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Local evaluation of adhesive failure in similar and dissimilar single-lap joints

Florin Adrian Stuparu [a], Dragos Alexandru Apostol [a], Dan Mihai Constantinescu [a,*], Catalin R. Picu [a,b], Marin Sandu [a], Stefan Sorohan [a]

[a] University POLITEHNICA of Bucharest, 060042 Bucharest, Romania
[b] Rensselaer Polytechnic Institute, 12180 Troy, NY, USA

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ABSTRACT

Single-lap joints made of aluminium and carbon fibre adherends are tested to understand better the behaviour of such dissimilar joints. Local deformation fields are monitored by using the digital image correlation method (DIC). Over the overlap length strain gauges are emulated as to measure properly the strains in the adhesive. Peeling and shearing strains are investigated, emphasizing that peeling is important in the region where failure is initiated, towards the extremity of the overlap region. Cohesive Zone Modelling (CZM) available in Abaqus® was used to simulate the behaviour and strength of dissimilar single-lap adhesively bonded joints. A linear elastic FEM was used. A distinct CZM model is used to show the variation of normalized stresses and damage in the process zone of the single-lap joint. Experiments show that the use of dissimilar aluminium-carbon and carbon-carbon adherends is reducing the strength and stiffness of the joints as the delamination and pull-out of the carbon fibres compromises their integrity. Numerical simulations overestimate the experimental strength and stiffness of the joints. FEM model has to be improved as to consider a refined laminate modelling.

1. Introduction

In engineering structural integrity applications the presence of imperfections can reduce significantly the load bearing capacity. Without a better understanding of progressive failure, the fracture criteria and predictive capabilities will be limited. Interface cracking is generally a mixed mode cracking, as both normal and shear stresses develop ahead of the crack tip even when the interface crack is loaded in pure Mode I, [1,2]. Experiments have shown that fracture energy can depend on mode mixity, [3–5]. A comprehensive literature review on the types of tests used for adhesive joints for single and mixed-mode fracture, underlining their advantages and disadvantages, was done by Chavez et al. [6]. They concluded that there is no general agreement about the test suitability for mixed-mode fracture assessment of adhesive joints.

During the crack growth process, two new surfaces are created. Before the physical crack is formed, these two surfaces are held together by traction within a cohesive zone. The traction varies in relation to the relative displacement of the surfaces, and a cohesive law describes the phenomena in the cohesive zone in terms of the traction and the separation of the surfaces to be formed during fracture. A cohesive law is also denoted as a traction-separation law. The concept to describe the

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* Corresponding author at: Department of Strength of Materials, University POLITEHNICA of Bucharest, 060042 Bucharest, Romania.
E-mail address: dan.constantinescu@upb.ro (D.M. Constantinescu).

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Nomenclature

E	Young's modulus [MPa]
F	force [N]
G	shear modulus [MPa]
G_n^c	fracture energy in tension [N/mm]
G_s^c	fracture energy in shear [N/mm]
L	effective overlap length [mm]
x	coordinate measured along the overlap [mm]
x/L	normalized coordinate [–]
γ	shearing angle [°]
φ_xy	shearing strain [°]
ν	Poisson's ratio [–]
σ_n^0	normal traction at initiation [MPa]
σ_s^0	shearing traction at initiation [MPa]
CZM	cohesive zone modelling
DIC	digital image correlation
FEM	finite element method
SDEG	damage parameter [–]
XFEM	extended finite element method

cohesive phenomena before fracture has been established for almost half a century ago. The concept of cohesive zones ([7,8]) has revived interest and the cohesive zone modelling (CZM) approach has emerged as a powerful analytical tool for nonlinear fracture processes. This model considers the relation between the traction and separation that are normal to the fracture surfaces, and the unphysical stress singularity at the crack tip in the traditional linear elastic fracture mechanics is removed. The cohesive models were later extended to the mode II fracture process, in which the tangential traction and separation are considered instead. As Högberg mentions in [9], experimental observations show distinctive characteristics of the micromechanical failure mechanisms in peel and shear fracture, thus the cohesive behaviour is expected to be mode dependent, [10–12].

Cohesive zone models have particularly been used to analyse composite delamination problems. Cohesive strength and fracture energy are believed to have greater importance with respect to the specific shape chosen for the cohesive model. Most damage models, such as the Progressive Damage Model for Composites provided in Abaqus® [13] and typical cohesive elements ([14–16]), represent the evolution of damage with linear softening laws that are described by a maximum traction and a critical energy release rate. As discussed by Dávila et al. [16] the shape of the softening law, e.g., linear or exponential, is largely inconsequential for the prediction of fracture for small-scale bridging conditions, but plays a fundamental role in the prediction of fracture under large-scale bridging conditions, where the process zone length may be large relative to other length scales in the problem.

FEM analyses of single-lap joints were performed in [17] using a CZM approach and allowing the cohesive properties of the interface and plastic deformation of the adherends to be included in the analysis by means of a traction–separation law with a trapezoidal shape. Using cohesive-zone parameters determined for the particular combination of materials, the numerical predictions for different bonded shapes were confirmed by the experimental observations. The numerical models predicted accurately the failure loads, displacements and deformations of the joints. Also, Campilho et al. [18] evaluated the tensile behaviour of adhesively bonded single-strap repairs on laminated composites as a function of the overlap length and the patch thickness. A CZM with a trapezoidal shape in pure modes I and II was used to simulate a thin ductile adhesive layer. An excellent agreement was found between the experiments and the simulations. Cohesive laws are usually associated with cohesive zone modelling in the numerical simulation of the fracture process. Applications to material systems such as adhesively bonded joints, bimaterial interfaces, and the dynamic fracture of homogeneous materials have also been very successful.

The digital image correlation (DIC) method has inspired several researchers for CZM identification in order to analyse the strength of lap-joints. For example, Valoroso and Fedele [19] identified the mode I parameters of a cohesive zone model for the analysis of adhesive joints and Shen and Paulino [20] provided a full-field DIC algorithm to compute the smooth and continuous displacement field, which is then used as input to a finite element model for inverse analysis through an optimization procedure in order to compute the cohesive properties of a ductile adhesive. Richefeu et al. [21] proposed a CZM evaluation based on DIC full-field measurements. They showed that their identification does not assume any particular shape or predefined crack path, but focuses on the experimental validity of the projection of volumic (micro) damage onto a simple surface. However, the study is restricted to metallic materials subjected to uniaxial tension.

Moreira and Nunes [22] investigated the behaviour of a flexible adhesive and the critical shearing deformations which decrease towards the ends of the overlap, suggesting that the peeling strains are responsible for the initiation of the failure.

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