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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.

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 [1–6]. Subsequently, many studies [7–13,19–21] 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 overlaminate 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

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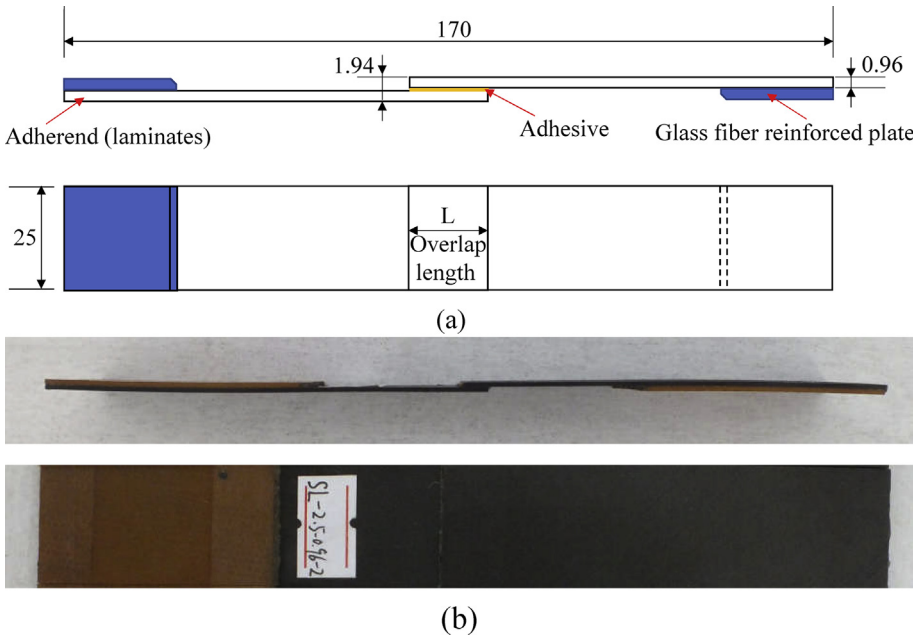

Fig. 1. Geometry of test specimens (unit: mm): (a) Diagram of specimens; (b) Photograph of specimens.

Table 1
Information of the specimens.

Group	Overall size (mm)	Adherend thickness (mm)	Overlap length L(mm)	Number of the specimens	Adherend stacking sequences	
					Upper	Lower
A	170 × 25	0.96	2.5	6	[45/0/−45/90]$_S$	[−45/0/45/90]$_S$
B	170 × 25	0.96	5.0	6		
C	170 × 25	0.96	10.0	6		

Table 2
Properties of T300/QY8911.

Elastic property	Value	Strength property	Value
E_{11} (GPa)	135	X_T (MPa)	1548
E_{22} (GPa)	8.8	X_C (MPa)	1226
E_{33} (GPa)	8.8	Y_T (MPa)	55.5
G_{12} (GPa)	4.47	Y_C (MPa)	218
G_{13} (GPa)	4.47	S_{12} (MPa)	89.9
G_{23} (GPa)	4.00	S_{13} (MPa)	89.9
ν_{12}	0.33	S_{23} (MPa)	51.2
ν_{13}	0.33	Density ρ (kg/m^3)	1600
ν_{23}	0.35		

Table 3
Properties of J116B.

Property	Shear strength (MPa)	Peel strength (90°) (kN/m)	Density ρ (kg/m^3)
Value	24.5	7.5	1000

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 unknown in terms of damage of 3D elements, and possible convergence problems caused by 3D element distortions [22] were generally not considered in these methods either. Thus, further studies are needed to be investigated.

The objective of this paper is to present a comprehensive study of the tensile failure behavior in adhesive-bonded composite single-lap joints. Single-lap joints with different overlap lengths are tested under a uniaxial tension load, and three types of parameterized 3D explicit models are established with user subroutines. Element deletion is adopted in user subroutines to overcome the convergence problems caused by element distortion. By comparing numerical results with experimental data, efficiency and accuracy of these models are comprehensively discussed in terms of load-displacement curves and failure morphology. The applicability of different explicit FEMs is also discussed based on different failure modes. Besides, the effect of cohesive elements on delamination is analyzed, and stress distribution of explicit models is compared with the implicit results.

2. Experiment

2.1. Specimens and experimental test methods

Specimens were made up of adherends and adhesive, and adherends were constituted by fiber-reinforced composite laminates consisting of fibers and polymer matrix. Fig. 1 and Table 1 display the geometry of the specimens. These specimens were divided into three groups, with each group containing six pieces. The overall sizes of all specimens were the same, with the length being 170 mm, the width being 25 mm, and the average thickness being 1.94 mm. But each group has different overlap length L (Group A: L = 2.5 mm, Group B: L = 5.0 mm, and Group C: L = 10.0 mm). The adherend consisted of eight layers, and the average thickness of the adhesive layer was 0.02 mm. The material of the adherend is T300/QY8911 (carbon fiber/BMI) with quasi-isotropic lay-ups ([45/0/−45/90]$_S$ or [−45/0/45/90]$_S$), and the material of the adhesive is J116B. The properties of the materials are presented in Tables 2 and 3. Besides, glass fiber-reinforced plates were appended on both ends of the joints to avoid damage of the clamping ends during loading.

The same axial tensile test of each specimen was performed to obtain reliable experimental results. The referenced test criteria are the