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Bearing strength and failure behavior of bolted composite joints (part II: modeling and simulation)

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Abstract

In part II of this study, an analytical model for simulating the bearing failure and response characteristics of bolted composite joints is developed. The model was implemented using the general-purpose finite element code ABAQUS. The analytical model has taken into account the contact conditions at the pin/hole boundary, progressive damage, finite deformation and nonlinear material behavior. A complex approach based on combining the nonlinear shear elasticity theory with a continuum damage mechanics approach was utilized to represent the nonlinear material behavior during loading. The damage accumulation criteria based on Hashin and Yamada-Sun's hybrid failure criteria were adopted and a degradation model for the damaged layers is proposed for the stress redistribution analysis. The numerical simulation results for joint's progressive damage and strength response agreed well with existing experimental data.

Keywords: Polymer matrix composites (PMCs); Damage mechanics; Nonlinear behavior; Bearing failure; Finite element analysis (FEA); Computational simulation

1. Introduction

Fiber-reinforced polymer matrix composites (PMCs) have already proven to be useful in today's aircraft industry due to their lightweight properties. These structural components, though, are often assembled using mechanically fastened joints, which poses a particularly challenging problem for engineering mechanic specialists. If the design for the mechanically fastened joints is inadequate, it not only becomes the primary source of failure in the composite structures, but also directly affects the durability and reliability of the aircraft structures.

In the past few years, the failure analysis of mechanically fastened composite joints has been performed by a method that combines continuum damage mechanics (CDM) [1] with finite element analysis (FEA). Several analytical models have already been developed and documented in [2–6]. The progressive damage model revealed that the description of the material degradation due to damage is critical for the stress redistribution analysis. Although the property degradation model for the previous studies adjusts the effective material properties in the damaged area using a material degradation factor that is determined by its damaged state, the material degradation factor was simply assigned a value of zero. As a result, these simple models were unable to reproduce the bearing damage process until the final structural fracture. In practice, experimental observation [7] has indicated that bearing failure and the response of bolted composite joints are strongly affected by the lateral constraints, and these conditions tend to prevent the reduction of laminate in-plane stiffness. Hung and Chang [4] developed a two-dimensional

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damage accumulation model that took into account the effects of clamping pressure and lateral constraints on the bolted joints. However, since the determination of the critical bearing damage area was not fully clarified, further modifications to the material degradation rule will be necessary.

The primary objective of this study is to develop an analytical model for predicting the response and bearing failure of bolted composite joints. The model must be easy to implement and use, and require a minimal number of input parameters. The basic damage mechanisms and mechanics governing bearing failure are considered, in order to accurately simulate the bearing damage behavior. Accurate prediction results that include the joints' progressive damage and strength response are presented and the applicability of the proposed stiffness degradation models is discussed.

Part I of this study included a detailed experimental investigation that clarified the relationship between bearing strength and damage progression behavior in bolted composite joints [7]. Fig. 1 illustrates the strength and damage characteristics determined by this study. Bearing failure induces a compressive damage accumulation process that can be classified into four stages: damage onset, damage growth, local fracture and structural fracture. Fiber micro-buckling and matrix cracking appear to be the dominant modes for the onset of damage, while the final failure stage is dominated by out-of-plane shear cracks and delamination. The lateral constraints and the matrix "toughness" based on the laminate also influence the bearing failure and damage mechanisms. Moreover, the accumulation of damage resulted from fiber micro-buckling, fiber–matrix shearing and matrix compression failure in the individual laminate layers. Therefore, this study focuses on developing a two-dimensional model that is capable of predicting the bearing failure and stiffness response for mechanically fastened composite joints. Bearing failure in laminated composites can be grouped into two basic in-plane failure modes: matrix compression and fiber compression-shear failure. Although through-thickness shear cracks and delamination are out-of-plane failure modes, they are beyond the scope of this work, and will not be considered in this study.

2. Constitutive modeling

A progressive damage model is needed to predict the damage progression and the extent of damage in

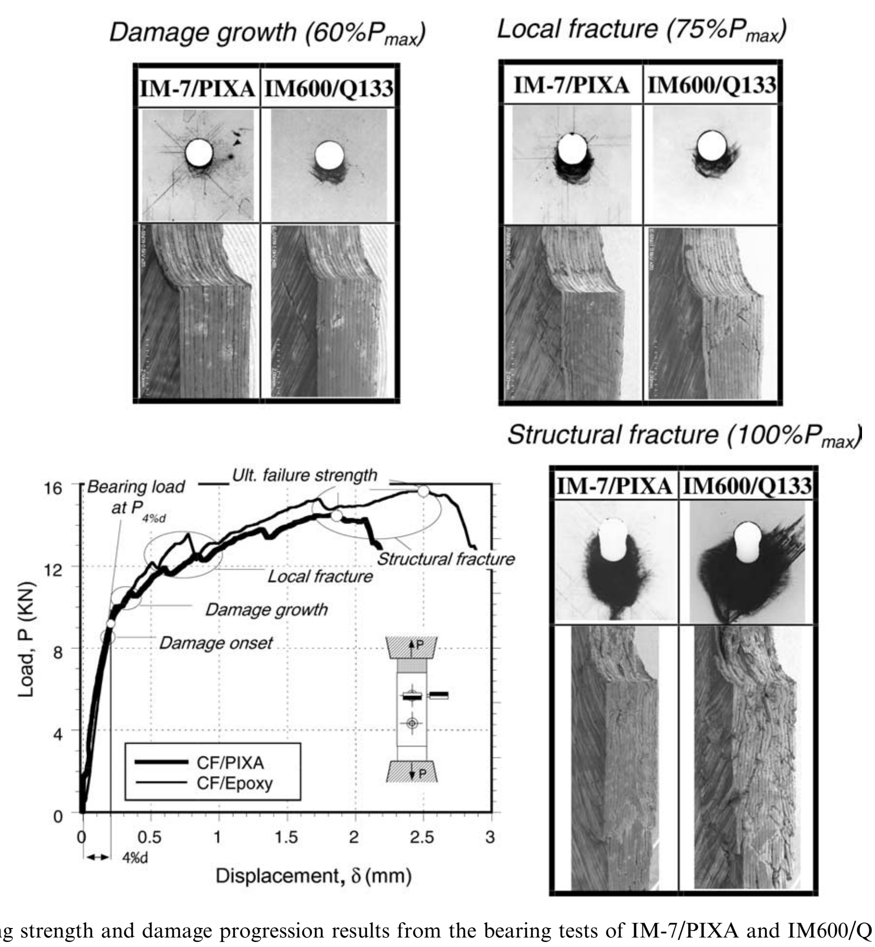

Fig. 1. Bearing strength and damage progression results from the bearing tests of IM-7/PIXA and IM600/Q133 laminates.