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3D explicit finite element analysis of tensile failure behavior in adhesive-bonded composite single-lap joints

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Abstract

The tensile failure behavior in adhesive-bonded composite single-lap joints with different overlap lengths is investigated through experiments and various three-dimensional (3D) explicit finite element methods (FEMs). Different failure modes are observed in different overlap lengths. Three parameterized finite element models are developed to discuss the accuracy and applicability of the 3D explicit FEMs based on different modeling strategies and improved failure criteria. All criteria are programmed with the explicit user subroutines employing element deletion to avoid convergence problems caused by element distortion. The load-displacement curves predicted by these models are consistent with the experimental results, while the prediction of failure morphology depends on model types. The models neglecting interface elements cannot simulate the delamination when cohesive zone models (CZMs) are adopted to predict adhesive failure. The influence of CZMs on delamination is analyzed comprehensively to address this problem. Analysis of stress distribution in an overlap of a length of 10 mm indicates that the peak stress of the adhesive layer occurs on the overlap ends along the axial direction, coinciding with implicit results.

Previous article in issue Next article in issue

Keywords

Adhesive-bonded joints; Explicit analysis; Finite element methods (FEMs); Failure modes

1. Introduction

Compared with the traditional mechanical joints, adhesive-bonded joints have the advantages such as lighter weight and smoother aerodynamic shape. Thus, the adhesive-bonded composite single-lap joint, as one of the low-cost and simple fundamental adhesive-bonded joints, has been widely used in the design of advanced composite structures.

Since the 1930s, research on adhesive-bonded composite joints has attracted increasing attention, and some theoretical investigations have been conducted [1], [2], [3], [4], [5], [6]. Subsequently, many studies [7], [8], [9], [10], [11], [12], [13], [19], [20], [21] have been carried out by FEMs to predict the failure load, stress distribution and damage propagation of adhesive-bonded joints. Harris et al. [7] proposed a non-linear finite element technique based on the plane strain assumption to predict the failure load of single-lap joints. Pickett et al. [8] used two analytical methods to determine distribution of elastic-plastic adhesive stress in bonded joints. The effect of various parameters on the performance of adhesive-bonded joints is studied in Ref. [9] by Gunnion and Herszberg. They found that an added over-laminate could reduce the peak stress in the adhesive. To simulate failure behaviors better, special elements and failure criteria were also developed by several scholars. Andruet et al. [10] developed special adhesive elements for load-displacement analyses, and represented the adherend with shell elements. Gonçalves et al. [11] established a new model for finite element analysis of single-lap joints using developed interface elements. Wahab et al. [12] proposed a damage criterion based on thermodynamics principles, and Anyfantis et al. [13] proposed a new T-S criterion to simulate the mixed-mode failure of the ductile adhesive layer. In recent years, CZMs have been used to model thin adhesive layers or adherend-adhesive interfaces in bonded joints. Blackman et al. [14] applied CZMs to bonded composite configurations and investigated the physical significance of the maximum stress. Li et al. [15], [16] used CZMs to model the mixed-mode fracture of adhesive-bonded joints. In their subsequent works, they showed that the CZMs can predict both strength and failure mechanism of joints. Moura et al. [17] used cohesive and continuum mixed-mode damage models to simulate damage propagation of bonded joints. Li et al. [18] and Luo et al. [19] performed finite element analyses to investigate the tensile failure behavior of adhesive-bonded joints with implicit methods. They used the same method to simulate the delamination with cohesive elements, and the laminates with shell elements.

Most scholars use implicit methods to analyze bonded joints. Severe convergence problems caused by divergent results of iterative computations and ill-conditioned solutions for simultaneous equations might easily occur in implicit FEMs, resulting from complicated distribution of stress and failure modes around adhesive regions. The convergence problems can be solved better by explicit FEMs, which can be used to perform quasi-static analysis [20]. A few studies have been conducted by using explicit solvers to model adhesive-bonded joints. For example, Neumayer et al. [21] presented an explicit cohesive element to enable the simulation of delamination in bonded joints on a full-scale structural level. However, these explicit methods are relatively incomprehensive and are mostly based on 2D elements. The efficiency and reliability of different types of explicit FEMs remained