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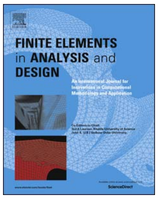

Numerical modelling of adhesively-bonded double-lap joints by the eXtended Finite Element Method

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ABSTRACT

The use of adhesive joints in industrial applications has been increasing in recent years because of the significant advantages offered compared to traditional joining methods such as welding, fastening and riveting. Thus, the existence of design tools is necessary to predict the joints' strength with high accuracy. The eXtended Finite Element Method (XFEM) is emerging as a method to predict the joints' behaviour, although this has not yet been adequately studied for the application to adhesive joints. This work presents an experimental and numerical study by XFEM of double-lap joints, in which adhesives ranging from brittle and strong, as the case of the Araldite® AV138, to more ductile adhesives, as the Araldite® 2015 and the Sikaforce® 7888, are applied. Aluminium substrates were considered (AW6082-T651) in joints with different overlap lengths (L_O), subjected to a tensile load, in order to evaluate their performance. In the numerical study, an analysis of the stress distributions in the adhesive layer, a strength prediction by XFEM considering damage initiation criteria based on stresses and strains, and also a study on the energy criterion for damage propagation, were carried out. The XFEM analysis revealed that this method is very accurate when using specific damage initiation criteria, and a parameter of 1 in the damage propagation criterion, are considered. The choice of criteria that are not consistent with the adhesives' behaviour and observed failure modes results in large errors.

1. Introduction

Adhesive joints have been used in various application fields. The aeronautical and marine industries were the ones that most contributed to the development of adhesive joints. The use of adhesive joints in industrial applications has been increasing in recent years because of the significant advantages offered compared to traditional joining methods such as welding, fastening and riveting. The most common bonded joints are single and double-lap, and also scarf joints. The single-lap joint is the most generally studied because of being the easiest to fabricate, although the specific strength (averaged to the bonded area) is the worst between these three joint configurations [1]. The poor performance is caused by the joint eccentricity and respective deflexion under load at the bonded region, which reflects on high through-thickness normal (σ_y) peak stresses at the overlap edges [2]. Moreover, shear (τ_{xy}) peak stresses coexist at the same locations due to the differential straining effect [3]. The double-lap joint behaves better by reducing both σ_y peel and τ_{xy} peak stresses. The decrease of σ_y peel stresses is linked to the elimination of the joint eccentricities, while τ_{xy} stresses reduce by diminishing the differential straining effect [4]. Scarf joints are the best in strength for the same bonded area, by reducing peak stresses even further [5], and they avoid the geometry disruption that occurs in the lap joints. The experimental and Finite Element Method (FEM) work of Shin and Lee [6] evaluated the strength of co-cured single and double-lap joints, considering a hybrid configuration with composite and steel adherends. σ_y and τ_{xy} stress for the double-lap joints revealed more uniform distributions along the adhesive and smaller peak values, especially at the end of the middle adherend. Because of this improved behavior, the strength of double-lap joints over single-lap joints with the same L_O was more than the double, which is the ratio of bonded area. Kinloch [7] compared τ_{xy} stresses of single and double-lap, and also scarf joints, between aluminium adherends. This analysis showed a reduction of peak stresses at the overlap edges for the double-lap over the single-lap joint, and even better results for the scarf joint.

Advanced modelling techniques are currently available that assure accurate failure predictions. Two alternatives can be chosen for the analysis of adhesive joints: closed-form analyses (analytical methods)

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and numerical methods (e.g. FEM). The FEM is the most popular technique for adhesive joints, and Adams and co-workers were pioneers in this technique [8]. In general, structural damage can occur by micro-cracks over a finite volume or interfacial region, reducing load transfer. A FEM simulation based on solid continuum modelling wrongly outputs generalised plasticization in the elements without damage evolution, while a damage mechanics model can actually induce damage in the elements by reduction of the transferred loads. As a result, the simulation of step-by-step damage and fracture at a pre-defined crack path or arbitrarily within a finite region is allowed [9]. Although these methods are available for quite a while, not just for bonded structures, only more recently these were applied to hybrid structures. Despite this fact, this is still an innovative field under intense development, regarding more accurate modelling techniques, reliable and simple material parameter estimation methods, increase of robustness and elimination of convergence issues [10]. Cohesive Zone Modelling (CZM) is a FEM-based technique that can be either local or continuum-based. Within local damage modelling, damage occurs in a zero volume line or a surface (two-dimensional, 2D, or three-dimensional, 3D, analysis, respectively), simulating an interfacial failure between materials, e.g. between the adhesive bond and the adherend, the interlaminar fracture of laminated composites or the interface between solid phases of materials. By continuum modelling, the damage extends over an area or volume (2D or 3D analysis, respectively), to simulate a bulk failure or to model a cohesive fracture of the adhesive. This technique combines conventional FEM modelling for the regions that are not expected to undergo damage and a fracture mechanics approach via the cohesive elements to simulate crack growth [11]. A very recent alternative to model the crack propagation within the material is XFEM [12]. The XFEM is a recent improvement of the FEM to model damage growth in structures. It uses damage laws for the prediction of fracture that are based on the bulk strength of the materials for the initiation of damage and strain for the assessment of failure (defined by the tensile fracture toughness, G_{IC}), rather than the cohesive strengths and failure displacements used for CZM. XFEM gains an advantage over CZM as it does not require the crack to follow a predefined path [13]. Actually, cracks are allowed to grow freely in a material without the requirement of the mesh to match the geometry of the discontinuities neither remeshing near the crack [14]. The XFEM relies on the concept of partition of unity and it consists of introducing local enrichment functions for the nodal displacements near the crack to allow its growth and separation between the crack faces [15]. Due to crack growth, the crack tip continuously changes its position and orientation depending on the loading conditions and structure geometry, simultaneously to the creation of the necessary enrichment functions for the nodal points of the finite elements around the crack path/tip [16].

