Composite Single-Bolted Joint Simulation for Dynamic Strength Prediction [†]

Zeliang Yu, Pu Xue * and Yue Chen

School of Aeronautics, Northwestern Polytechnical University, Xi'an 710072, China;
yuzeliang715@mail.nwpu.edu.cn (Z.Y.); chenyue715@hotmail.com (Y.C.)

* Correspondence: p.xue@nwpu.edu.cn; Tel.: +86-136-7918-1653

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Abstract: Composite material has been widely used in various fields for its high specific strength and high specific stiffness, so the connectors applicable to composite structures capture many researchers' attention. With the advantages of higher carrying capacity and repetitive assembling and disassembling, bolted joint becomes one of the most popular connectors in engineering practice. Cutting off the fiber and causing stress concentration are more serious to composite than metal, so it is necessary to predict the strength of the composite joints. Most investigations focus on the response under quasi-static loading, while dynamic effects should be in consideration in increasing impact conditions. The dynamic mechanical properties of composite joint may have a significant impact on the structural deformation and damage modes. For this purpose, this paper conducts dynamic composite single-bolted joint simulations in ABAQUS/Explicit, which used for predicting dynamic strength of the composite joint. T800/X850 laminates were tested to investigate their dynamic properties in our lab. Then the three-dimension progression damage model was established, while the dynamic constitutive model, damage initial criteria and damage evolution law of composite materials were coded in VUMAT of the finite element software ABAQUS/Explicit. The model was validated by quasi-static experiments of composite joint. The simulation results indicate that the yield strength and ultimate strength of the single-bolted composite joint are obviously increasing when consider the strain rate effect and dynamic loading. And the load-displacement curves show significant difference in damage stage. The main damages are sub-layer buckling and fiber breakage caused by extrusion.

Keywords: composite single-bolted joint; VUMAT; dynamic strength

1. Introduction

Fiber-reinforced composite materials have higher specific strength and specific modulus and good designable performance. They have been widely used in the defense industry as well as in the fields of construction, chemical engineering and transportation. It is an indispensable special engineering material for aerospace field. Impact loads are a main problem for composite material structures. Composite materials are more sensitive to impact loads than metal materials. The failure modes and failure mechanisms under dynamic load are very different from those under static conditions due to the strain rate effect [1].

Bolted joint is a one of most used way to connect composite structures. The stress concentration around the holes will be more serious than metal structures because the bolt holes cut off the fibers. Therefore, it is necessary to analysis the composite bolted structure and to predict connection strength.

Winter [2] discussed the effects of various variables such as plate thickness and bolt margins on the performance of joints by testing approach. Kim et al. [3] studied the optimal design of bolted joints with carbon fiber/epoxy resin and glass fiber/epoxy under tensile load. Using finite element software to establish a three-dimensional model, the mechanical properties of the joints were simulated. The model could predict the first peak load due to delamination but failed to predict the failure strength. Ireman [4] established a three-dimensional finite element model to describe the composite bolted joints and calculated the stress distribution at the edge of bolt hole. The simulation results were basically consistent with the experimental data. The errors were mainly due to the friction coefficient. Ger et al. [5] conducted a dynamic tensile test on a carbon fiber/epoxy laminated plate bolt joint. They found that the strength of the bolt joint was lower than that under quasi-static load when the loading speed was 5 m/s. Due to differences in test methods, equipment, and data processing methods, as well as differences in properties of composite materials and geometries of bolt joints, the research conclusions on the failure modes, energy absorption, and strain rate effects of joints under dynamic loading are inconsistent. So it is necessary to establish an accurate finite element model to analyze the dynamic mechanical properties of the composite bolt joint.

2. Nonlinear Progressive Damage Model

A progressive failure model is developed to simulate the failure of composite single-bolted joint, the proposed damage model is applied to a 3D solid element by using ABAQUS/Explicit with VUMAT to analyze the intralaminar failure behavior for composites.

X850/QY8911 is used in this study. The material properties are obtained from experiments in our lab. E_{11t} = 225.6 Gpa, E_{11c} = 178.6 Gpa, E_{22t} = 15.5 Gpa, E_{22c} = 6.71 Gpa, G_{12} = 6.335 Gpa, G_{23} = 3.0 Gpa, G_{13} = 4.857 Gpa, ν_{12} = 0.334, ν_{23} = 0.599, ν_{13} = 0.334, X_t = 2707.4 Mpa, X_c = 1254.4 Mpa, Y_t = 19.898 Mpa, Y_t = 212.0 Mpa, S_{12} = 80.0 Mpa, S_{13} = 97.77 Mpa, S_{23} = 97.77 Mpa, ϱ = 1500 kg/m^3.

In this study, we adopt the Hashin damage failure criteria to predict composite damage. Hashin damage failure criteria consider the four typical failure modes under dynamic loading, including fiber breakage, fiber extrusion, matrix cracking and matrix cracking for in-plane damage of unidirectional laminates.

