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THE FINITE ELEMENT MODELLING OF BOLTED STRUCTURE BETWEEN SELECTIVE LASER MELTING ALUMINIUM AND COMPOSITE PLATES

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Abstract

The multi-bolt joint of SLM aluminum and composite under tensional load was analyzed via numerical simulation and experiment. Damage initiation and progression in the structure was present in 3D FEM based on the progressive damage analysis (PDA), and the bolt load distributions as well as the failure loads and modes were compared with the physical test. It is found that there was little difference of the failure loads predicted by test and FEA based on the UMAT subroutine including Ductile Damage for SLM aluminum and Hashin criteria for CFRP, together with the fracture stain to stress triaxiality curve approximated by the authors. Besides, the failure modes are both pulling out illustrated in FEA and experiment. The method assessed in this study has enough accuracy to satisfy the application requirement for such an engineering problem.

Keywords: Composite; Joint; Ductile Damage; Hashin Criteria

1. General Introduction

At present, mechanical connection is still the main connection mode of advanced aeronautic spacecraft, and metal component and composite laminate connection structure is the common structure form in the structure of the aircraft, is the hub of the whole structure load transfer, the damage of the whole structure often originates from the connection structure, according to statistics, more than 70% of the structural damage of the aircraft occurs in the connection area[1]. There are many factors affecting the strength of mechanical connections between composites and metals, and many researches have been done at home and abroad.

In the aspect of composite bolt connection structure, researchers at home and abroad have carried out progressive damage analysis and research on composite bolt connection structure. Thoppul et al. [2] has summarized the research progress of mechanical fiber-reinforced composite bonding strength. Garnich and Akula[3] generalize existing material degradation models. Tan[4] used two-dimensional progressive damage method to study the failure behavior of perforated plate under tensile load. Dano et al. [5] A two-dimensional progressive damage model was established by using ABAQUS to predict the response of composite laminates loaded with pins. Camanho and Matthews[6] analyzed the three-dimensional finite element model of pin-loaded composite orifice plates in ABAQUS. Kishore et al.[7] analyzed the 3-D progressive damage model of the connection structure of multi-pin glass fiber/ epoxy resin composite laminate. McCarthy et al. [8] studied the effect of bolt-hole clearance on the load distribution and failure mechanism of multi-nailed double-shears joint. Olmedo and Santiuste[9] used 3-D progressive damage analysis to study the failure behavior of single-lap bolted composite connector. Based on the theory of energy damage evolution, using Hashin failure criterion[11] and stiffness reduction caused by damage, the progressive damage and failure mode of composite bolt connection were studied by using Abaqus-UMAT user material subroutine, and the influence of width-diameter ratio and end-diameter ratio on the bearing capacity of bolt connection was analyzed. Zhu Honghong[12] improved the final failure judgment criterion of composite bolt joint. The estimation of plate-nail load of multi-nailed composite was studied by Zhang

In the aspect of metal-composite connection structure, the load distribution of metal-composite multi-pin connection was studied by experiments and numerical simulation. The structural finite element method (FEM) developed by Ekh Johan et al. [15-16] is used to simulate the multi-pin, single lap and composite aluminum alloy connections effectively, and the load distribution of fasteners is predicted accurately.

There are many structural forms of composite connection with metal in aircraft structure. There is little research on the factors that affect the mechanical properties of metal-composite hybrid structures at home and abroad. In this paper, the load distribution and failure mechanism of SLM aluminum alloy and composite bolt connector are numerically analyzed and tested. First of all, the distribution ratio of two series of four-pin single shear connections and its variation law with applied load are measured by experiment. Secondly, based on ABAQUS software, a three-dimensional finite element model is established, considering the actual factors of bolts and connected plates, adding friction, pre-tightening force and initial assembly gap, and considering SLM aluminum alloy and composite constitutive model, so as to verify the accuracy of the calculation model.

