**FAILURE PREDICTION OF COMPOSITE ADHESIVE SCARF-LAP JOINTS USING FINITE FRACTURE MECHANICS**

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**Abstract**

The increasing application of composite structures with complex shapes propels the use of adhesive bonding for joining different parts. Predicting the load to failure and crack formation is, therefore, crucial to design composite adhesive bonded joints.

When using bruttle adhesives, the crack initiation typically occurs at the interface between the adherend and adhesive, because of the stress singularity in proximity of the bi-material corner.

In the present study, a coupled-criterion in the framework of Finite Fracture Mechanics (FFM) is adopted to predict the failure load of composite adhesive scarf-lap joints. The FFM approach requires a simultaneous fulfillment of a stress and an energy criterion. A theoretical treatise developed for the bi-material corners and 2D Finite Element (FE) models are considered to obtain the stress fields, whereas the energy release rate is calculated through FE analyses, by employing the VCCT technique. To validate the approach, the available experimental data in the literature are considered. A good agreement between the predicted crack initiation loads and the measured failure load is obtained for several scarf angles.

1. Introduction

Nowadays, adhesive bonding is the most effective and diffused technique with a number of benefits for assembling and repairing composite structures, offering simple and light assembling, compared to traditional mechanical fastening methods. The widespread use of bonded connections makes it necessary to define a comprehensive model to predict their failure load and the way it is affected by the geometry and the materials involved.

Several studies have been conducted to understand the effect of the adhesive type on the failure load of the joints. It has been proven that, for ductile adhesives, the failure can be predicted by using the average shear stress in the adhesive layer [1].

In the case of brittle adhesives, the static failure typically involves the initiation and unstable propagation of an interface crack starting at a bi-material corner [2,3]. In such a case, the load-displacement curve shows a linear behavior until fracture.

Harris and Adams [4] proposed a failure criterion based on the use of the maximum principal stress for brittle adhesive, evaluated at a point along the bi-material corner. In another study, Gleich et al. [5] proposed another point criterion, evaluating the peel and shear stresses at the interface at a finite arbitrary distance from the corner, to explain the adhesive thickness effect on the failure load. The use of a point criterion can be questionable in the presence of sharp bi-material corners giving rise to a singular stress field. Afendi et al. [6] proposed a criterion based on the use of a Generalised Stress Intensity Factor (GSIF) evaluated along the interface at the bi-material corner. They succeeded in predicting the influence of the adhesive thickness in metal-epoxy scarf joints. This approach was also suggested by Soler et al. for bonded joints in composite smaterials [7]. A GSIF-based criterion was also successfully adopted by Lefebvbre and Dillard [8] and Quaresimin and Ricotta [9] for predicting the fatigue crack initiation in bonded joints made of metallic and composite materials, respectively.

An approach that is recently gaining a significant attention is the Finite Fracture Mechanics, introduced by Leguillon [10] in 2002, which found several applications, also in metallic bonded joints [11].

The aim of present study is to propose a failure criterion for the assessment of the static interface failure load of bonded composite joints obtained with brittle adhesives. A coupled stress-energy criterion is adopted, according to the Finite Fracture Mechanics approach [10].

2. Finite Fracture Mechanics

The sharp bi-material corner of the joints causes a stress singularity that needs to be accounted for through a proper failure criterion to predict the ultimate load. Leguillon [10], introducing the concept of Finite Fracture Mechanics (FFM), proposed a coupled criterion to identify the critical failure load in the presence of stress gradients. The FFM approach requires a simultaneous fulfillment of a stress criterion and an energy criterion, so that the failure load Pf can be calculated as:

 (1)

Where f(σij) is a stress-based failure criterion and G is the Energy Release Rate (ERR).

Δa is the length of the finite crack initiated when the failure load is reached and it is an unknown of the problem, to be calculated, together with Pf, by fulfilling the stress and energy criteria.

3. Application of FFM to Composite Scarf Joints

The application of the stress criterion needs the knowledge of the singular stress fields at the interface, in the vicinity of the bi-material corner. These can be expressed as a function of GSIFs, according to the expressions proposed by Zappalorto et al. [12], where the GSIFs can be computed through proper FE analyses.

This approach has been applied to scarf joints by Ghorbani [1], showing a good agreement between finite element analyses and theoretical results. A multiaxial stress state is present at the interface, so that the peel (σθ) and shear (τrθ) stresses need to be coupled through a criterion. A quadratic criterion is chosen in this work, through the definition of an equivalent stress:

 (2)

where c is a constant considered equal to 3 in this work.

For the energy criterion, the energy release rate for a crack propagating at the interface from the bi-material corner is calculated through FE analyses and the Virtual Crack Closure Technique (VCCT). In this context, the length of the elements immediately before and after the crack tip is extremely crucial. It must be small enough to supply a reasonable number of elements in the adhesive thickness, but large enough to avoid oscillating results [13].

To validate the proposed coupled criterion approach, a comparison to experimental results is performed. Two available experimental data sets in the literature are considered. Kumar et al. [2] carried out the tensile test on the adhesive bonded composite joints with scarf angles of 1.8˚, 2.9˚ and 4˚, 4.7° and 5°. According to Ref. [2], the interface failure was the dominant failure mechanism for all the specimens. In order to understand the effects of scarf angle, Li and his coworkers [3] considered scarf angles of 3.81˚, 5.71˚. 8.13˚ and 11.3˚. A brittle adhesive was used in these experimental studies.

**Figure 1.** Comparison of the experimental failure load by Kumar et al. [2] and the failure load prediction of the coupled criterion for Gc=0.1 kJ/m2 and σc=42 MPa

**Figure 2.** Comparison of the experimental failure load by Li et al. [3] and the failure load

 prediction of the coupled criterion for Gc=0.4 kJ/m2 and σc=150 MPa.

The comparison of the failure load prediction by the present model and the experimental results is shown in Figs. 1 and 2. A satisfying agreement is achieved and the effect of scarf angle on the joint strength is captured very well. The predicted finite crack length ranged from 0.16 to 0.24 mm and 0.01 to 0.021 mm for Kumar et al. [2] and Li et al. [3], respectively. The values of the critical stress and ERR for the adopted bi-material systems were not reported by the authors. Therefore, they were obtained by fitting the experimental trends. The reported results show that using a single couple σc-Gc, the scarf angle effect can be predicted for the entire range of angles covered by the experimental activity. This is of course an encouraging result, although an experimental methodology for the characterisation of these interface properties remains absolutely necessary in view of the actual validation and application of the criterion.

4. Conclusions

In the present study, a coupled stress and energy criterion, in the frame of Finite Fracture Mechanics, was proposed for predicting the failure load of composite bonded joints in the presence of brittle adhesives and failing in an adhesive manner.

A preliminary validation of the approach was carried out on scarf joints tested by other authors in the literature. The singular stress distributions at the bi-material corner and the ERR were calculated through Finite Element analyses. It can be concluded that the coupled criterion is capable of predicting the effect of the scarf angle on the failure load, once the critical interface stress and ERR are properly chosen. These are encouraging results in view of the application of the criterion for predicting the failure load of composite bonded joints, even though an experimental procedure for measuring such interface properties remains to be defined.

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