When local failure occurs in the composite laminate, the corresponding material point is subjected to a reduction in stiffness. Different stiffness degradation methods are used to consider the effect of different failure modes on the mechanical properties of laminates. This study adopt the stiffness degradation model proposed by Tan [6], as shown in Table 1.

Table 1. Stiffness degradation model.

Failure Mode	Stiffness Degradation Criterion
Fiber tensile failure	Q^d = 0. 07Q (Q = E_{11}, G_{12}, G_{31}, ν_{12}, ν_{31})
Fiber compression failure	Q^d = 0. 14Q (Q = E_{11}, G_{12}, G_{31}, ν_{12}, ν_{31})
Matrix tensile failure	Q^d = 0. 2Q (Q = E_{22}, G_{12}, G_{23}, ν_{12}, ν_{23})
Matrix compression failure	Q^d = 0. 4Q (Q = E_{22}, G_{12}, G_{23}, ν_{12}, ν_{23})
Tensile delamination	Q^d = 0. 2Q (Q = E_{33}, G_{31}, G_{23}, ν_{31}, ν_{23})
Compression delamination	Q^d = 0. 2Q (Q = E_{33}, G_{31}, G_{23}, ν_{31}, ν_{23})

3. Quasi-Static Model

To validate the numerical model, corresponding quasi-static tensile experiments of carbon–epoxy composite plates with single-bolted joint were conducted by using a universal testing machine. Figure 1 shows the geometry of the bolted joint.
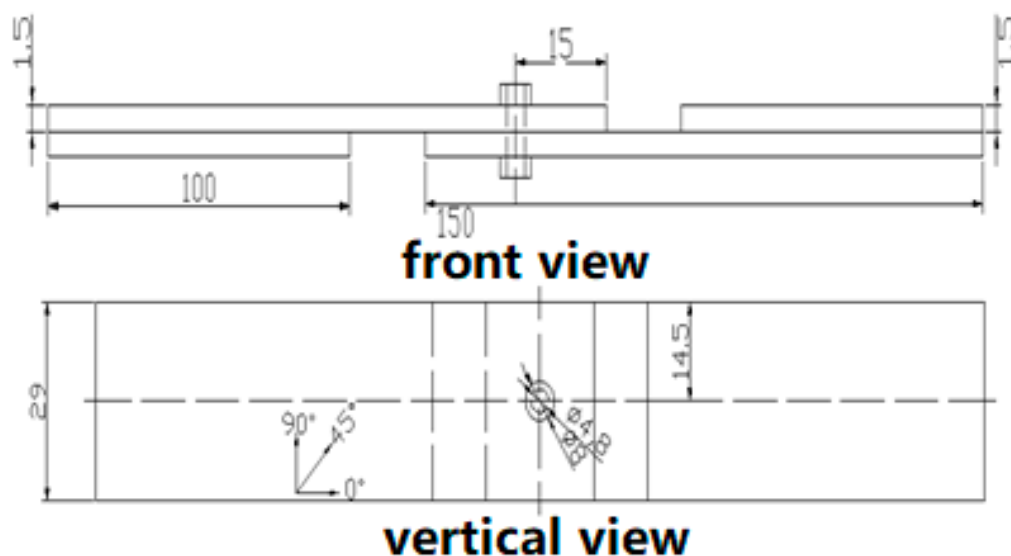
Figure 1. Geometry of the bolted joint.

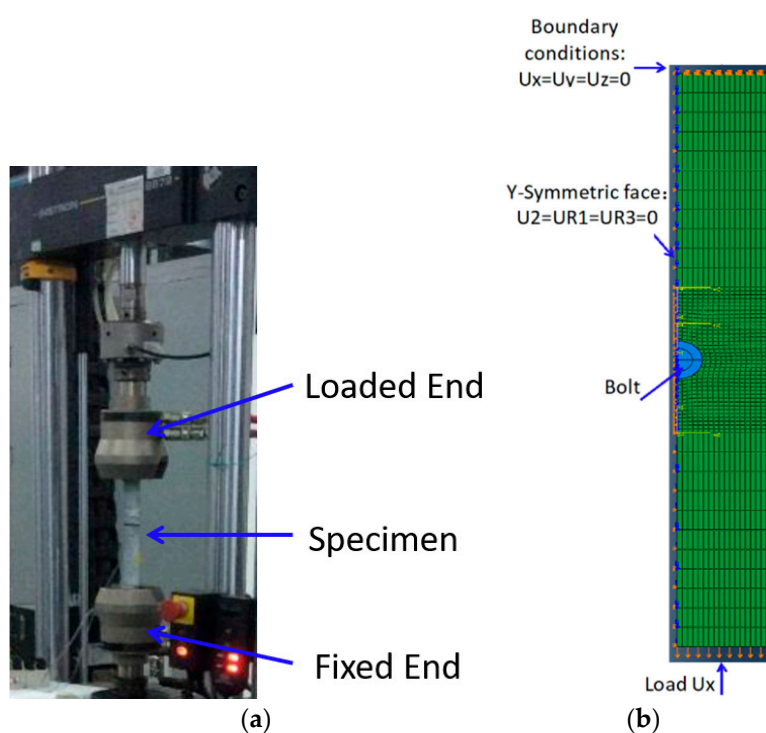Figure 2a,b show the experiment and diagrammatic sketch of numerical model, respectively.