2. The method of progressive damage analysis

2.1 Failure Modes and Failure Criteria of Laminate

In failure analyses of composite structures a number of methods have been established that can be applied to describe the onset and propagation of failure [4]. These damage methods are generally developed according to theories of strengths as well as fracture mechanics. To accomplish a more accurate and realistic failure analysis, using a distinctive failure criterion is applicable to define every single damage mechanism independently. Basically, failure criteria are able to be classified to two types when considering the ability to separate the different failure modes integrated into the failure of composite materials: independent and interactive. The former one is simply to utilize and provide the failure modes without the effect of stress interactions in the failure mechanisms. In contrast, the latter one performs in a reverse way, as the stress interactions are considered while the failure mode is not given.

There exist various failure criteria for in-plane failure including the maximum stress, maximum strain, Tsai-wu, Tsai-Hill and Hashin. Albeit the maximum stress and Tsai-Hill have the consideration of different stress status and the interactions, these criteria do not describe the failure modes clearly . However, the Hashin failure criteria predict the damage modes including fibre tension, fibre compression, matrix tension, and matrix compression. Due to the accuracy, Hashin criteria have been widely used in the industry, and Abaqus contains an in-built evolution law to assess the damage onset and progression using Hashin criteria and fracture energy las respectively.

Hashin initiation criteria can be expressed by the following general forms :

Fibre failure mode in tension: $\widehat{\sigma_{11}} \geq 0$

$$e_f^2 = (\frac{\widehat{\sigma_{11}}}{X_T})^2 + (\frac{\widehat{\tau_{12}}}{S_{12}})^2 \tag{1}$$

Fibre failure mode in compression: $\widehat{\sigma_{11}} < 0$

$$e_f^2 = (\frac{\widehat{\sigma_{11}}}{X_C})^2 \tag{2}$$

Matrix failure mode in tension: $\sigma_{22} > 0$

$$e_m^2 = (\frac{\widehat{\sigma_{22}}}{Y_T})^2 + (\frac{\widehat{\tau_{12}}}{S_{12}})^2 \quad (3)$$

Matrix failure mode in compression: $\sigma_{22} < 0$

$$e_m^2 = \frac{1}{Y_C}\left[\left(\frac{Y_C}{2R}\right)^2 - 1\right]\widehat{\sigma_{22}} + \left(\frac{\widehat{\sigma_{22}}}{2R}\right)^2 + (\frac{\widehat{\tau_{12}}}{S_{12}})^2 \quad (4)$$

$$e_s^2 = (\frac{\widehat{\tau_{12}}}{S_{12}})^2 \quad (5)$$

Where:

X_T represents the material longitudinal tensile strength;

X_C represents the material longitudinal compressive strength;

Y_T represents the material transverse tensile strength;

Y_C represents the material transverse compressive strength;

S_{12} represents the material longitudinal shear strength;

R represents the material transverse shear strength;

$\widehat{\sigma_{11}}$, $\widehat{\sigma_{22}}$, $\widehat{\tau_{12}}$ are the components of the effective stress tensor which are utilized to evaluate the initiation criteria and calculated from:

$$\hat{\sigma} = M\sigma \quad (6)$$

Where σ is the nominal stress and M is the damage operator.

$$M = \begin{bmatrix} \frac{1}{(1-d_f)} & 0 & 0 \\ 0 & \frac{1}{(1-d_m)} & 0 \\ 0 & 0 & \frac{1}{(1-d_s)} \end{bmatrix} \quad (7)$$

In the above equation, d_f, d_m, and d_s are damage variables that characterize fibre, matrix, and shear damage, which are derived from damage variables d_{ft}, d_{fc}, d_{mt} and d_{mc} corresponding to the four modes discussed previously, and they can be defined as:

$$d_f = \{\begin{matrix} d_{ft} \;\; if\; \widehat{\sigma_{11}} \geq 0 \\ d_{ft} \;\; if\; \widehat{\sigma_{11}} < 0 \end{matrix} \quad (8)$$

