Influence of stacking sequence and number of pin on load distribution of composite joints

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Abstract. In this paper, finite element model of multi-pin composite joint is established. Matlab program is adopted to calculate equivalent material properties of composite laminate. Load distributions of double-lap composite joint are investigated, and simulation results show excellent agreement with experiments. By using equivalent material properties method, influence of stacking sequence on load distribution is studied. Equivalent material properties method could provide a simple and efficient method for optimizing load distribution of multi-pin composite joint.

1. Introduction

Advanced composite materials with fiber reinforcement are widely used in aerospace, shipbuilding and civil engineering due to their high stiffness and strength to weight ratios [1].

There are many methods for determining load distribution in bolted joints. Analytical and finite element methods are common means for load distribution investigation of multi-pin joint. Tate [2] developed a spring-based method for double-lap joints manufactured by isotropic materials. Nelson [3] extended spring-based method to composite joints. All these two mentioned methods are analytical ones. In recent years finite element method is widely used to determine load distribution of multi-pin joint. Fan [4] used a complex variable approach, while McCarthy [5] used three-dimensional finite element method.

Although three-dimensional finite element analysis is relatively simple, build of finite element (FE) model is complicated. Composite laminate material properties need to be given layer by layer, which need a lot of time. In this paper, a new FE model is established for load distribution investigation of multi-pin composite joint. In FE model, composite laminate is treated as one whole plate whose equivalent engineering material properties including modulus and Poisson's ratio are calculated by Matlab program developed by author. Matlab program is verified by experiments in literature [6]. To test and verify the new FE model, load distributions of double-lap and multi-bolt composite joints are investigated. At the same time FE model whose composite laminate material properties are given layer by layer is also created. Simulation results of two FE models and experimental results are compared with each other. At last, influence of stacking sequence and number of pin on load distribution of joint are investigated and load distribution of multi-pin composite joint is optimized.
2. Equivalent material properties of laminates

A new FE model is developed in this paper, composite laminate in FE model is treated as one whole plate. Equivalent material properties of laminate are calculated by Matlab program according to equations in literature [7].

| $E_{11}$ (GPa) | $E_{22}$ (GPa) | $G_{12}$ (GPa) | $G_{13}$ (GPa) | $G_{23}$ (GPa) | $\nu_{12}$ | $\nu_{13}$ | $\nu_{23}$ |
|----------------|----------------|----------------|----------------|----------------|------------|------------|------------|
| 140            | 10             | 10             | 5.2            | 5.2            | 3.9        | 0.3        | 0.3        | 0.5        |

To verify program of equivalent material properties, a numerical example is chosen in literature [6]. In numerical example the composite laminate is manufactured from HTA/6376, a high-strength carbon fiber–epoxy material currently used in primary structures in the European aircraft industry. The unidirectional stiffness properties are shown in table 1. Equivalent material properties of laminate are shown in table 2.

| Equivalent material properties | $E_x$ (GPa) | $E_y$ (GPa) | $E_z$ (GPa) | $G_{xy}$ (GPa) | $G_{xz}$ (GPa) | $G_{yz}$ (GPa) | $\nu_{xy}$ | $\nu_{xz}$ | $\nu_{yz}$ |
|-------------------------------|-------------|-------------|-------------|--------------|--------------|--------------|------------|------------|------------|
| Experiments                   | 54.25       | 54.25       | 12.59       | 20.72        | 4.55         | 4.55         | 0.309      | 0.332      | 0.332      |
| Matlab                        | 54.249      | 54.249      | 12.587      | 20.722       | 4.550        | 4.550        | 0.309      | 0.3326     | 0.3326     |
| Error (%)                     | 0.002       | 0.002       | 0.024       | 0.010        | 0.000        | 0.000        | 0.181      | 0.181      | 0.181      |

Table 2 indicates that the error of equivalent material engineering constants calculated by Matlab program is quite small, so that the program can be used to calculate the material properties of three-dimensional laminate.

3. Numerical study

In this section, load distributions of multi-bolt composite joints are investigated by equivalent material properties (EMP) FE model. To verify the FE model, double-lap joint model is established. Simulation results are compared with experiments in literature [5].

3.1. Geometry, FE model and boundary condition

As shown in figure 1, the joint has three bolts and all the bolts are in single-column. Geometric parameters can be seen in figure 1. Diameter of bolt is 8mm. Composite laminates have stacking sequences $[45^\circ /0^\circ /-45^\circ /90^\circ ]_{ns}$, thickness of each ply is 0.13mm. Unidirectional stiffness properties are shown in table 1. By using Matlab program, equivalent material properties of laminates can be obtained. The titanium bolt was modeled with isotropic material properties, with material constant $E_x=110$GPa, $\nu_b=0.29$. 

![Figure 1. Joint configurations with three pins (mm): double-lap.](image-url)
According to geometric parameters of joints, two FE model are established in ABAQUA shown in figure 2. In FE model, bolt and washer are simplified as one component. Bolt torque is 0.5Nm. To compare with experiments in literature [5], Bolt–hole clearances in FE model are 0. The laminates are modeled using three-dimensional solid elements with reduced integration which is C3D8R (8-node linear brick, reduced integration, hourglass control) in ABAQUS. Double-lap joint is symmetrical with respect to X-Z and X-Y plane, so one quarter of joint is modeled. Boundary conditions are shown in figure 2. One end of joint is fixed, and displacement load in X direction is carried out on the other end of joint.

