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Numerical investigation of constitutive material models on bonded joints in scarf repaired composite laminates

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ABSTRACT

The purpose of this study is the assessment of the mechanical behaviour of bonded composite repairs. An original multi-linear material model for the elastic-plastic response of adhesives is used in conjunction with an effective FE progressive damage approach for the computation of adhesive stress state within bonded joints in repaired composite structures. The proposed numerical model has been applied to several bonded joints configurations and the obtained numerical results have been compared to experimental and predicted data available in literature providing an interesting insight on bonded composite repairs. Simultaneously, a first demonstration has been given about the capability of the proposed material model to provide detailed and reliable information on the adhesive stress distribution, failure onset, and crack-path propagation.

1. Introduction

The use of composite materials for replacement and for repair of metallic alloys in aircraft structures offers the possibility to reduce weight and preserve good efficiency in terms of part strength and stiffness. Composite repairs' development and dissemination in the aerospace field requires appropriate research campaigns, able to assess the behaviour of repaired composite structures in operating conditions. However, while the repair process of metallic structures is well established, such treatment for composite materials still needs deep investigations. Indeed, bolting and riveting techniques of damaged metallic structures are widely used while, in case of fibre-reinforced laminates, drilling operations can result in a reduction of the load-carrying capability of the whole structure. Indeed, the repairing process causes fibres' cutting and produces high stress concentrations in proximity of the holes.

Furthermore, design of composite bonded joints is far more complicated. Patch stacking sequence and dimensions need to be carefully arranged in order to match the original damaged laminate both geometrically and mechanically. Common bonded repair configurations are single-lap, double-lap, and scarf. Single and double laps configurations can be easily designed and laid out, although stress concentrations at the overlap extremities can be an issue. Scarf repairs can be an effective alternative to single and double-lap configurations because the free edge effects are limited. Moreover, they give the chance to recover the original shape of the structure without losing any aerodynamic or stealth characteristic. Whatever the repair configuration, the benefits of composites patches make mandatory the continuous improvement of materials models and design tools in order to provide effective repair solutions.

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Nomenclature

i	point of the discrete stress-strain curve
E	elastic modulus
G	shear modulus
$\varepsilon_{avg(i)}$	averaged strain for the point i of the tabular stress-strain curve
$\varepsilon_{avg(elastic)}$	elastic part of the averaged strain
ε_{eqv}	equivalent input strain
ε_{log}	logarithmic strain
ε_{nom}	nominal strain
ε_{y}	tensile yielding strain
v	Poisson's ratio
σ_{eqv}	equivalent input stress
σ_{y}	tensile equivalent yielding stress
τ_{nom}	nominal stress
τ_{true}	true stress
τ_{y}	shear engineering yielding stress

As a matter of fact, the Finite Elements Method can be considered a valuable and effective tool to evaluate the stress distribution in adhesive layers with good accuracy [1–6] giving the chance to minimize stress and strain peaks [7–9].

Concerning the scarf configuration, some design practices [10–15] recommend that a scarf patch should match the original structure lamination. In this situation, adhesive stresses along the scarf are considered uniform and the joint maximum strength is the ultimate shear strength of the adhesive, hence the real challenge with the FE modelling of scarf joints is the definition of a valid material model capable of simulating the adhesive mechanical behaviour.

The adhesives forming the bond may present a non-negligible degree of ductility resulting in more or less extended non-linear response before failure onset and propagation. Several works analysed the elastic-plastic phase of the joints in order to compute the stress distribution within the bonded area [15–21], while others focused their efforts into defining the joints' strength mostly by making use of the Cohesive Zone Model [22–24]. However, it looks mandatory to take simultaneously into account non-linear response, failure initiation, and damage growth in order to correctly predict the mechanical behaviour of bonded composite joints [25–27].

In this paper, the mechanical behaviour of different bonded joints configurations is investigated by means of an original material model, introduced by the same authors in a previous work [28], able to simulate the elastic-plastic and failure behaviour of structural ductile adhesives. The proposed elasto-plastic material model makes use of equivalent stresses and strains as input to the FE code material model, rather than the usual true stresses and true strains, in order to take into account different data, such as uniaxial and shear stresses, considering only one input curve. In other words, a "shear stress-strain curve" is turned into an equivalent uniaxial true stress vs true strain curve for use with a standard commercial FE code plasticity model or damage evolution model.

The material model has been implemented into the commercial FE code ABAQUS, and it has been used in conjunction with the damage evolution models already implemented in the code. Numerical analyses, involving 2-dimensional and 3-dimensional FE models, representing a three-point bending test, a scarf joint under tension, and a scarf repair under tension, are presented. Numerical results have been compared to numerical and experimental data available in literature providing an interesting insight on the behaviour of bonded composite repairs and providing, at the same time, a first evaluation of the proposed material model capabilities to predict the crack onset and propagation within adhesive layers.

In Section 2, a short description of the model employed to simulate the elastic-plastic behaviour of structural ductile adhesives is given. Numerical applications are presented in Section 3, together with the comparisons between numerical results and experimental data found in literature [25–27]. Section 3.1 proposes a three-point bending test of a thick bond between two adherents, while in Section 3.2 the stress distribution within the bond line in a scarf composite joint is investigated by means of a 2-dimensional FE model. Finally, in Section 3.3, a 3D FE model of an 8-plies plate with a scarf repair is adopted to evaluate the repair strength and stress distributions.

2. Multi-linear elastic-plastic model for adhesives

In order to investigate the elasto-plastic behaviour of bonded composite joints adhesive including failure onset and evolution, the material model introduced in [28] and implemented in ABAQUS FE code has been adopted. A brief description of the proposed model is given hereafter.

The plastic behaviour of a material is simulated in ABAQUS giving as an input the uniaxial true stress and the equivalent plastic strain. However, according to this approach, it is not possible to input both the shear and the tensile plastic stress-strain curves simultaneously.