Composites Part B 91 (2016) 414–421

Contents lists available at ScienceDirect

Composites Part B

journal homepage: www.elsevier.com/locate/compositesb

Influence of the cohesive law shape on the composite adhesively-bonded patch repair behaviour

Lorena M. Fernández-Cañadas, Inés Iváñez, Sonia Sanchez-Saez*

Department of Continuum Mechanics and Structural Analysis, University Carlos III of Madrid, Avda. de la Universidad 30, 28911 Leganés, Madrid, Spain

ARTICLE INFO

Article history:
Received 25 September 2015
Received in revised form
21 January 2016
Accepted 27 January 2016
Available online xxx

Keywords:
A. Laminates
B. Adhesion
B. Fracture toughness
C. Finite element analysis (FEA)
Cohesive zone model

ABSTRACT

In this study, the cohesive failure of the adhesive layer of an adhesively-bonded joint under uniaxial tensile loads in static conditions is discussed as an approximation to the behaviour of adhesively-bonded repairs. A three-dimensional finite-element model of a single-lap joint was developed using the commercial code Abaqus. Cohesive Zone Models (CZM) coupled to Finite Element Analysis, were used to study the failure strength of the joint. They allowed the prediction of the initiation of the crack and its growth. CZM are governed by a traction-separation law, which can acquire different shapes. The numerical model, considering a linear cohesive law, was validated with 2D numerical and experimental results available in the literature. The effect of different cohesive law shapes, such as exponential and trapezoidal, on the failure load of the joint was studied. In addition, a cohesive parametric analysis was performed, varying the adhesive toughness and cohesive strength. The most suitable cohesive law was the trapezoidal, since the failure load results were close to the experimental data taken from the literature. The cohesive strength is identified as the most influential parameter on the studied variable.

1. Introduction

Structural components made of composite materials are widely used in several fields, such as the aircraft industry, due to its excellent mechanical and lightness properties, representing a reduction in the weight and, consequently, lower fuel consumption. The high level of integration and large size of these components may make very difficult the replacement of damaged parts during its service life. The repair of the damaged components is an efficient solution that saves economic and temporal costs.

In contrast to mechanical repairs, adhesively-bonded repairs offer certain advantages being the most suitable to thin laminates. In particular, patched repairs are more efficient than scarf repairs, which requires small bevel angles that result in additional damage when considering thin laminates [1]. Most repair techniques involve removing the damaged material, creating a hole, whose presence may modify the state of load on the structure, reducing the bearing capacity and fatigue life due to the appearance of stress concentration in the area near the hole. Thus, adhesively patch repairs are designed to minimise these stress concentrators without adding weight [2–4]. In addition, these repairs present non-uniform shear and peeling stresses distributions inside the adhesive that give stress concentrations in the overlap edges [5], resulting that the adhesive failure is the main damage mechanism in a repaired plate. The overall failure of a repaired plate is sensitive to the adhesive properties and adhesive parameters related. Thus, it is important to perform parametric studies to determine the sensitivity of the repair behaviour to the damage evolution and the adhesive parameters selected [6]. Several authors have studied the behaviour of these repairs [7–10], being fewer who focus their efforts on analysing the influence of different parameters on the failure load [11,12].

Different methods are used to predict the stresses of an adhesive repair: analytical, numerical, and experimental [5,13]. In the last years, the use of progressive damage models, such as the Cohesive Zone Models (CZM) couple to Finite Element Analysis (FEA), was extended in front of Virtual Crack Closure Technique (VCCT) restricted to the Linear Elastic Fracture Mechanics (LEFM) which needs the existence of an initial crack [14–16]. CZM predict the onset of failure and its growth within regions of continuous materials or interfaces between different materials, resulting in more accurate results [5]. The crack growth is controlled by a traction-separation law, being the linear, due to its simplicity, the exponential, and the trapezoidal the most used [17–19].

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* Corresponding author. Tel.: +34 91 624 88 82.
E-mail address: ssanchez@ing.uc3m.es (S. Sanchez-Saez).

http://dx.doi.org/10.1016/j.compositesb.2016.01.056
1359-8368/

Some authors approximate adhesively-bonded repairs to single-lap joints [7,20]. In this context, a detailed analysis of the critical parameters affecting the integrity of adhesive joints (i.e. geometry modifications, overlap length and adhesive properties) is needed. Recent research investigations on single-lap joints formulate predictive equations considering thin laminates bonded to pre-existing members, in order to study the collapse of the adhesive joint and optimal bonding length [21,22]. Many studies dealing with CZM [23] develop two-dimensional finite-element models to simplify the computational cost; however, an exhaustive analysis of the behaviour of a repair requires three-dimensional models in order to obtain accurate results [13,24–27].