Although being a recent method, the XFEM showed reliable and accurate results in specific cases [17–19]. The XFEM is also emerging as a method to predict the joints' behaviour, although this has not yet been adequately studied for the application to adhesive joints. Despite this fact, few works were performed regarding the application of this technique to bonded joints. Campilho et al. [20] compared the CZM and XFEM models available in Abaqus® in which regards the strength prediction of single and double-lap bonded joints with aluminium adherends and a brittle adhesive (Araldite® AV138), considering L_{O} values between 5 and 20 mm. The damage laws for both techniques were estimated from previous characterization of the adhesive in both tension and shear. The CZM results were in high agreement with the experiments but, by the XFEM, it was not possible to promote damage growth in the adhesive due to the mixed-mode loading, which resulted in mixed-mode crack growth in the direction of the adherends, since the crack direction is orthogonal to the maximum principal stress. However, due to the adhesive's brittleness, reasonable strength predictions were found by assuming that the maximum load (P_{m}) is attained when crack initiates in the adhesive layer. In the work of Sugiman et al. [21], CZM were used to simulate damage propagation in the adhesive layer of single-lap joints. Initially, the authors used the backface strain technique to track the spread of damage to the adhesive layer, and also calibrate the cohesive laws of the adhesive. In the authors' work, the fillet region was modelled by XFEM enriched continuum elements, whilst failure in the adhesive bond was evaluated by CZM. It has been experimentally observed that the zone connecting the vertical edge of the fillet and the adherend's edge was poorly bonded. Thus, two models were created: considering a good bond between the substrate surface and the vertical face (case I), and another in which the connection between these two materials was poor (case II). Case I simulations resulted in the FEM backface strains being smaller than those of the experiments, while case II simulations gave similar results to the joint with no fillet and provided a good match to the experiments. In the end, the hybrid CZM/XFEM approach was considered valid, but it was discarded in subsequent simulations since it provided identical results to the simulation without fillet. A similar analysis was undertaken by Mubashar et al. [22], which considered a hybrid CZM/XFEM approach to simulate single-lap joints between aluminium adherends. The adhesive layer was modeled by a combination of solid elements with elasto-plastic properties, cohesive elements and regions enriched by XFEM. Despite this fact, the hybrid methodology was somewhat different to the work of Sugiman et al. [21]. In this work, the adhesive layer including fillets in the overlapping ends was modeled with XFEM enriched solid elements, whereas the adherend/adhesive interface was modelled by CZM elements to account for damage growth along the adhesive layer's length. It was found that P_{m} was very close to the experimental values, enabling to conclude that it is possible to accurately predict the joints' behaviour by this hybrid approach. In the work of Curiel Sosa and Karapurath [23], delamination damage in Fibre Metal Laminates (FML) was simulated by CZM and XFEM. The specimens were tested using the Double-Cantilever Beam (DCB) configuration, which promotes crack propagation under pure tension. The FML was composed of outer aluminium layers with a thickness of 4.1 mm and an inner glare laminate layer with a thickness of 1.25 mm. Interfacial strengths of 25 and 35 MPa were considered in the CZM damage laws, and the value of 35 MPa gave an accurate match to the experimental tests. However, the XFEM load-displacement (P-δ) curves were slightly under the experimental curve, oppositely to the CZM data, which exceeded the experimental values. On the other hand, the XFEM provided good results even with a coarse mesh.

This work presents an experimental and numerical study by XFEM of double-lap joints, in which adhesives ranging from brittle and strong, as the case of the Araldite® AV138, to more ductile adhesives, as the Araldite® 2015 and the Sikaforce® 7888, are evaluated. Aluminium substrates were considered (AW6082-T651) in joints with different L_{O}, subjected to a tensile load, in order to evaluate their performance. In the numerical study, an analysis of the stress distributions in the adhesive layer, a strength prediction by XFEM considering damage initiation criteria based on stresses and strains, and also a study on the energy criterion for damage propagation, were carried out.

2. Experimental work

2.1. Joint materials

The ductile aluminium alloy AA6082 T651 was chosen for the adherends. The tensile mechanical properties of this material were obtained in the work of Campilho et al. [20]: Young's modulus (E) of 70.07 ± 0.83 GPa, tensile yield stress (σ_{y}) of 261.67 ± 7.65 MPa, tensile failure strength (σ_{f}) of 324 ± 0.16 MPa and tensile failure strain (ε_{f}) of 21.70 ± 4.24%. Fig. 1 compares the obtained experimental tensile stress-tensile strain (σ-ε) curves and respective approximation to input in the numerical models.

The experimental testing programme included three structural