### 3.2. Model validation

Composite joint is a contact FE problem, and material properties of three-dimensional (3D) composite laminate are usually given layer by layer which called as 3D FE method. To compare 3D FE method and EMP method, two FE models are established, and simulation results and experimental results [5] of load distribution are shown in figure 3. Simulation results show an excellent agreement with experiments.

**Figure 2.** Mesh of FE model and boundary conditions: double-lap.

**Figure 3.** Load distribution comparison of experiments, 3D FE method and EMP method. (a) Experiments [5] (b) 3D FE method (c) EMP method.
As shown in figure 3, stress distributions of bolts are quite different. Load distribution difference results in the reduction of joint efficiency.

3.3. Influence of stacking sequence, number of bolt and interference
In this section influences of stacking sequence, number of bolt and interference on load distribution are investigated. Firstly, four stacking sequence programs are design which can be found in table 3. Equivalent material properties of four laminates are shown in table 4.

Table 3. Stacking sequence program.

| Number | Stacking sequence       | Ratio (%) |
|--------|-------------------------|-----------|
|        |                         | 0° | 90° | ±45° |
| Joint1 | [±45/90/±45/90/±45]S    | 0  | 40  | 60  |
| Joint2 | [±45/0/90/±45/0/90/±45]S| 20 | 20  | 60  |
| Joint3 | [±45/0/90/±45/0/90/±45]S| 40 | 20  | 40  |
| Joint4 | [±45/0/±45/±45/0]S      | 60 | 0   | 40  |

Table 4. Equivalent material properties of laminate for different stacking sequence program.

| Number | Equivalent material properties |
|--------|--------------------------------|
|        | $E_x$ (GPa) | $E_y$ (GPa) | $E_z$ (GPa) | $G_{xy}$ (GPa) | $G_{xz}$ (GPa) | $G_{yz}$ (GPa) | $\nu_{xy}$ | $\nu_{xz}$ | $\nu_{yz}$ |
| Joint1 | 25.06       | 67.79       | 12.24       | 23.83          | 4.29           | 4.81           | 0.26       | 0.37       | 0.12       |
| Joint2 | 48.64       | 48.64       | 12.59       | 23.83          | 4.55           | 4.55           | 0.38       | 0.30       | 0.30       |
| Joint3 | 71.40       | 46.87       | 12.53       | 17.62          | 4.68           | 4.22           | 0.31       | 0.33       | 0.39       |
| Joint4 | 92.33       | 21.50       | 11.88       | 17.62          | 4.94           | 4.16           | 0.65       | 0.14       | 0.43       |

Figure 4. FE model of four-bolt joint.

FE model is shown in figure 4. Geometric parameters are similar to figure 1. Boundary condition is similar to section 3.1. Load bearing ratio of bolt is shown in figure 5. Here load bearing ratio bolt is defined as bolt load is divided by sum of all bolt load which represents joint efficiency. It can be seen from figure 5 that with increase of 0° ply, nonlinear of load bearing ration curve decreases.

Figure 5. Load distribution of four-bolt joint.
Secondly, load distributions of two types of joint with four and five pins are investigated. Stacking sequence is same as joint 3. Load bearing ratios of every pin are shown in figure 6. Figure 6 shows that difference between maximum and minimum load bearing ratio in four-pin and five-pin joint are 10.98% and 15.79%, respectively. It presents that the more pins there are, the more nonuniform of load distribution is.

![Figure 6. Comparison of load distribution of four-pin and five-pin.](image)

At last, effect of interference between bolt and bolt-hole on load distribution is studied. It is known that proper interference could improve joint strength. 1% interference is the best choice for composite mechanical fastened joint. In this section four interference programs are shown in table 5. Stacking sequence of composite laminates in joint is according to Joint 3. Load bearing ration is shown in figure 7.

| Number | Interference | 1^a | 2^b | 3^c | 4^d |
|--------|--------------|-----|-----|-----|-----|
| A      |              | 0   | 0   | 0   | 0   |
| B      |              | 0   | 0.25% | 0.25% | 0   |
| C      |              | 0   | 0.5% | 0.5% | 0   |
| D      |              | 0   | 1.0% | 1.0% | 0   |

**Table 5. Interference for four-pin double-lap joint.**

![Figure 7. Load distribution of joint with different interference.](image)

As shown in figure 7, uniformity of load distribution using interference C is the best, and nonlinear of interference A is the worst.

**4. Discussion and conclusions**

Composite mechanical fastened joint is widely used in various trades and industries. Load distribution investigation of multi-pin composite joint quite interesting.
Based on EMP method, FE model of double-lap is established, simulation results have an excellent agreement with experiments. Error of simulation result is caused by simplification of bolt and washer, which are simplified as one whole bolt. But the error is small, and the accuracy is good enough. Compared with 3D FE model, calculation accuracy based on EMP method is higher. Meanwhile, since laminate is treated as one whole plate, complication of model building is decreased greatly.

Influences of stacking sequence, number of bolt and interference on load distribution are investigated, respectively. From the simulation results we can see that increase of 0° ply could make load distribution more uniform; increase of bolt will result in load distribution more nonuniform. But 0.5% interference will made load distribution uniform, and joint efficiency could be improved effectively.

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