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Research on Pin-load Distribution for Countersunk Joint Considering Accumulated Damage of Composite Laminates

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Abstract. The paper presents a numerical simulation about the damage process of the multiple countersunk bolted double-lap joints based on the cumulative damage theory which is widely used to estimate the mechanical strength of fastener joints, the Hashin's failure criterion, and the Tan's stiffness degradation model, and investigates the influence of the composite materials cumulative damage on the pin-load distribution. The numerical model of composite joints has been established in the commercial finite element software ANSYS to research the influence of the composite cumulative damage on the pin-load distribution, to assess the feasibility of integral analysis as well as to evaluate the error and rationality of traditional methods by applying the global analysis technology. The conclusions demonstrate that the results obtained with the method of composite cumulative damage considering properties degradation are close to those of conventional methods. The pin-load distribution is characterized by "Bolts at both ends bearing greater load, the central bolts bearing smaller load" during the whole loading process. Using conventional methods to study the pin-load distribution is easy and efficient to meet the needs of engineering application.

1. Introduction

Composite materials have been widely applied in the aircraft load-bearing structure owing to their excellent mechanical properties. The connection types between composite material components and other components are gluing, mechanical connection, and mixed connections primarily. The most common connection is a mechanical joint which possesses the characteristics of simple process, reliable connection, easy disassembly and maintenance, and transmitting heavy load. Unlike glued structures, in structures with bolted joints it is required to drill holes in the composite. The openings destroy the continuity of the fiber, result in stress concentration near the holes, and further impair the load-bearing capacity of the composite structures. The connection strength of composite materials directly affects the safety and service life of aviation structures. The stress concentration around holes is more serious than that of the metal structures due to the anisotropy of the composite material. Therefore, determining pin load is the basis for calculating the strength of the structures with the common multiple-bolted joints.

The methods of determining the pin-load proportion of composite materials with multiple-bolted joints mainly include the test method, analytical method and finite element method, respectively [1-4]. The brittle nature of the composite is not conducive to pin-load redistribution and homogenization, thus,

for the static analysis of the mechanical connection of the composite structures, the present research usually does not consider the effect on pin-load distribution due to material damage leading to its properties degradation under the external load, and only considers the initial state of the pin-load distribution, regardless of its changes with the applied load; In the ideal condition, the pin-load distribution remains essentially constant[1-8], however, this idealized result is obtained by an approximately linear analysis that does not consider the composite damage process. In fact, as the external load increases, the gradual accumulation of bearing and other damage will lead to changes of bearing stiffness around in pin-hole zone and affect the overall load distribution.
A series of experimental results show that the pin-load distribution will change with the change of the external load after the occurrence of pin-hole bearing damage. Therefore, it is necessary to consider the effect of the composite material on pin load after the damage. This paper intends to use three-dimensional cumulative damage model analysis technology, start from the overall analysis to study the effect of composite material cumulative damage on the pin-load distribution, reveal the feasibility of the overall analysis, and estimate the error and reasonability of traditional methods.

2. Cumulative damage analysis method

When exerting the numerical method to simulate the process of damage accumulation, it is needed to determine whether the material is damaged or not at the first. Secondly, the variables that quantitatively describe the damage are introduced and correlated with the macroscopic mechanical behavior of the material, that is, the damage constitutive relationship is to be established and material degradation will be implemented. Finally, the failure criteria of structures are proposed. In summary, material failure criterion, damage constitutive relation, and destruction criterion are called three elements of the cumulative damage criterion in the process of the cumulative damage simulation in composite structures. Therefore, it is important to choose the reasonable failure criterion and damage constitutive relation for the numerical simulation. In the analysis of composite structures, there are more than ten kinds of theories about composite strength [9-12], among them, the most commonly used criteria include Hashin’s criterion, Tsai-Hill criterion and the maximum stress criterion and others.

2.1 Failure criteria

In the analysis of composite material damage, the failure criterion of the stress quadratic polynomial for the composite lamina was proposed by Hashin[12]. Hashin’s criterion is also widely used to the analysis of structural damage of composite material, and has been developed continuously in the applications, and a variety of Hashin’s criteria derivatives are developed. Through the study of composite material structure strength analysis, it is found that delamination damage usually appears firstly in damage mode, and reduces the compression strength of composite laminated plates and the impact resistance strength during the loading process of composite laminated plate. Hashin’s failure criteria considering the delamination damage was shown in Table 1[13].

