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Strength and damage growth in composite bonded joints with defects

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ABSTRACT

The use of adhesive joints is increasing in various industrial applications because of their advantages such as weight reduction, reduction of stress concentrations and ease of manufacture. However, one of the limitations of adhesive joints is the difficulty in predicting the joint strength due to the presence of defects in the adhesive. This paper presents an experimental and numerical study of single-lap joints (SLJ) with defects centred in the adhesive layer for different overlap lengths (L_O) and adhesives. The numerical analysis by cohesive zone models (CZM) included the analysis of the peel (σ_y) and shear (τ_{xy}) stress distributions in the adhesive layer, the CZM damage variable study and the strength prediction. The joints' behaviour was accurately characterized by CZM and showed a distinct behaviour as a function of the defect size, depending on the adhesive.

1. Introduction

The use of adhesive joints is increasing in various industrial applications such as aeronautical, automotive and civil engineering [1–4] because of their advantages such as weight reduction, reduction of stress concentrations and ease of manufacture. One of the limitations of adhesive joints is the difficulty in predicting the joint strength due to the presence of defects in the adhesive. Defects are typically generated by the fabrication procedure, inadequate joint preparation, kissing bonds, micro-cracking, air bubbles, foreign bodies, grease, dirt or degradation due to the environment (e.g. humidity), reducing the joint quality and influencing the joint strength [1]. Actually, at the sites of these defects the loads are not transmitted between the structure's components, and have to be transferred by the neighbouring portions of the adhesives, where stresses locally increase, thus reducing the joint strength [5]. An important issue is the understanding of the joint behaviour when these defects are present in a structural joint, and the knowledge of how a joint designed without taking into account these defects will behave when these defects appear. Thus, accurate tools must exist such that these effects are fully understood and a clear assessment can be made on whether a joint with a given defect can continue to operate or it must be repaired or replaced. Different experimental studies are available regarding joints with bondline defects [6–8]. Heslehurst [9] experimentally addressed the influence of debonds and weak bonds on the strength and durability of adhesively-bonded repairs, considering holography interferometry to spot the defect sites. This technique was effective in detecting the defects by variation of the fringe patterns near the zone with defect. Yang et al. [10] proposed an experimental non-destructive procedure based on vibration damping and frequency measurement to locate defects in adhesively-bonded joints between composite adherends. Llopart P et al. [11] used ultrasonic C-scan and X-ray imaging to inspect full adhesive spread to the bonding area of the joint. Tserpes et al. [12] also considered ultrasonic C-scan to detect defects in the adhesive layer of noncrimp fabric double-lap joints, and digital macrographs enabled concluding that the specimens failed in the adhesive by shear (debonding) and fracture of the composite boundary layer.

The initial theoretical works regarding bonded joint bondline defects were based on the shear lag model, i.e., in which the adherends are purely axially loaded and the adhesive is solely under shear stresses. This is only applicable to joints in which no or only negligible bending exists [13–16]. In an early analytical study on the effect of bonding defects by Wang et al. [17], it was concluded that the strength of a SLJ bonded with a brittle two-part epoxy adhesive is ruled by the overlap ends. Thus, a bondline defect

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in an intermediate region of the joint does not alter significantly the strength. In a different work by the same authors [18], a ductile adhesive was used (low-density polyethylene) and, under these conditions, the sustained load by the joint is dictated by the bonded area without defect rather than by the overlap ends, because ductile adhesives have the ability to undergo plasticization before failure, which occurs with a more uniform state of stress in the bondline. Olia and Rossettos [19] proposed an analytical closed-form analysis for SLJ with symmetrical and centred defects loaded in tension and/or bending, applicable to both isotropic and orthotropic adherends. It was concluded that σ_y and τ_{xy} stresses are virtually unaffected by the void if it is sufficiently far from the overlap ends, while if the void is near to the overlap ends it will result in a significant effect on stresses, up to 25%. Berry and d'Almeida [7] considered the maximum load variations in composite SLJ by introducing circular centred defects in the adhesive layer, by analysing σ_y and τ_{xy} stresses using a closed-form model. Whilst the average τ_{xy} stress was not affected by the defect, the joint compliance highly increased with the defects. Chadegani and Batra [20] considered the first-order shear deformation theory to compute nodal displacements and stresses in bonded joints with interfacial cracks and defects, simplifying the analysis to linear elastic for the adherends and adhesive. A good agreement was found by comparing with the Finite Element Method (FEM).

