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Progressive damage analysis of PFRP double-lap bolted joints using explicit finite element method

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ABSTRACT

To numerically investigate failure behavior of pultruded fiber reinforced polymer (PFRP) bolted joints, a progressive damage analysis (PDA) material model integrating nonlinear shear response, Hashin-type failure criteria and strain-based continuous degradation rules was proposed in the present study. The PDA model was implemented via user subroutine VUMAT, detailed 3D finite element models were established in Abaqus/Explicit. Experiments were conducted to validate the proposed PDA model. Result shows that explicit finite element method is computational efficient and can effectively avoid convergence problem. The predicted joint loading response correlates well with the test result. The FE model can accurately capture various failure modes including bearing, shear-out and net-tension and reveal failure propagation and damage mechanism of PFRP bolted joints. Emergence of first fiber compression failure is found to be a good indicator to identify the load at which the load–displacement response becomes nonlinear.

1. Introduction

Pultruded fiber reinforced polymer (PFRP) has received lots of attention from civil engineering industry for its high strength and stiffness-to-weight ratios, corrosion-resistant material nature, advantage in mass production and ease of structure fabrication [1,2]. Mechanical connection, especially bolted connection is a common approach in joining PFRP structural members. Many experimental researches [3–10] have been conducted on PFRP bolted joints, suggesting that the mechanical properties and failure modes of PFRP bolted joints are influenced by many factors including geometric parameters, material parameters, loading direction, lateral constraint and joint configuration. Moreover, after the drilling process, material around the bolt hole becomes sensitive to local stress concentrations, irreversible damage propagates prior to ultimate failure due to the brittle nature of composites [10]. Therefore, it is very complicated when it comes to the design of PFRP bolted joints and usually large number of experimental tests are required to determine the joint mechanical properties, which not only consumes large sum of money, time and labor but also hinders the application of PFRP materials in civil engineering.

To avoid repetitive and numerous experiments and increase design efficiency, numerical method validated by experiment tests is an efficient and promising solution. So far, limited research has been done on FE modeling of PFRP bolted joints. Hassan et al. [11] carried out FE analysis on PFRP double lap joints, Tsai-Wu failure criterion was implemented to predict material failure but it can only identify the failure region rather than failure modes. Turvey [12] and Feo et al. [13] conducted numerical investigation on PFRP bolted joints to examine the stress and load distribution, the PFRP material was considered to be linear elastic, no damage of PFRP material was introduced.

As for damage simulation of FRP composite material, researchers in aerospace industry have done extensive work. Continuum Damage Mechanics (CDM) and progressive damage analysis (PDA) are the two commonly used FE damage simulation approaches. In CDM models, damage initiates at a relatively low load level and evolves with increasing load according to the damage evolution laws, gradual and smooth degradation can be obtained [14]. The method turned out to be accurate and capable of capturing various failure modes [14–16]. One issue with CDM models is that besides standard longitudinal, transverse and shear tests, additional non-standard test work is required for parameter calibration in CDM models. By contrast, PDA models rely on the stress/strain based failure criterion to judge whether an element is ‘intact’ or ‘damaged’ and the degradation law to achieve progressive damage in the ‘damaged’ elements [17]. Many researches have been done on numerical simulation of composite bolted joints using PDA models. Literatures [18–22] developed PDA models incorporating shear nonlinearity, Hashin-type failure criterion and constant degradation law, this method turned out to be easy

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to implement and computational efficient but sudden stiffness drop may induce severe convergence problem. Literatures [23,24] employed continuous degradation rules to obtain smoother loading response and better convergence. In most of the researches in PDA models, only certain type of failure mode is concerned, little attention has been paid on capturing various failure modes of composite bolted joints. However, PFRP laminates used in civil engineering structures exhibit much more severe anisotropy due to the zero-dominated nature of pultrusion process and accurate prediction of failure modes is an important issue.

Due to complicated material progressive damage behavior and contact interaction, finite element models of composite bolted joints exhibit strong nonlinearity and the commonly employed implicit finite element method often encounters severe convergence problems. By contrast, the explicit method provides more robust contact interaction, efficiency in dealing with large problems, and avoidance of convergence issues, up to date, only a few researches [16,25,26] drew light on using explicit finite element method to simulate composite bolted joints.

The aim of the present study is to develop a progressive damage analysis (PDA) material model that can accurately predict the loading response and failure modes of pultruded fiber reinforced polymer (PFRP) bolted joints. A PDA material model integrating shear nonlinearity, Hashin-type failure criterion and strain-based continuous degradation rules is proposed and is implemented via user subroutine VUMAT. 3D FE models are established in explicit finite element solver Abaqus/Explicit. Experiments are conducted to validate the FE models and failure propagation and mechanism of PFRP bolted joints are discussed according to the FE result.

