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Efficient progressive damage modeling of hybrid composite/titanium bolted joints

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ABSTRACT

In an attempt to gain better understanding and predictability of the mechanical behavior of titanium-lamella reinforced CFRP bolted joints, an efficient progressive damage model was developed in this work. The model was used to represent bearing effects in a double-lap composite bolted joint subjected to tensile loading. The progressive damage model relies on stress-based failure criteria accounting for three orthogonal fracture planes and a continuous degradation method depending on stress-state and stress history. It is shown that the model, which for material specification uses available elastic moduli and strength values, can be refined to reasonable accuracy with regard to experiments through a parameter identification process. For pure CFRP bolted joints, the model predicts accurately both bolt strength and total displacement at final failure. The predicted strength enhancement, achieved by replacing CFRP layers with titanium sheets, is in good agreement with experimental data obtained from the literature.

1. Introduction

Ever since the introduction of carbon fiber-reinforced plastics (CFRPs) into aerospace design, significant engineering efforts have been employed to adopt existing metal-related designs to the new requirements, induced particularly by the material's anisotropy and brittleness. In doing so, the optimization of structural joints has been a substantial field of interest [1,2]. However, fiber-compatible joint design often proved unsatisfactory in regard to weight, required space or notably the ease of assembly and disassembly, having crucial effects on the economical feasibility of a design-for-functionality approach.

Integral design featuring adhesive bonding can incorporate different functionalities in one part, thus being a beneficial application of CFRPs. In turn, it often evokes conflicts with product requirements regarding handling, assembly and maintenance. To overcome these conflicts, new non-permanent bonding techniques are obligatory, since simple bolted laminate joints featuring drilled holes (Fig. 1a) were widely considered not to be fiber-compatible due to notching and fiber-rupture, and thus would not allow for highly efficient primary structure joints. Bolted joints can generally be distinguished in double-lap and single-lap configurations, the latter inducing bending and extensive bearing stress peaks along the outer laminate regions even under purely tensile load, due to off-axis pulling. As opposed to the aforementioned inappropriate designs with regard to CFRP, anchor-loaded fiber-loop connector straps [3] have been successfully tested in applications with mainly tensile loading, yet the required geometries and space deviated significantly from metal practice.

In order to make use of the advantages associated with bolted joints, different approaches to reducing bearing stress have been followed. Most common in design practice is the local reinforcement of the base laminate with additional layers of CFRP. This, though, does not overcome the material's brittle characteristic and furthermore entails secondary bending as well as a considerable increase in total weight [4]. Sophisticated metal inserts are supposed to combine the structural advantages of CFRPs and the toughness of metal joints. Previous work has proved that bonded metallic inserts can increase the joint's efficiency, though it is necessary to carefully optimize load paths and bonding strength [5].

In many applications it is, however, desired to avoid geometrical transitions between the joint laps and the base laminate, be it for space-restriction reasons or structural effects such as secondary bending or notching. Kolesnikov et al. [6] have performed a laminate reinforcement by locally substituting CFRP plies within the laminate by equally thick titanium sheets as schematically shown in Fig. 1b. In a multidirectional laminate, those plies contributing least to the primary load direction, i.e. e.g. 90°-layers, are preferentially replaced and bonded by the matrix resin of the adjacent remaining CFRP layers, resulting in a hybrid CFRP-titanium laminate With reference to a laminate build-up with [50% 0°; 40% 45°; 10% 90°], improvement factors in joint strength of 1.78 and 1.91 were achieved for single-row and three-row layout configurations, respectively, in case of uniaxial loading.

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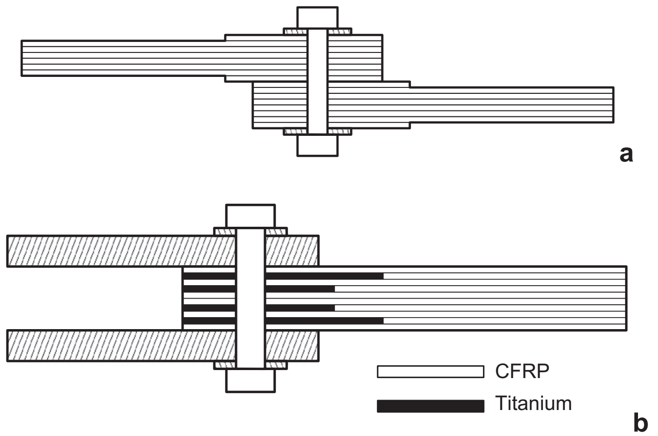

Fig. 1. Schematic sectional view of: (a) Single-lap bolted CFRP joint; (b) Double-lap bolted hybrid composite joint with four composite layers locally substituted by titanium plies.