Table 1. Three dimensional Hashin’s failure criteria for composite materials based on delamination

Failure Mode		Hashin’s Failure Criteria
Fiber tensile cracking	$\sigma_{11} \ge 0$	$(\sigma_{11}/X_T)^2 + (\sigma_{12}/S_{12})^2 + (\sigma_{13}/S_{13})^2 \ge 1$
Fiber compressive cracking	$\sigma_{11} < 0$	$(\sigma_{11}/X_C)^2 \ge 1$
Matrix tensile cracking	$\sigma_{22} \ge 0$	$(\sigma_{22}/Y_T)^2 + (\sigma_{12}/S_{12})^2 + (\sigma_{23}/S_{23})^2 \ge 1$
Matrix compressive cracking	$\sigma_{22} < 0$	$(\sigma_{22}/Y_C)^2 + (\sigma_{12}/S_{12})^2 + (\sigma_{23}/S_{23})^2 \ge 1$
Fiber-matrix shear out	$\sigma_{11} < 0$	$(\sigma_{11}/X_C)^2 + (\sigma_{12}/S_{12})^2 + (\sigma_{13}/S_{13})^2 \ge 1$
Delamination in tension	$\sigma_{33} > 0$	$(\sigma_{33}/Z_T)^2 + (\sigma_{13}/S_{13})^2 + (\sigma_{23}/S_{23})^2 \ge 1$

Delamination in compression	$\sigma_{33} < 0$	$(\sigma_{33}/Z_C)^2 + (\sigma_{13}/S_{13})^2 + (\sigma_{23}/S_{23})^2 \geq 1$

2.2 Material properties degradation after damage

With the increase of load, the fiber and matrix of laminates will be gradually destroyed and the rigidity of the structural will be decreased. The degradation of composite elastic constants can be used to characterize the development of material damage. The commonly used method of material properties degradation assumes that if one of the elements is deteriorating, the degradation of material properties affects only the element itself without affecting other elements. The proper choice of parameter degeneration method has great influence on the ultimate strength of the laminated plate to be solved.

The parameter degradation method used by Chang[14] is that the material constants are degenerated to zero whenever failure occurs. Taking into account the convergence of the finite element calculation, these elastic constants are set to a very small value during the calculation. Tan [15] proposed material stiffness decrease caused by different damage modes is expressed with damage state variables in the planar case and different elastic constants degraded in proportion, which is extended to three-dimensional situation by Camanho and Matthews[1]. The two kinds of degradation rules are shown in Table 2.

Table 2. Material property degradation rules

Failure Mode	Chang's rule	Tan's rule
Matrix tensile cracking	$E_{22} = v_{12} = 0$	$E_{22}\to0.2E_{22}$, $G_{12}\to0.2G_{12}$, $G_{23}\to0.2G_{23}$
Matrix compressive cracking	$E_{22} = v_{12} = 0$	$E_{22}\to0.4E_{22}$, $G_{12}\to0.4G_{12}$, $G_{23}\to0.4G_{23}$
Fibre tensile failure	$E_{11} = E_{22} = E_{33} = G_{12} = G_{23} = G_{13} = v_{12} = v_{23} = v_{13} = 0$	$E_{11}\to0.07E_{11}$
Fibre compressive failure	$E_{11} = E_{22} = E_{33} = G_{12} = G_{23} = G_{13} = v_{12} = v_{23} = v_{13} = 0$	$E_{11}\to0.14E_{11}$
Fibre-matrix shear-out	$G_{12} = v_{12} = 0$	$G_{12} = v_{12} = 0$
Delamination in tension	$E_{33} = G_{23} = G_{13} = v_{23} = v_{13} = 0$	$E_{33} = G_{23} = G_{13} = v_{23} = v_{13} = 0$
Delamination in compression	$E_{33} = G_{23} = G_{13} = v_{23} = v_{13} = 0$	$E_{33} = G_{23} = G_{13} = v_{23} = v_{13} = 0$

2.3 The process of cumulative damage analysis

The analysis procedure of cumulative damage prediction was as follows: first of all, the stress of laminates was analyzed, and then failure criteria was used to determine whether laminate element failed. If element failure occurs, its material properties are correspondingly degraded. Then, continued to apply the load and repeat the previous process until the overall structure failed.

