Study on the Pin-load Distribution of Composite Joints with Protruding-head Bolts Based on Cumulative Damage

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Abstract. This paper presents the investigation of the pin–load distribution law of composite mechanical joints with protruding-head bolts based on the theory of composite cumulative damage. The three-dimensional finite element analysis have been carried out by using the software ANSYS for the composite plates connected with protruding-head bolts. The friction on the contact surfaces of the composite joints, and the nonlinearity of the contact state and the preload on the bolts have been considered. The effect law of cumulative damage on the pin-load distribution of multiple-bolted joints has been achieved. The results manifest that the proportion of the pin-load distribution varies with the external load and is slightly different at diverse stages of loading considering the cumulative damage of the composite materials, that pin load at both ends is greater than in the middle.

1. Introduction

Composite materials have been widely used in aerospace, automobile, shipbuilding and other fields because of their excellent mechanical properties. The joint forms of bolt fastening and riveting are widely adopted in the composite laminates. Compared with the rivet connection which is not easy to disassemble and repair, bolt connection is more commonly employed. Protruding-head bolts and countersunk bolts are commonly used bolt types. In general, the bearing force of the protruding-head bolts is larger than that of the countersunk ones. The composite materials around the bolt hole of the connection will be crushed and destroyed due to their low compressive strength when the structure is subjected to a larger load, which is the main failure mode of the structure. For the common multiple-bolted joint, it is unfavourable to the redistribution and homogenization of the pin load due to the brittle properties of the composite, which will adversely affect the strength of the multiple-bolted joint. The joint strength of composite materials has a significant influence on the safety and service life of aviation structure. To determine the pin-load distribution of multiple-bolted joints is the basis for calculating the strength of the composite structure.

For the composite structures displays complexity in the aspects of transferring load, configuration and boundary condition, and it is difficult to solve by analytic method, so they are mainly solved by test method and finite element method. When static analysis was carried out on the mechanical joints of composite structures, the existing research work usually only considered the initial load distribution state, did not consider the effect of the degradation of material properties on pin load due to material damage, and ignored the change of the load distribution with the applied load [1-3]. Because of the brittleness of the composite material, it is unfavourable to the redistribution and homogenization of the
pin load, and as the load increases, the bearing damage of the composite gradually accumulates, which will result in the change of the pin-hole bearing stiffness and affect the overall load distribution.

The previously established experimental results have shown that the pin-load distribution will change with the external load when the materials are damaged [4-10]. In view of this, in this paper, the three-dimensional finite element analysis would be carried out by using the software ANSYS for the two composite plates connected by 3(row) ×2(column) protruding-head bolts. The friction between the composite plate and the bolt, between the composite plate and the composite plate, and the nonlinearity of the contact state and the preload on the bolts would be considered. The effect of cumulative damage on the pin-load distribution would be investigated.

2. Pin-load analysis model
The experimental model [4] was selected, and the test configuration was shown in figure 1. A three-dimensional finite element model was made to calculate the pinning distribution of composite joints with multiple bolts by using the commercial finite element software ANSYS. Compared with the composite materials, the stiffness of the metal material was larger, so the bolts, nuts and gaskets could be simplified to a whole part. The bolts meshed with the 3-D 8-node structural solid element SOLID185, and composite plates were meshed with the 3-D 8-node layered solid SOLID185 with the mapping method, respectively. The influence of contact friction and preload was considered in the model, and the contact element type between the pin-hole, the pin head-plate and the plate-plate were CONTA173, and the target element type was TARGET170. The magnitude of the frictional force between the contact surfaces was controlled by Coulomb friction, and the friction coefficient was 0.2; the preload force was applied by defining the preload element PRETS179, the preload torque exerted on the three-dimensional model was consistent with the test in the literature [4]. The three-dimensional finite element mesh model of the joints was presented in figure 2. The load applied on the modal was consistent with the test, the one end of the model in 6.24mm thickness was fixed, and the uniform displacement of the other end of the model in 3.12mm thickness was executed.