In order to entirely utilize the proposed technique, optimization for the most efficient layer build-up as regards strength enhancement has to be performed. Thus, numerical models have to be developed, capable of detecting the damage progress. A variety of past works have established progressive damage models (PDMs) based on finite element (FE) formulation for pure CFRP bolted joints, but so far little effort has been done on the simulation of hybrid laminated materials.

Existing PDM approaches can be classified regarding the failure criteria and degradation strategies adopted. Employing stress-based criteria and directly coupling the failure variables to stiffness degradation using material strength data is a self-evident method that can exhibit accurate predictions of failure onset with comparatively low computational costs. Tserpes et al. [7] developed a 3D model of a single-lap single-bolt joint of a CFRP-laminate that was subjected to tensile loading. Hashin-type failure criteria [8] were used for the computation of local failure variables, partly due to their ease of implementation into FE applications. Eventually, the model produced overly conservative strength predictions in consequence of the shear-stress contribution to fiber failure in the failure criteria used, as stated in [7]. In [9], the model was further refined aiming for a model set-up that would meet the particular demands for simulating textile and cellular materials. Thereby, the Hashin criteria were transposed to a strain based formulation, which enabled them to account for strain softening. The constant and sudden degradation method was replaced with an exponential course of the damage variables, as well as a refined failure mode interference treatment was introduced.

As opposed to the aforementioned class of PDM concepts based on stress or strain state variables and strength data, other approaches involve the use of energy-based degradation strategies. There, the dissipated energy from evolving cracks is evaluated considering the fracture toughness for each failure mode and the degradation is carried out in compliance with the energy equilibrium. Models making use of this technique (e.g. [10,11]) claim a decrease in mesh dependency on the model's characteristics. However, the application of fracture toughness values oftentimes implies excessive material testing, given that they are rarely available in the literature. Further refinement of the energy-based method has been carried out in [11,12]. A short introduction into the theory of complimentary free energy, energy dissipation and their interference with the tensor components in the constitutive equations is given in the accompanying papers. The authors introduced damage activation functions based on the failure criteria LaRC03 and LaRC04 [13,14], including the effects of fiber-kinking under longitudinal compression and transverse compressive cracking on effective planes in distinctive angles, also known as C-mode failure. The damage activation functions exhibit hysteretic characteristics, enabling them to consider crack-closure effects on load reversal. In order to represent the damage process accurately, the damage evolution laws distinguish primary failure onset (e.g. fiber failure) and entailed effects (e.g. fiber pull-out) in different strain regimes for every failure mode.

The scope of this work is to develop a parametric model of a symmetric double-lap hybrid CFRP/Ti composite bolted joint that can be used to study the optimal reinforcement strategy for a given laminate design. The emphasis is being put on an accurate reproduction of the characteristic of nominal bearing stress against longitudinal displacement under tensile loading. Moreover, the model shall allow for analyses on the damage propagation within the specimen and the global failure mode induced.

The model involves a PDM approach based on constitutive orthotropic composite strength data and a basic isotropic material model that incorporates plasticity for the composite fraction and the titanium fraction respectively. ANSYS implicit FE-formulation is used for analysis computation and while the model is built up of basic geometrical shapes, it is well suited for implementation in ANSYS Parametric Design Language (APDL) implicit FE-code, which allows for a very flexible and fast model set-up.

2. Model topology

For a better overview and classification of the terms defined in the subsequent sections, a brief introduction into the global model topology is given here. It is schematically shown in Fig. 2.

The developed parametric model can be subdivided into two substantial units, the *static fraction* and the *dynamic fraction*, with their particular sets of parameters, the *modeling parameters* and the *identification parameters* respectively. The FE entities used to model the bolted joint are herein considered the static fraction, since they are created in advance to the sequential PDM procedure and not altered in either shape or structure throughout the process. The PDM process is the dynamic fraction that accesses the static model and manipulates its properties iteratively.

The model is implemented as a mixed physical and parametrical formulation, often referred to as gray-box model. Therein, the major behavior is specified by physically founded equations. A mathematical model, relying on a set of parameters, is applied to those parts of the model that are yet mostly unknown or where the complexity of physical sub-modeling exceeds reasonable limits. These parameters are the aforementioned identification parameters, which are gained in a process called parameter identification. As a main component in the modeling process, during the parameter identification, the model output is iteratively matched with measurement data, i.e. mathematically it is considered a curve fitting or optimization problem.

3. Stress-based PDM approach

In this section, the PDM strategy developed during this work as a key component for the integral model will be described. It

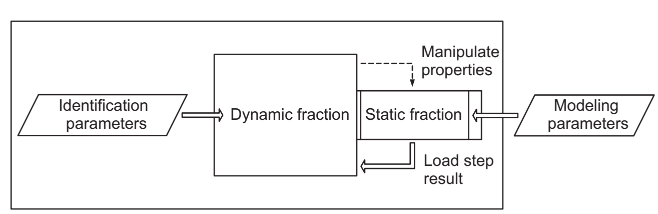

Fig. 2. Structure of the global progressive damage model.