In contrast with theoretical techniques, numerical techniques are typically easier to work with and the associated simplifying assumptions many times mandatory to attain a solution are straightforward to deal with. The experimental and stress analysis (by the FEM) study of Pereira and de Morais [21] showed that the inclusion of defects at the overlap edges had little effect on the effective joint strength (averaged to the bonded area) for an adhesive with some degree of ductility. Ribeiro et al. [22] used the FEM to analyse the stress distributions in SLJ with different defect types and showed that defects at one of the adhesive layer's edges were particularly harmful to the joints' strength, oppositely to using centred defects in the adhesive layer, since the overlap ends remain the main zone for load transfer. You et al. [23] addressed by experimentation and the FEM adhesively-bonded double-lap joints with different gap lengths and different positions in the bondline (including centred defects). It was concluded that short length defects centred in the adhesive layer's length do not significantly affect the joints' strength because of the small disruption to stress distributions, oppositely to large size defects. Chow and Woo [24] used the FEM to assess the size and distribution effects of internal defects in bonded joints, revealing the major influence of these defects on τ_{xy} stresses and maximum load (P_m) sustained by the joints. Karachalios et al. [5] studied the impact of rectangular and circular defects at the middle of the overlap on the strength of SLJ loaded in tension and four-point bending, considering different adhesives (brittle and ductile) and adherends (steel adherends: low strength/high ductility and high strength). Under tension and with a ductile adhesive, the joints' strength depends on the type of steel: (1) high strength steel adherends lead to a practically linear reduction of P_m with the reduction of the effective bonded area and (2) for mild steel or medium carbon adherends small dimension defects have virtually no influence, while large-area defects significantly reduce the strength. Considering the brittle adhesive the behaviour is different: (1) for non-yielding adherends (high-strength steel) the strength reduction is not proportional to the defect size, which shows that the overlap ends rule the joints' behaviour and (2) for yielding adherends the strength is dependent on overlap end-plasticization, which triggers premature failure by crack onset due to excessive strains. Under bending, it was found that the overlap ends govern failure in joints bonded with a ductile adhesive and high-strength steel adherends. CZM is particularly recommended for bonded joints, since it clearly accounts for the coupling between tension and shear that occurs in the mixed-mode fracture of adhesive layers [25]. Several studies regarding the suitability of this technique and failure criteria/law types are available in the literature [26–28]. Serrano [29] used CZM modelling to simulate the effect of geometrical imperfections on the strength of bonded joints with different configurations between wood members. The softening laws in tension in shear developed for the adhesive layer included both the influence of the bulk adhesive and respective interfaces with the wood adherends. It was found that the sensitivity to geometrical imperfections in the tested joint configurations highly depends on the adhesive type. Ascione [30] used the CZM technique to test different CZM models to predict the strength of composite double-lap joints with defects, namely the models of Hutchinson & Suo, Xu & Needleman, and Camacho & Ortiz. It was found that the two latter models are more conservative than the model of Hutchinson & Suo. Xu and Wei [31] numerically studied the tensile strength of bonded joints with three types of defects: local debonding, weak bonding and voids. Local debonding and weak bonding were addressed by CZM implemented in user-defined sub-routines to account for the effect of the defect size and location. In the models for the void analyses, the Gurson-Tvergaard-Needleman model was used, enabling to account for the void size. Overall, the joints' strength diminished by increasing the defect size, and the fracture properties of the weak adhesive revealed a major influence on the strength results when the weakly-bonded area is large.

This paper presents an experimental and numerical study of SLJ with defects centred in the adhesive layer for different values of L_O. The adhesives used were the brittle Araldite® AV138 and the ductile Sikaforce® 7752. The experimental part consisted of tensile testing different SLJ allowing to obtain the load-displacement (P-δ) curves. The numerical analysis by CZM included the analysis of peel (σ_y) and shear (τ_{xy}) stress distributions in the adhesive layer, the CZM damage variable study during the failure process and the CZM evaluation to predict the joint strength. The main innovations of the proposed work over the previously mentioned studies are related to the use of CZM for an integrated damage analysis/strength prediction and the assessment of the joints' behaviour under different geometric (L_O) and material conditions (adhesive type), which will enable selecting the best adhesive depending on the defect size and value of L_O.

2. Experimental work

2.1. Materials characterization

The composite adherends were fabricated from unidirectional carbon-epoxy pre-preg (SEAL® Texipreg HS 160 RM; Legnano, Italy) with 0.15 mm thickness by hand-lay-up of 20 unidirectional plies and curing in a hot-plates press for 1 h at 130 °C and pressure of 2 bar. Table 1 provides the elastic-orthotropic properties of a unidirectional lamina for identical curing conditions [32]. The strong and brittle epoxy Araldite® AV138 and the less strong but ductile polyurethane Sikaforce® 7752 were evaluated. These adhesives were characterized in previous works regarding the Young's (E) and

Table 1
Elastic orthotropic properties of a unidirectional carbon-epoxy ply aligned in the fibres direction (x-direction; y and z are the transverse and through-thickness directions, respectively) [32].

$E_x = 1.09E+05$ MPa	$\nu_{xy} = 0.342$	$G_{xy} = 4315$ MPa
$E_y = 8819$ MPa	$\nu_{xz} = 0.342$	$G_{xz} = 4315$ MPa
$E_z = 8819$ MPa	$\nu_{yz} = 0.380$	$G_{yz} = 3200$ MPa