$$d_m = \{\begin{matrix} d_{mt} \;\; if\; \widehat{\sigma_{22}} \geq 0 \\ d_{mt} \;\; if\; \widehat{\sigma_{22}} < 0 \end{matrix} \quad (9)$$

$$d_s = 1 - (1-d_{ft})(1-d_{fc})(1-d_{mt})(1-d_{mc}) \quad (10)$$

Hence, the damaged material elasticity matrix can be expresses as:

$$C = \frac{1}{D}\begin{bmatrix} (1-d_f)E_1 & (1-d_f)(1-d_m)\nu_{21}E_1 & 0 \\ (1-d_f)(1-d_m)\nu_{12}E_2 & (1-d_m)E_2 & 0 \\ 0 & 0 & D(1-d_s)G \end{bmatrix} \quad (11)$$

Where $D = 1-(1-d_f)(1-d_m)\nu_{12}\nu_{21}$, E_1 and E_2 are the Young's modulus in the fibre direction and matrix direction respectively. G represents the shear module, and ν_{12} and ν_{21} are Poisson' ratios. Failure appears when one or more of the failure indices (e_f^2, e_m^2, and e_s^2) generates a value equal or greater to one. The dominating failure mode of a specific ply at the i^{th} displacement step is determined by the biggest value of the all the failure index, which is considered to activate the material property degradation law.

2.2 Progressive failure analysis

Based on ABAQUS platform, UMAT subprogram is used to introduce the material failure criteria and stiffness degradation scheme to realize the progressive damage analysis of the connecting structure. See Figure 3 for the flow chart.

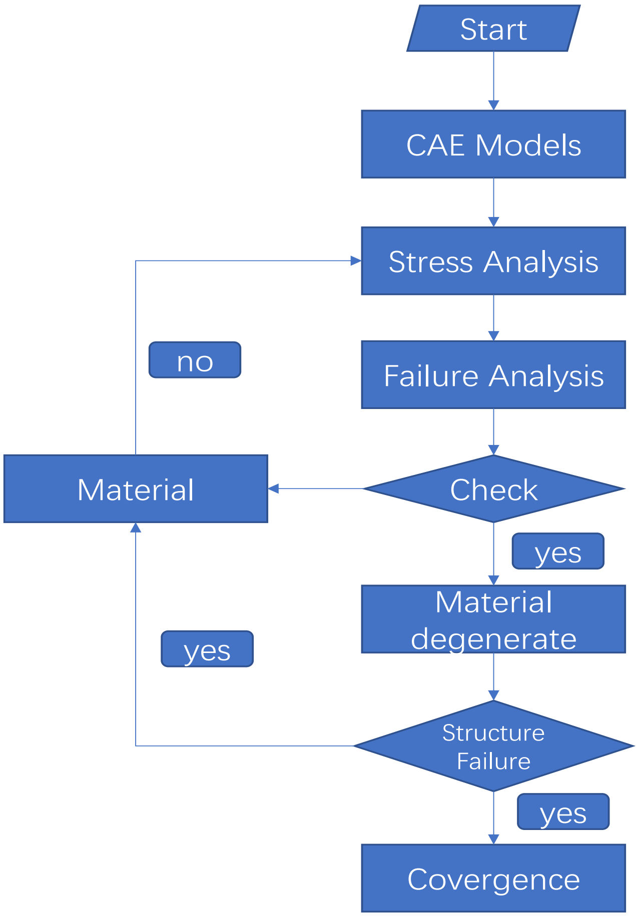

Fig.3 Progressive damage analysis flow

In the process of progressive damage analysis, the external load is applied by step loading. The following steps are mainly used in each load step:

1)The finite element model of the connection structure is established.

2)Calculate the stress at the integral point of the material.

3)The stress at the integral point of material is brought into the damage criterion of the corresponding material to judge whether the material is damaged or not.

4)If the material is damaged, the stiffness of the material is degraded according to the preset scheme. The finite element equilibrium equations are re established according to the degradation properties of materials. Repeat the stress calculation, damage judgment and stiffness degradation process before the structure no longer produces new damage.