In the present work, a 3D numerical model was implemented by using Abaqus finite-element code, which was validated with numerical and experimental results extracted from the literature. The influence of the cohesive law shape (linear, exponential and trapezoidal) and certain adhesive parameters (fracture toughness and cohesive strength) on the adhesively-bonded single-lap joint failure load was analysed, considering the cohesive failure of the adhesive.

2. Problem description

As a first approach to the study of the behaviour of adhesively-bonded patch repairs, a single-lap CFRP joint was analysed. To achieve this purpose, a three-dimensional numerical model of an adhesively-bonded single-lap joint under uniaxial tensile loads in static conditions was developed by using the finite-element code Abaqus/Standard [28], considering non-linear effects.

The geometry considered consists of two laminates of unidirectional carbon-epoxy, $[0]_{16}$ lay-up and a thickness for each lamina of 0.15 mm, bonded with an epoxy adhesive, Araldite 2015 (Fig. 1). The total length between the two end edges is $L_t = 240$ mm, while its depth is $b = 15$ mm. The length of the bonded area L was modified for values from 10 mm to 80 mm. The considered geometry was taken from the literature [29] in order to validate the proposed numerical model.

The main failure mechanism of a repaired structure is the adhesive failure. Therefore, this work is focused on the study of the adhesive behaviour under tensile loads. In particular, the cohesive failure in the adhesive layer was analysed. Thus, the effect of the variation of several cohesive parameters on the maximum load, that causes the joint failure, was studied.

2.1. Numerical model

Each composite adherend was modelled as orthotropic, linear elastic (Table 1). The selected adhesive was modelled by using the mixed-mode CZM formulation with a traction-separation law (Table 2). The adhesive is characterised by a ductile behaviour due to the wide difference between the fracture toughness G_n^C in the normal direction (x-axis) and G_s^C and G_s^C in the shear directions (y-and z-axis, respectively).

Table 1
Elastic orthotropic properties of the adherend in the fibres direction [27].

Elastic modulus [MPa]	Poisson ratio	Shear modulus [MPa]
$E_x = 109 \cdot 10^3$	$\nu_{xy} = 0.342$	$G_{xy} = 4315$
$E_y = 8819$	$\nu_{xz} = 0.342$	$G_{xz} = 4315$
$E_z = 8819$	$\nu_{yz} = 0.380$	$G_{yz} = 3200$

The adhesive stiffness was defined as the ratio of the normal modulus (E) and shear modulus (G) to its thickness (t), Eqs. (1) and (2)

$$K_n = \frac{E}{t} \tag{1}$$

$$K_s = K_t = \frac{G}{t} \tag{2}$$

where K_n, K_s and K_t are the stiffness of the cohesive elements in the normal and shear directions.

To simulate the experimental test conditions, one of the edges was clamped, while the opposite end was pulled in tension by imposing a constant and uniform displacement through this end (Fig. 1). A sensitivity analysis was carried out to ensure that the model was capable of accurately calculating the stresses and associated deformations; as a result, the mesh of the adherends consisted of 75,000 eight-node continuum shell elements with reduced integration (SC8R in Abaqus). For an overlap length of 10 mm, the mesh of adhesive consisted of 3750 eight-node three-dimensional cohesive elements (COH3D8 in Abaqus) compatible with the previous elements used. In addition, a mesh refinement was applied nearby the bonded area, to obtain more accurate results in this zone (Fig. 2). The surface-to-surface contact interaction was used to define the contact between the composite plates and the adhesive.

2.2. Progressive damage analysis

CZM reproduce the adhesive behaviour in terms of cohesive traction-separation response, in which different damage mechanisms occur simultaneously. Each mechanism consists of a damage initiation, which depends on the criterion chosen, a damage evolution that produces a stiffness reduction up to failure due to the progressive adhesive degradation, and the element removal when that failure is attained.

It is assumed that damage occurs in a local zone where the stress grows until a peak value t_n^0 in the normal direction and, t_s^0 and t_t^0 in shear directions, simulating the linear elastic behaviour. This behaviour is defined by a constitutive elastic matrix that relates the nominal stresses to the nominal strains across the interface, and can be written as follows in Eq. (3):

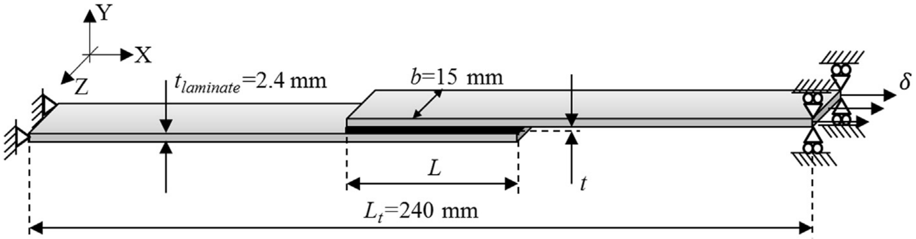

Fig. 1. Single-lap joint configuration: geometry and boundary conditions.