Liu [8] studied the strength of composite laminate joints by experiment and numerical method. The calculated results manifested that when the load is small, the degradation results by Chang's or Tan's rules are both smaller, and the latter's is closer to the experimental results. Both Chang's and Tan's degradation methods are based on the tensile and compressive loading of opening plates. Tserpes[7] developed the three-dimensional finite element model to investigate the cumulative damage process of single-bolted composite and proved that Tan's material degradation rule was more reasonable than that of Chang's.

3 Analysis of cumulative damage influence on pin-load distribution

By using large-scale commercial finite element software ANSYS, the three-dimensional finite element model was built to calculate the pin-load distribution of multiple countersunk bolted double-lap joints.

3.1 Analysis example

The analysed specimen was the same as presented in [6], composite plates were manufactured from carbon fiber/epoxy material system (HTA7/6376[4]) with quasi-isotropic layups $[(\pm 45/0/90)_3]_s$ and $[(\pm 45/0/90)_6]_s$ for the outer and middle plates, respectively. The nominal ply thickness was 0.13 mm. The thickness of the composite laminates was 3.12 and 6.24 mm for the outer and middle plates, respectively. The composite plates were joined by six fasteners of titanium[4] Torque-set. The nominal diameter was 6 mm for all fastener systems. The specimen geometry and configurations of six fastener systems are shown in Figure 1.

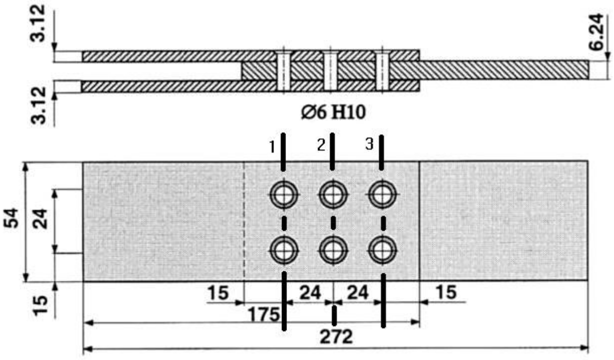


Figure 1. Dimension of test specimens with three row-bolt double-lap joint

3.2 The three-dimensional model for pin-load analysis
As shown in figure 2 and figure 3, bolts, nuts and gaskets were simplified as a part in this 3-D model which were meshed by 8-node solid element SOLID185, composite laminates were meshed by 8-node solid layer element SOLID185. A geometric model was meshed with a mapping method. In the model, the influence of contact friction and pretension force was also considered. The contact element between pin-hole, pin-plate and plate-plate adopted CONTA173 and the target element was TARGET170. The magnitude of the friction between the contact surfaces was controlled by Coulomb friction, and the friction coefficient was 0.2. The pretension force was applied by defining the prestress element PRETS179.

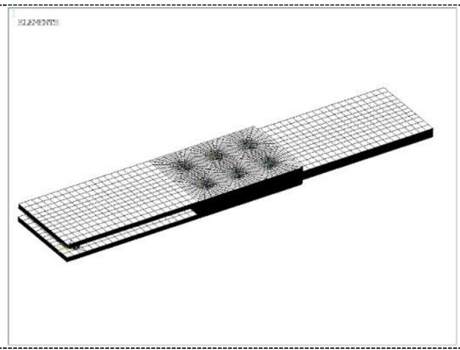


Figure 2. 3-D finite element mesh models

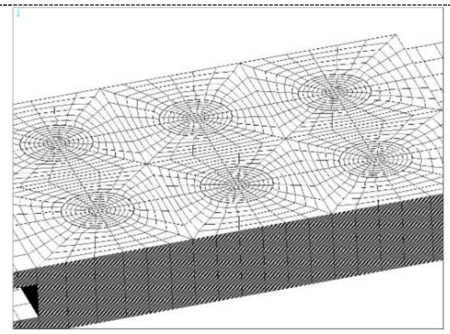


Figure 3. The modeling details of bolt-hole local mesh

The load was applied on the modeling in the same way as in the test, one end of the model (6.24 mm thick) was fixed and the other end was applied with displacement.