2. Experimental investigation

2.1. Material properties

The pultruded glass fiber reinforced polymer in this study was made of E-glass fiber and epoxy resin. The pultruded section has a 6 mm thickness and the stacking sequence is shown in Fig. 1, with 3 types of layer: (1) rovings 0°, (2) unidirectional fabrics 90°, and (3) woven fabrics ±45° (the angles are relative to the pultrusion direction). Mechanical properties of PFRP laminates are shown in Table 1.

Coupon tests were conducted on pultruded unidirectional lamina that consisted E-glass rovings and epoxy resin with the same the fiber volume fraction as the pultruded laminates to acquire the mechanical properties (as shown in Table 2).

2.2. Experimental setup

PFRP double shear bolted joint test rig is shown in Fig. 2, with PFRP plate and steel plate as skin plates and two steel plates as splice plates. The steel skin plate was fabricated slightly thinner than the PFRP plate in order to ensure the bolt clamping force fully applied to the PFRP plate. A4-70 half threaded stainless steel hex head bolts with a nominal diameter of 12 mm were employed. The bolt hole clearance was 0.3 mm. The width-to-diameter ratio (W/D) was 6, end-distance-to-diameter ratio (E/D) was 5 and specimen length was 200 mm. A constant 10Nm tightening torque was applied to the bolted joint. Test group ‘LT’ represents the longitudinal joints with loading direction parallel to the pultrusion direction while test group ‘TT’ represents the transverse joints with loading direction perpendicular to the pultrusion direction. Each test group contained 3 repetitive specimens.

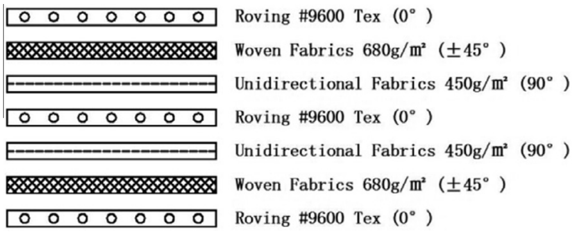

Fig. 1. Stacking sequence of PFRP laminates.

Table 1
Mechanical properties of PFRP laminates.

E_1 (GPa)	E_2 (GPa)	G_{12} (GPa)	υ_{12} (GPa)	V_f (%)	ρ (g/cm^3)
42.02	16.24	6.98	0.294	56.0	2.00

Table 2
Mechanical properties of pultruded unidirectional lamina.

Longitudinal modulus, E_1 (GPa)	47.53
Transverse modulus, E_2 (GPa)	15.48
Transverse modulus, E_3 (GPa)	15.48
In-plane shear modulus, G_{12} (GPa)	6.54
Out-of-plane shear modulus, G_{13} (GPa)	6.54
Out-of-plane shear modulus, G_{23} (GPa)	4.05 (Ref. [15])
Major Poisson’s ratio, υ_{12}	0.287
Through thickness Poisson’s ratio, υ_{13}	0.287
Through thickness Poisson’s ratio, υ_{23}	0.287
Longitudinal tensile strength, X_T (MPa)	1155
Transverse tensile strength, Y_T (MPa)	46.2
Transverse tensile strength, Z_T (MPa)	46.2
Longitudinal compression strength, X_C (MPa)	1000
Transverse compression strength, Y_C (MPa)	168
Transverse compression strength, Z_C (MPa)	168
In plane shear strength, S_{12} (MPa)	73 (Ref. [27])
Out-of-plane shear strength, S_{13} (MPa)	40
Out-of-plane shear strength, S_{23} (MPa)	40

Tightening torque was applied using a torque wrench. Clamping force was estimated by analytical formula presented in Eq. (1):

$$F_c = \frac{T}{\phi D} \tag{1}$$

where T is the torque (Nm), F_c is the clamping force (kN), D is the bolt nominal diameter (mm), ϕ is the torque coefficient. To accurately determine the clamping force, calibration was conducted in advance to determine the torque coefficient ϕ. The applied torque was read on torque wrench while corresponding clamping force was recorded by a force-measuring sensor as shown in Fig. 3.

Test setup is shown in Fig. 4. Joint tensile tests were conducted using a 500 kN universal testing machine. Two extensometers were employed, with one end attached to the steel splice plates and the other end attached to the PFRP specimen, to collect the relative displacement. The relative displacement was then calculated by taking the average readings of the two extensometers to minimize the influence of hole eccentricity and rotation of PFRP plate during loading process. Strain gauge locations are shown in Fig. 5, gauge S2 was used to record bearing strain near the hole, gauge S1 and S3 were used to record tensile strain on the net section along loading direction. Displacement load was applied at a constant stroke speed of 1 mm/min.

3. PDA model of PFRP material

Material model was implemented via a user-defined material model subroutine VUMAT in Abaqus/Explicit.

3.1. Stress–strain relationship

Orthotropic strain–stress relationship for PFRP material is given in Eq. (2):