3. Pin-load analysis process

3.1. Cumulative damage analysis method
In the process of loading, the fibers and the matrix of the composite materials were damaged, which results in the deterioration of the mechanical properties of the composites. In order to objectively reflect the degradation of material properties, it was necessary to consider the degradation of material properties during calculation. The cumulative damage theory of composites was widely used to deal with the degradation of material properties. When the numerical method was proposed to simulate the cumulative damage process, firstly, it was indispensable to determine whether the material was damaged or not, then to introduce the variable to quantitatively describe the damage, and to associate this variable with the macroscopic mechanical behaviour of the material, that was, to establish the constitutive relation of the material damage, and to exert the degradation of the material properties [10]. The whole analysis process of the composite joints was consistent with figure 4 in the literature [11].
3.2. Material damage criterion
A reasonable failure criterion was one of the key factors affecting the numerical simulation precision of cumulative damage of composite structures. There were more than dozens of kinds of strength theories of composite materials[12-15], the most commonly used criteria in composite structure analysis included Hashin’s criterion, Tai-Hill criterion and maximum stress criterion and others. Since the Hashin’s three-dimensional failure criterion had been successfully developed by many researchers, it was well applied in the damage analysis of composite joint structures, and could clearly judge a variety of damage forms in the process of damage, which was simple in form and easy to use. The model, therefore, adopted the Hashin’s criterion [10] considering delamination damage to complete the analysis.

3.3. Criteria for degradation of material properties
With the increase of load, the fiber and the matrix composed of composites were damaged and the stiffness of the structure was decreased, so the damage could be characterized by the degeneration of the elastic constants of the material properties. Generally used degradation of material properties, assuming that for an element if a failure occurred, the degradation of material properties affected only this element, not other elements. The choice of parameter degradation method had a great effect on the ultimate strength of the laminated plate.

The paper [16] combined with the compressive strength test results of T300/QY8911 single-lap and single-bolted composite Joint, verified the validity of the material performance degradation criterion proposed by Camanho and Matthews [17]. This computational model adopted Camanho degradation criterion [11].

4. The calculation result and discussion

4.1 Calculation results
The finite element method was employed to estimate the pin load by obtaining the bearing force of the pin-hole contact region along the loading direction. The load-displacement curve of 3 (row) × 2 (column) protruding-head bolts with the cumulative damage method calculated was shown in figure 3. As could be seen from figure 3, the load-displacement curve was linearly related when the load is small. With the increase of load, the matrix and the fiber were damaged, and the load -displacement curve appeared non-linear, which accords with the experimental results.

Figure 4 showed the numerical calculation results of the pin-load distribution proportion of composite joints.

![Figure 3. The Load displacement curve of composite joints](image1)

![Figure 4. Pin-load distribution on double-lap of multiple-bolted joints](image2)

As could be seen from figure 4:
(1) Considering the cumulative damage of composite materials, the pin load proportion was not a fixed value, but it varied with the change of the external load, and when the load was small, the change...
of the pin load was not obvious. While the load was large, the proportion of the pin load was transformed greatly.

(2) Throughout the loading process, the pin load of the row1, 3 were basically the same; the distribution proportion was significantly higher than the row 2, showing the law of "larger load at both ends, smaller in the middle".

(3) At the beginning of loading, the pin load of the row 1, 3 had increased, while the row 2 had decreased; then, the pin load proportion of three rows was stabilized; When the load was increased to a certain value, the pin load of the row1, 3 increased significantly, and that of the row 2 drops significantly. With the further increase of load, the pin load distribution of the row1, 3 and of row2 was changed in reverse direction, and finally the proportion of each row tended to be evenly distributed.

It was that the friction force of contact surface of the structural was much larger than bearing force on the pin in the initiation of loading, and the external load was mainly used to overcome the friction force, and the change of the load distribution was obvious. With the increase of the load, the matrix of the composite laminates was damaged first, and the change of the pin load was not distinct, which showed that the matrix damage had less influence on the distribution of the pin load. When the load continues to increase, the fiber in the composite laminates was damaged, the proportion of the pin load was changed clearly, and the row2 was gradually reduced, while the pin load of the row 1, 3 increased gradually. As the structural approaches failure, the pin load tended to be uniform.

