacturing, and whether changing the loading conditions significantly impact the effectiveness of the grading. An analytical study is conducted to address these three concerns. An enhanced joint finite element, which uses an analytical formulation to obtain exact shape functions, is used to model the joint. Furthermore, proof-of-concept testing is conducted to show the potential advantages of functionally graded adhesives. In this study, grading is achieved by strategically placing glass beads within the adhesive layer at different densities along the joint.

1. Introduction

With the increasing demand for composites in lightweight aerospace structures, adhesively bonded joints are becoming increasingly attractive. Bolts and rivets cause stress concentrations and premature failure in composite materials, while adhesive bonds spread the load more evenly over the composite, facilitating a lighter overall structure.

One major drawback of adhesively bonded joints is that the load path eccentricity causes the appearance of peel stress concentrations at the end of the adhesive layer. There has been a vast amount of research conducted in an attempt to reduce these stress concentrations, such as tapering the end of the adherend [1], increasing thickness of the adhesive at the end [2], fillets [3], novel joint geometries [4], and joint insertions [5], to name a few. All of these methods involve local details of adherend geometry (except the adhesive fillets), which typically increases part complexity.

Material grading occurs in nature at material interfaces to reduce stress concentrations [6]. Biological interfaces such as tendon to bone joints have been found to have graded material properties to distribute stress more evenly across the joint [7,8]. In this same spirit, material grading has been applied to adhesively bonded joints. Although grading the adherends has shown promise [9], many more researchers have investigated grading the adhesive properties. Some of the earliest grading of the adhesive was reported by Patrick [10] and Raphael [11], where grading was discretely achieved using two adhesive materials (i.e., bi-adhesive). Recently many other researchers have investigated bi-adhesive joints with mixed results. Sancaktar and Kumar [12] graded the adhesive by making rubber toughened regions, and found that the selectively toughened joints had the same strength as the fully toughened joints. Piresa et al. [13] used two adhesives to bond aluminum, and found up to a 22% increase in joint strength. Fitton and Broughton [14] bonded CFRP to steel, and found that it was crucial to optimize the amount of each adhesive and that some configurations did not benefit from grading. Da Silva and Lopes [15] looked at the influence of the ductility of adhesives on bi-adhesive joint strength experimentally and theoretically. It was found that the bi-adhesive joints out-performed joints with the more brittle adhesive alone, but did not always improve on the more compliant single adhesive joints. More recently, Kumar and Pandey [16] modeled bi-adhesive joints using nonlinear 3D finite elements compared with a 2D finite element model, and found that the 2-D model could not fully capture the complex multi-axial stress state. Valleé et al. [17] investigated bi-adhesive joints, among other stress reduction methods, and found that the adhesive stress was not linked to the joint strength of the configurations tested (which displayed adherend failure).

It appears that the first instance of grading the adhesive with a non-stepwise function was Kumar [18]. This purely theoretical investigation first compared a continuous (non step-wise) functionally graded adhesive (FGA), where the modulus was graded using a quadratic function, with a step-wise graded equivalent for different overlap lengths and adhesive thicknesses in a tubular

* Corresponding Author. Tel.: +1 734 764 8227; fax: +1 734 763 0578.
E-mail address: dcw@umich.edu (A.M. Waas).

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joint. It was found that the continuous FGA reduced the shear and peel stresses in all cases. Second, four "arbitrarily chosen" functions were compared to show that the grading function can be manipulated to optimize joint performance. The current study aims to increase the understanding of both bi-adhesive and non-stepwise FGAs to make them a more viable, realistic, and advantageous choice for actual application in composite structures.

Some potential drawbacks to FGAs have also been discussed in the literature. The first two were identified by Hart-Smith [2], where he pointed out that: (1) small gains over just using the ductile adhesive alone may be inadequate when considering the production difficulties and (2) during manufacturing, there is the "inevitable tendency for the stiff adhesive to squeeze out and displace the ductile adhesive," making it probable that the resulting joint will be worse-off than using the ductile adhesive alone. A third concern was raised by Aboudi et al. [19] while investigating the response of metal matrix composites with tailored microstructures. They found that functionally grading the properties of a material may be detrimental when the loading is changed, such that the stress gradient in the material is reversed; this is a valid concern for practical situations where all loading cases cannot necessarily be predicted.