Figure 2. Diagrammatic sketch: (**a**) Experiment; (**b**) Numerical model.

Figure 3 shows the comparison of experiment and simulation. The two bearing stress curves show an excellent agreement. The results indicate that the numerical model has sufficient accuracy to reflect the deformation process of bolted joint.
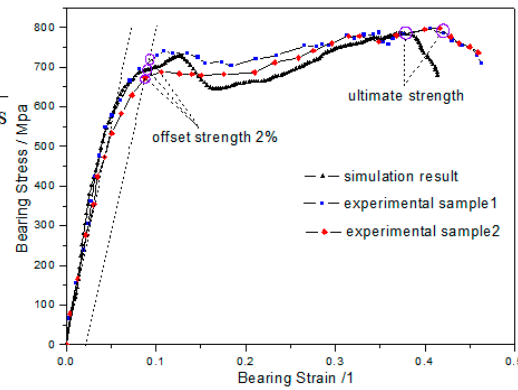
Figure 3. Comparison between experiment and simulation.

4. Dynamic Model

The composite material has strain rate effect under high speed loading. It needs to consider the effect of strain rate effect on the strength parameter. Therefore, assume the strength S of the T800/QY8911 consists of two parts:

$$S(\dot\varepsilon) = \alpha + \beta\dot\varepsilon^\gamma \tag{1}$$

where α is the initial strength at the reference strain rate, β and γ are modification items of strain rate effect.

Through testing on Hopkinson Bar, we obtain the parameters of the strain rate effect, as shown in Table 2. The strengths and modulus of the other directions are not strain-rate-dependent.

Table 2. Parameters of strain rate hardening.

Material Property	α	β	γ
E_{22t} (GPa)	15.5	−0.2	0.63
E_{22c} (GPa)	6.7	1.44	0.2
X_t (MPa)	2707.04	0.0000568	2.5
X_c (MPa)	19.9	−0.29	0.60
Y_c (MPa)	212.0	3.97	0.48

Then dynamic compression simulation is conducted. Figure 4a shows the simulation results and indicate that the strain rate effect has obvious influence on dynamic compression yield strength and ultimate strength of composite single-bolted joint. Strain rate hardening increases the carrying capacity of bolted joint. Figure 4b shows the deformation mechanism. The main damages are 0^0 sublayer buckling and fiber breakage caused by extrusion.
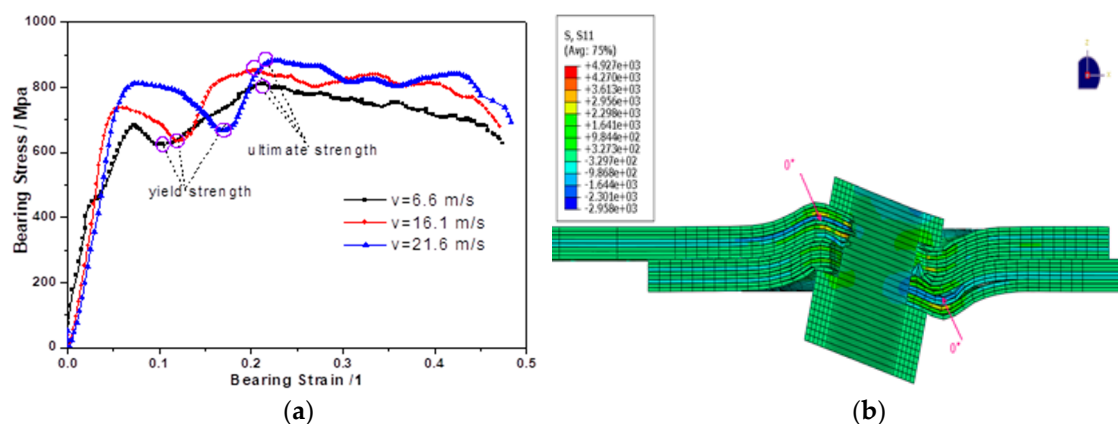

(**a**)

(**b**)

Figure 4. Simulation results: (**a**) Bearing stress-strain curve under different strain rates; (**b**) Deformation schematic under v = 2.16×10^1 m/s.

5. Conclusions

This study investigates the dynamic strength of the composite joint. Using finite element technique, we present a three dimensional progressive damage model based on the theory of continuous damage mechanics for composite laminates to be used for composite single-bolted joint is presented. Under dynamic compression loading, the yield strength and ultimate strength increase with the increasing load rate due to strain rate effect. The significant damages are fiber breakage and buckling in 0^0 sublayer.

Author Contributions: Y.C. did the experiments; Z.Y. did the simulation and analysis; P.X. guided all work.

Conflicts of Interest: The authors declare no conflict of interest.

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