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Finite element predictions of composite-to-metal bonded joints with ductile adhesive materials

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ABSTRACT

This work provides finite element predictions of adhesive joints that involve dissimilar materials and a ductile adhesive layer. A recently developed mixed-mode law is utilized for the description of the elastoplastic loading and fracture response of the adhesive layer under Mode I and Mode II conditions. This model is implemented in interface elements that are used to replace conventional continuum elements for modeling the adhesive area. The potential of the proposed model for analysis and design purposes is shown through simulations of experimentally tested CFRP-to-steel adhesive joints taken from the literature. Additionally, a numerical parametric study is conducted on an effort to investigate the effect of the overlap length and the thickness of the adherents to the strength of the joints.

1. Introduction

There are several techniques available for the repair of defected materials where some type of discontinuity is present or their stiffness or strength have been partially lost. A typical repairing practice involves the utilization of supplemental structural materials on and in the vicinity of the defect. The corresponding structural design aims at compensating the loss of strength or stiffness owed to the corresponding defect. A problem under examination is the reliable cooperation of the materials involved, i.e. the repairing and the parent structural elements.

Among the methods that are widely used for bringing together two similar or dissimilar structural materials, adhesive bonding has attracted the interest of many researchers and design engineers because of the distinct properties it offers. One of the major reasons or needs for the development of the adhesive bonding technology is that joining of dissimilar materials is permitted and thus these can be used in a complex structure or assembly, creating so-called "hybrid structures" (i.e., structures that, as a result of being composed of more than one material, offer properties, performance, or other attributes not attainable in any individual material). Dissimilar materials often enable the attainment of high structural efficiency in several ways. They do this by minimizing weight by using the lowest density material with the appropriate strength (i.e., highest specific strength) for strength critical designs, or modulus or stiffness (i.e., highest specific modulus or stiffness) for stiffness-critical designs, or other properties critical to a design, in each area of the assembly or structure [1]. Common combinations of dissimilar materials in aeronautics, racing automotive/marine engineering, civil engineering and robot structures are composites (CFRP or GFRP) and metals (aluminum or steel).

Adhesively bonded joints of dissimilar materials are frequently expected to sustain static or cyclic loads for considerable periods of time without any adverse effect on the load-bearing capacity of the structure. However, a lack of suitable material models and failure criteria has resulted in a tendency to 'overdesign' adhesive joints. The development of reliable design and predictive methodologies can be expected to result in more efficient use of adhesives [2].

There are two basic mathematical approaches for the analyses of adhesively bonded joints: closed-form solutions (analytical methods) and numerical methods (i.e. finite element analysis). Structural analysis of single and double lap/strap adhesive joints has been well addressed from an analytical point of view by providing to the literature closed-form solutions for the displacement and stress field of both the adherents and the adhesive [3,4]. However, the analysis of adhesive joints with complexities that arise from geometrical configurations and geometric or/and material non-linearities, is based on Finite Element Methods.

As an adhesive joint is loaded, the stresses are being transferred from one substrate to the other through the adhesive layer and via the adhesive/adherent interface. Thus, two types of failures are present within the adhesive layer interphase, i.e. cohesive and adhesive failure. It is significant to incorporate these types of failures into finite element predictions in order to evaluate the behavior and strength of adhesive joints.

Continuum mechanics provide strength predictions based on damage initiation by utilizing damage criteria, e.g. von Mises stress criterion. However, such predictions are crude in the case where

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the utilized adhesive layer consists of ductile adhesive materials. Under the framework of continuum damage mechanics, an alternate criterion can be utilized based on the Damage Zone Theory (DZT). According to the DZT, an adhesive joint is assumed to fail when the damage zone (defined by a stress or strain criterion) reaches a reference value. In fact, the DZT method is an empirical approach, which does not provide predictions regarding the crack path and crack propagation. Thus, the separations cannot be calculated either within the adhesive layer or in the adhesive/adherent interface, since the element nodes are continuously connected in a consistent manner.

Within the framework of Linear Elastic Fracture Mechanics, the Virtual Crack Closure Technique (VCCT) has been adopted by several researchers for modeling adhesive or/and cohesive fracture [5,6]. The great drawback in such simulation techniques is that different models must be solved with different locations of the crack, crack lengths and crack angles. A step forward has been made with the combination of damage and fracture mechanics, which has yield the well-known interface (or cohesive) elements for the simulation of adhesive joints, under the framework of Cohesive Zone Modeling (CZM) techniques [7–12]. In CZM, the element nodes are unconnected and thus are capable to separate from each other by embedding interface elements between the adjacent element faces, where cracking is expected to initiate and propagate. This methodology allows the study of the debonding initiation and propagation process, without considering the presence of initial flaws and leads to the calculation of the load carrying capacity of the considered adhesive joint.