The current study aims to address these practical concerns to show that FGAs are a viable means of decreasing the peel stress in an adhesively bonded joint. An analytical model is constructed and used to compare the stresses in a butt-end joint configuration with four different functions of modulus graded adhesive: constant (single adhesive), discrete (bi-adhesive), linear, and exponential. First, the potential gains in stress reduction for FGA joints over joints with a single adhesive are shown. Along these lines, it is shown that additional stress reductions can be achieved by lowering the modulus of the more compliant adhesive. Since it is likely that step-wise grading will appeal from a manufacturing perspective, stress reduction of a step-wise graded adhesive with many steps is investigated (with single or bi-adhesive being a special case). Second, the study addresses the issue of adhesive flow during bonding by showing how sensitive the optimum for the three FGAs is to perturbation of the grading. Third, multiple load scenarios are examined to address the concern of changing loading conditions. Results indicate that the stress magnitude gradient in the adhesive remains unchanged under different loading conditions, making joints a perfect application for material grading. Additionally, it is shown that the grading can still be optimal under different loading cases. Addressing these three concerns provides significant impetus for the use of FGAs in industrial applications.

The model used to obtain the adhesive stress for different FGAs is a structural finite element made specifically for adhesively bonded joints. Motivated by the desire to create a computationally efficient tool for designing joints within a coarse, vehicle scale finite element model [20], we combined an analytical formulation with a finite element in the joint element. This concept has been often referred to as the exact stiffness matrix method, and has been previously applied to the beam on an elastic foundation problem [21,22]. The joint element is capable of capturing the stresses in a mesh-independent, efficient manner. Such an efficient method is pivotal to the current study, allowing the analysis of over 20,000 different joints for optimization and parametric studies on a desktop computer in a fraction of a second per joint. The formulation adopted here is altered from past formulations [23,24] to account for a graded adhesive modulus and is presented below. A linear elastic material model is used for several reasons, simplicity being the most prominent. Also, since a controlled method and material system for manufacturing FGAs has not yet been identified, failure of the joint and post-failure response is not addressed. Finally, it should be noted that after initial departure from material linearity (due to damage or plasticity) and before crack formation, the adhesive modulus is effectively a continuous function across the joint, which causes more load to be transferred to the inner regions of the joint. However, the main idea of a FGA is that this effect can be achieved without taking on irrecoverable damage. Since the benefit of FGAs can be realized without material damage, this study will be limited to the linearly elastic regime of the adhesive. Geometric nonlinearity is also ignored for simplicity and because it is not expected to have a large effect on a stress comparison study between adhesive systems.

The analytical findings are complemented with an experimental "proof-of-concept" testing to illustrate the benefits of FGAs. The adhesive was graded by adding different volume percentages of glass beads, although no precise method was used to control the grading except the eye and hand of the person preparing the specimens. By showing that a joint can benefit from grading in such a rudimentary manner, the potential for more drastic gains through controlled and precise grading can be argued for.

2. Method

2.1. Formulation

An adhesively bonded joint finite element was used to assess the performance of FGA joints. This joint finite element uses an analytical formulation to get the exact stiffness matrix for N number of adherends held together by $N-1$ adhesive layers. The adhesives and adherends were assumed to be linearly elastic, but not necessarily isotropic. The adherends were modeled as wide plates under cylindrical bending, using Euler–Bernoulli beam theory and Classical Lamination Theory (CLT). The adhesive response is captured through a continuous bed of shear and normal springs. This assumption ignores the traction-free boundary condition which is present for an adhesive modeled as a continuum. However, most joints in application have some sort of adhesive spew coming out of the joint, which makes the imposition of a traction-free boundary condition unrealistic. The material and geometric parameters are shown in Fig. 1. The subscript i refers to adherend i, and a_i refers to adhesive layer i. The width of the joint in the y-direction is b.

2.1.1. Governing equations

The strain energy of the joint, U_{joint}, is written as:

$$U_{\text{joint}} = \sum_{i=1}^{N} \sum_{j=1}^{M_i} \frac{1}{2} \int_{V_i^j} \sigma_i^j \varepsilon_i \mathrm{d}V + \sum_{i=1}^{N-1} \frac{1}{2} \int_{V_{a_i}} (\sigma_{a_i} \varepsilon_{a_i} + \tau_{a_i} \gamma_{a_i}) \mathrm{d}V \tag{1}$$

where σ_i^j is the axial stress in the jth layer of the ith adherend, and ε_i represents the axial strain in adherend i in the x-direction. σ_{a_i} and ε_{a_i} are the normal stress/strain in the ith adhesive in the z-direction, τ_{a_i} and γ_{a_i} represent the shear stress/strain in the ith adhesive on the xz-plane, and all integrals are taken over the volume, V_i^j or V_{a_i} of adherend i, layer j or adhesive i, respectively. Using CLT, the stress can be written in terms of the strain and the

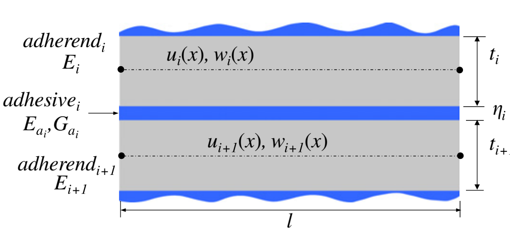

Fig. 1. Geometric and material parameters for overlap region of an adhesively bonded joint.