4.2 Failure process of laminated plates

Figure 5 showed the damage extension process the matrix of the laminated plates. At different loading levels, each layer occurred kind of main damage forms coexisting with multiple other damage forms. When the external load reaches 56kN, the matrix of laminated plates near the holes of the row 1, that was, the contacting part with the bolts, yields bearing damage. With the increase of load, the matrix around the holes of the row 3 had been damaged, and then so had been the matrix around the holes of the row 2. In all loading process, the damage of the matrix was expanded in two directions along the extrusion and the plate width. But the expansion speed of extrusion direction was smaller than that along the width direction of the plates, in which the number of elements with matrix failure was the most near to 1-row holes, followed by the 3-row holes, and at least the elements with matrix damage was near 2-row holes.

![Figure 5](image-url)

Figure 5. The matrix damage expansion process of the laminated plates
The fiber damage expansion process of the laminated plates was given in figure 6. When the applied load increased to 73kN, a variety of damage models appeared including compressive damage and delamination damage of matrix and fiber. When the load was increased to 116kN, the fibers of the laminated plates around the 1-row holes, that was the part contacting with the bolts which were damaged by extrusion. With the increase of load, the fibers around the 3-row holes were also damaged, and then the fibers around the 2-rows holes were damaged. When the load was increased to the 154kN, most of the fibers around the 1-row holes had been damaged and lost their carrying capacity. During the whole loading process, the damage of the fibers was expanded in two directions along the extrusion and the plate width. But the expansion speed of the extrusion direction was smaller than the expansion speed along the width direction of the plates, in which the number of the elements with the fiber damage was the most near the 1-row holes, followed by the 3-row holes, and at least the fiber damage element was near the 2-row holes.

![Figure 6. The fiber damage expansion process of the laminated plates](image)

### 4.3 Discussion
As could be seen in figure 4, the fiber and the matrix in the composite materials did not appear to be damaged at the beginning of loading, and the proportion of the pin load was not changed with the increase of the load after overcoming the frictional force. When the load increased to a certain value, the matrix bearing damage occurred near the 1-row holes first, the stiffness degeneration made the compressive stiffness of the region decrease, and the compressive stiffness of the matrix increased with the increase of the load, which made the bearing stiffness decrease continuously, but it could be seen from figure 5 that the number of matrix-damage elements occurring in the pin-load stable phase was lower, and did not affect the pin-load redistribution.

As shown in the figure 6, with the increase of the load, in the initial phase of the fiber damage occurring, and the proportion of the 1, 3-row pin load was basically unchanged, but it did not cause the mutation of the pin-load proportion. It was that the initial damage region was small; the overall pin-load proportion in the degradation way with abrupt stiffness decline did not behave a sudden change. On the one hand, the bearing damage region expanded to reduce the overall bearing stiffness of the pin holes. On the other hand, the bearing stiffness of the bearing-damaged elements was increased because the stiffness degradation mode was amended by the abrupt descending of stiffness first and then
ascending. The result of the two-side interaction was that the bearing stiffness and the bearing proportion of the pin hole decreased slowly. In addition, with the increase of the fiber damage, the 1, 3-row pin-load distribution significantly changed, first rose and then fell. In the rising stage of the pin-load proportion, the fiber damage expanded faster and loading capacity weakened. The load was transferred to the middle-row pin, which resulted in the middle-row bearing damage and caused the pin-load proportion of the 1, 3 rows to reduce.

5. Conclusion
Based on the cumulative damage theory of composite laminates, this paper has studied the problem of the pin-load distribution of multiple-bolted mechanical joints of laminated plates, and concludes as follows:

(1) The results obtained by finite element method and the test results are quite close about load-displacement curve and the law of the pin-load distribution of the composite joints, which shows that the finite element model is feasible and has high accuracy.

(2) Considering the cumulative damage of the composite materials, the proportion of the pin-load distribution varies with the external load, and the pin-load proportion is slightly different at diverse stages of loading.

(3) As with the traditional method of pin-load analysis, the cumulative damage analysis technique of composite material is used to conclude that the proportion of the pin-load distribution in the whole loading process shows the law of "larger load at both ends, smaller in the middle".

6. References
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