5) Load increase goes to the next load step, repeat step 1), and cycle until the connection structure

finally fails.

6) The ultimate strength of the connecting structure is obtained by reading the highest point of the displacement load curve (at tangent level).

3. The experimental progress

3.1 The tested specimen

The test piece is in the form of metal-composite single lap, with two rows of four-pin connections in longitudinal direction.

The upper plate is carbon fiber/ double horse resin-based thermosetting composite laminate, the laminate is[45/0/ - 45/45/90/ - 45/0/90] S, the single layer thickness of prepreg is 0.125mm, the data of mechanical properties of materials are shown in Table 1. The fasteners are made of titanium alloy shear-type countersunk head high-lock bolts. The elastic modulus and Poisson ratio of titanium alloy are 109 GPa and 0.29 GPa respectively.

Table 1 Mechanical properties of T300/BA9913

	T300/BA9913
E_1(GPa)	135
E_2(GPa)	8.8
μ_{12}=μ_{13}	0.33
μ_{23}	0.45
G_{12}= G_{13} (GPa)	4.47
G_{23}(GPa)	3.034
X_T(MPa)	1548
X_c(MPa)	1226
Y_T(MPa)	55.5
Y_C(MPa)	232
S_L=S_T(MPa)	89.9

The bottom plate of the connecting structure is SLM aluminum alloy, and the data of the mechanical properties of the materials are shown in Table 2.

Table 2 Mechanical properties of SLM aluminum

	SLM
E(GPa)	62.7
μ	0.3
X_0(MPa)	180
$X_{0.0255}$(MPa)	315

Strain electrometric method is used to measure the variation of strain around the nail hole with load. A row of strain gauge is pasted at the four section positions of the test piece, and the strain arrangement is shown in Figure 4.

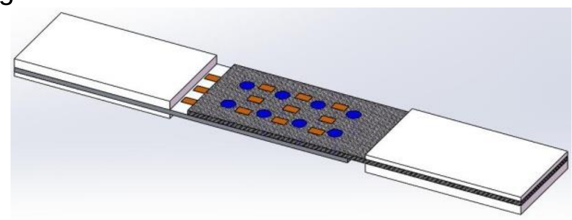

Fig.4 Specimen and the positions of strain gages

As shown in Figure 5. The two ends of the test piece are clamped and aligned to prevent the phenomenon of eccentric tension. The constant rate loading control is adopted in the test, and the loading rate is 1 mm / min. In the test, the pre tension should be carried out first, and the stability of strain gauge should be tested, so that the deviation of each strain value measured by three times of pre tension is less than 5%, and the pre tension load can be unloaded when it reaches 50% of the expected failure load. During the test, the strain, load and displacement data of the specimen are recorded in real time, and more than 500 sampling points are ensured for each specimen during the tensile process.

Fig.5 Experimental installation of specimen

ABAQUS software is used to establish the three-dimensional finite element model. The finite element model and load constraint of the test piece are shown in Figure 6. One end of the model is completely constrained, and the longitudinal tensile displacement load is applied at the other end, and the displacement of the other two directions is constrained at the same time.

The model consists of three parts: SLM plate, titanium alloy bolt and composite plate. Continuous shell element (sc8r) is used to simulate composite plate, solid element (c3d8r) is used to simulate SLM plate and bolt. Hashin criterion and toughness criterion are used to simulate progressive damage of composite plate and SLM plate respectively. The bolt preload is 4kn, and the friction coefficient between SLM plate and composite plate is 0.1.