4 The results and discussion of pin-load distribution

4.1 Calculation Results
The resultant force of bearing pressure along the direction of the loading in pin-hole can be obtained by finite element method. The pretension load applied to the three-dimensional model was consistent

with the experiment. The results of pin-load distribution of six countersunk bolts double-lap joints are shown in Figure 4.

As can be seen from Figure 4(a):

(1) At the beginning of loading, the change of 1-row, 2-row pin load was more obvious, the 1-row pin load increased gradually, and 2-row pin load decreased gradually under the condition of small load. When the load increased to a certain value, the pin load of each row tended to be stable.

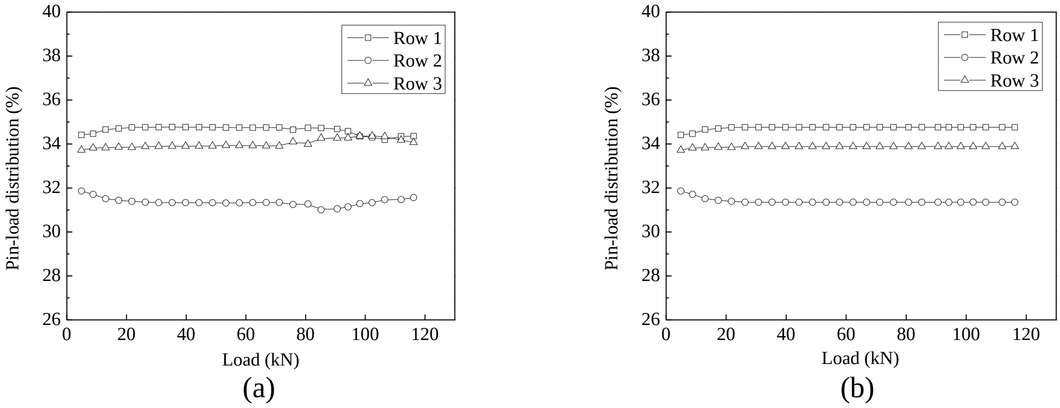


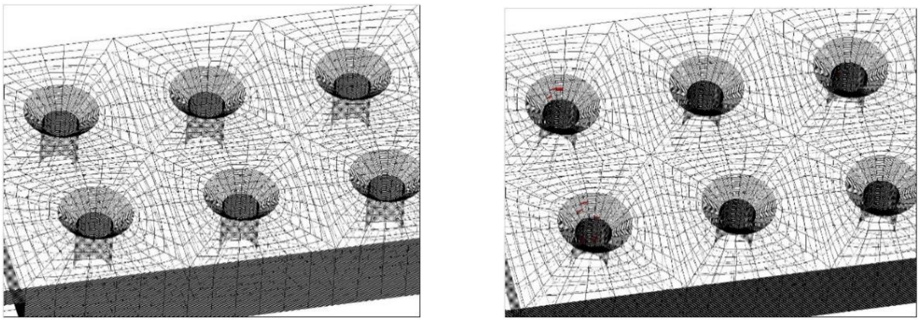
Figure 4. Pin-load distribution on double-lap of multiple-bolted joints: (a) with cumulative damage; (b) without cumulative damage

This was that the frictional force at the contact surface of the structure was much greater than the load on the pin in the early stage of loading. The external load was mainly used to overcome the friction, and the change of load distribution was obvious. With the further increase of the load, the matrix in the composite laminates was damaged first, and the change of the load was not distinct at this time, which showed that the matrix damage had a little influence on the pin-load distribution. When the load continued to increase, the fiber in composite laminates was damaged, pin-load distribution slowly changed, the 1-row pin load gradually decreased, and the 3-row pin load gradually increased. When the structure was destroyed, pin-load distribution changed suddenly.

(2) Considering the cumulative damage of composite materials, pin-load distribution varied with the change of external load, but the change was small. Throughout the loading process, the pin-load distribution proportion showed that the 1,3-row pin was higher than the 2-row pin.