In contrast to DZT and VCCT methods, CZM techniques require the definition of a constitutive relation (traction σ – separation δ response) of the utilized interface elements, that is a cohesive law. Several cohesive laws are available that can be categorized into the following groups, based on their shape: polynomial, piece-wise linear, exponential and rigid-linear [12]. A methodology which relies on intrinsic cohesive laws, under the framework of CZM techniques, for the numerical prediction of the loading and fracture behavior of adhesive joints is based on the Embedded Process Zone (EPZ) approach, introduced by Thouless and his co-workers [13–15]. According to the EPZ, the adhesive layer works as the continuum which provides and transfers tractions between the adherents. From the numerical point of view, the adhesive material is totally represented by interface or cohesive elements that can model the kinematics incorporated in the EPZ. The constitutive relations are given in terms of opening and shear traction–separation laws under pure Mode I [13] and pure Mode II [15] loading and fracture, respectively.

The EPZ approach has been also applied in finite element models to simulate mixed-mode loading and fracture. Campilho and his co-workers [16–19] developed a cohesive mixed-mode damage model to predict the behavior of ductile adhesives with a trapezoidal shape T–S law representing loading and fracture of each fracture mode, within the framework of Elastic Plastic Fracture Mechanics.

Anyfantis and Tsouvalis [10] have recently developed a new EPZ law and mixed-mode model for the prediction of the mixed-mode response of ductile adhesive joints. This model has been validated with metal-to-metal adhesive joints and it has been concluded that it can adequately model the coupling between the behavior of the adhesive/adherent interface and the behavior of the bulk adhesive.

The main scope of this paper is to present the potential of the new model for the structural analysis and design of adhesively bonded joints with dissimilar adherents. For this purpose, this work provides finite element predictions, of experimentally tested CFRP-to-steel adhesive joints from the literature. Initially, the numerical predictions with the EPZ model are compared with the experimental results and with predictions obtained with the DZT. In the following, the developed EPZ tractions are provided as these evolve during the loading of the joints. Additionally, a numerical parametric study is conducted on an effort to investigate the effect of the overlap length and the thickness of the adherents to the strength of the joints.

2. Description of problem

2.1. Geometries

The experimental work of Ban et al. [20] has been adopted for numerical predictions with the proposed EPZ mixed-mode model. The authors have conducted a parametric experimental study of composite-to-steel adhesive joints subjected to uni-axial loading. The six considered cases are based on the Double Lap Joint (DLJ) configuration (see Fig. 1) and the corresponding dimensions of each case are listed in Table 1. According to this table, the six cases differ in the overlap length L, thickness of steel t_s, thickness of composite t_c and the width w, in a combined way. For this purpose, these well defined cases are ideal for validating the proposed model.

The adhesive thickness t_a used in all cases is equal to 0.15 mm. The steel material has elastic properties: E = 200 GPa and ν = 0.3. As for the composite material, 31 CFRP layers were combined in order to achieve the following stacking sequence: [$\pm45_3/90/\pm45_2/0_4/90/\pm45_2/90/\pm45_3$]. The authors provide the on-axis elastic material properties of the CFRP material. In the numerical models, the effective elastic material properties have been considered for reasons of CPU savings. For their calculation the Classical Laminated Theory (CLT) has been utilized. Table 2 lists the elastic material properties

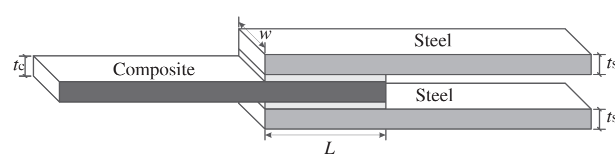

Fig. 1. Schematic representation of the adopted DLJs experiments.

Table 1
Cases and dimensions.

Specimen	w (mm)	L (mm)	t_s (mm)	t_c (mm)
A01	26.8	38	6.05	3.255
A02	38	38	6.05	3.255
A03	19	38	6.05	3.255
A04	26.8	20	1.6	3.255
A05	38	20	1.6	3.255
A06	19	20	1.6	3.255

Table 2
CFRP elastic properties.

	Layer (on-axis)	Effective
E_1 (GPa)	131	90.197
E_2 (GPa)	8.2	60.4
E_3 (GPa)	8.2	8.2
ν_{12}	0.281	0.5723
ν_{13}	0.281	0.281
ν_{23}	0.47	0.47
G_{12} (GPa)	4.5	87.631
G_{13} (GPa)	4.5	4.5
G_{23} (GPa)	3.5	3.5