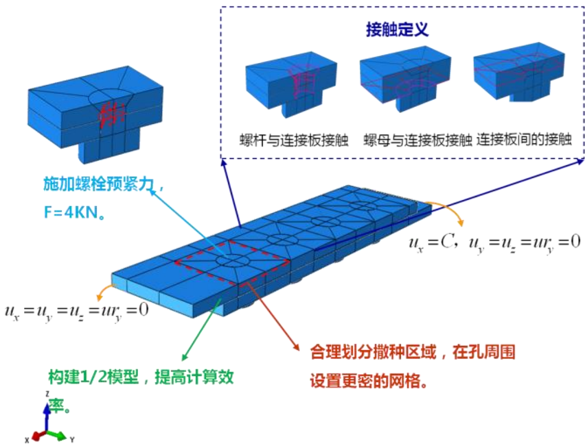

Fig.6 Finite element model of composite-SLM aluminum multi-bolt joint

3.2 Ultimate load and failure mode

After progressive damage analysis of group A, the load-strain curve is obtained, as shown in Figure 9. Compared with the test results, it can be found that the ultimate load of the structure predicted by progressive damage analysis is 19.09kn, and the test result is 19.46kn.

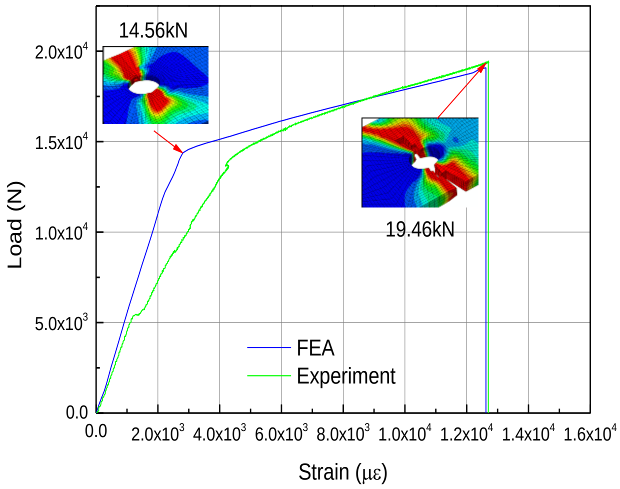

Fig.7 Load-strain curve of the specimen

It can be seen from Figure 7 that the load-strain curve of multi pin connection can be divided into the following two parts: before 14.56kn, the load-strain curve shows linear elastic characteristics, the damage area is small, and the load at the inflection point of numerical analysis and test curve is close; After reaching 14.56kn, the axial tensile stiffness of the structure decreases due to material degradation, and the slope of the load-strain curve obviously decreases, but it still increases in a nearly linear line until the failure load is reached. At this time, the damage area gradually increases until the structure fails.

It can be seen from Fig. 8 that the failure mode obtained from the test and the three-dimensional finite element model is net section fracture, and the fracture position is consistent.

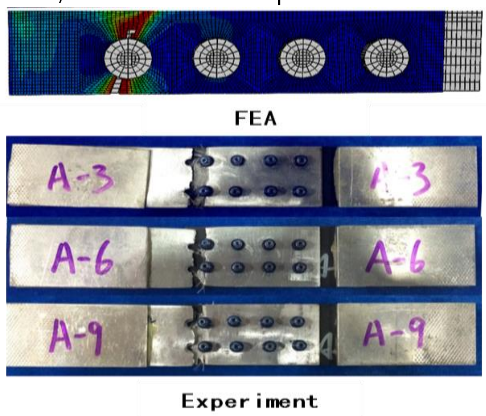

Fig.8 Comparison of failure modes between FEA and Experiment

4. Conclusions

Based on the researches presented in previous chapters, it can be concluded that:

(1) Based on continuum damage mechanics and toughness criterion, the progressive damage analysis model of connector is established. By comparing with the load-strain curve obtained by electrical measurement method, it shows that the three-dimensional finite element model constructed in this paper is reasonable.

(2) The results show that the errors of the nail load distribution ratio and the measured values are within 10%, which can meet the accuracy requirements of engineering application.

(3) The method of fracture strain and stress triaxiality curve fitting in this paper is reasonable and feasible. The ultimate load and failure mode predicted by the three-dimensional finite element model

of progressive damage failure analysis method based on UMAT subroutine of ABAQUS software are consistent with the test results. This method has reference value for similar structures in engineering.

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6. Copyright Statement

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