4.2 Laminate destruction process

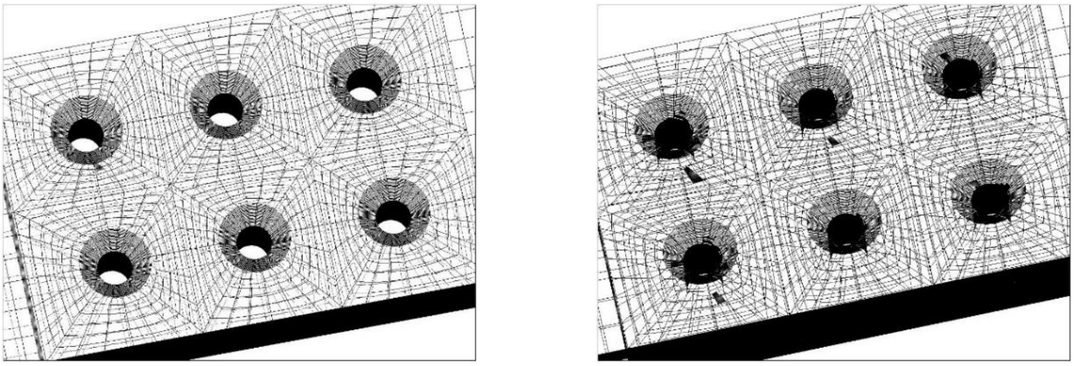
The process of matrix damage development in a composite plate is shown in Figure 5. When the external load reached to 48kN, the laminates contacted with the 1- row bolts appeared bearing damage. With the load increasing, the matrix around the 3-row holes also underwent bearing damage, followed by the destruction of the matrix around the 2-row holes. Throughout the loading process, a number of the elements which matrix was damaged is the largest in the vicinity of 1-row holes, followed by the 3-row holes, and the least elements were damaged in the vicinity of the 2-row holes.



(a) 48 kN (b) 76 kN

Figure 5. Laminate matrix damage expansion process

The process of fiber damage development in composite plate is shown in Figure 6. A variety of failure modes appeared, including bearing damage of the matrix and fiber, and delamination as the external load was increased to 81kN. The fiber of laminated plate is crushed around the 1- row holes, that is, the part in contact with the bolts. As the load increased, the fiber around the 3-row holes also underwent bearing failure, followed by the fiber failure around the 2-row holes. When the load was increased to 115 kN, most of the fiber around the 1-row holes was damaged, losing load-carrying capacity. In the whole process of loading, the number of the elements damaged in fiber was the highest in the vicinity of 1- row holes, followed by 3-row holes, and the least fiber damage elements occurred near the 2-row holes.



(a) 81 kN (b) 115 kN

Figure 6. Damage expansion process of composite laminates

4.3 Discussion

In Figure 4(a), the pin-load distribution does not change significantly with the increase of loading after the 1-row pins closest to the loading end overcome the friction force. The reason was that the matrix bearing damage occurred firstly around 1-row pins, then the bearing stiffness declined with the corresponding material properties degrading; The damage zone of the matrix was gradually increased with the loading increasing, so that the bearing stiffness continued to decline. However, as can be seen in Figure 5, a smaller number of damaged elements occurred in the stable phase of the pin-load distribution, it did not affect the pin-load redistribution.

When the fiber damage occurred, the loading on 1-row pins continued to decrease but did not cause a sharp change in pin load of each row. At the beginning of bearing damage, the damage zone was smaller and the stiffness degradation did not lead to rapid change of the pin load. On the one hand, the enlargement of the bearing damage zone reduced the overall bearing stiffness of the pin-hole. On the other hand, in the case of the bearing damage, the method of stiffness degradation was to degrade material stiffness abruptly then to amend and improve its stiffness. The bearing stiffness of the material had a tendency to improve after bearing damage. As a result of the combined effect of above-mentioned factors, the pin-hole bearing stiffness and load-bearing proportion decreased slowly. In addition, as the load increased, other pin-hole material gradually reduced stiffness, and it would further retard transferring process which the load of 1- row pins transfers to other rows pins. Another phenomenon observed from Figure 4(a) is that as the load-bearing proportion of one row of pins decreased, the load gradually shifted to 2-row pins, so that the load proportion of the middle-row pins increased slightly as the load increased, whereas the 3-row pins far from the loading end and 1-row pins, the loading was not significantly affected.

The bolt was made of metal, which was a ductile material and has remarkable plastic deformation before destruction. Therefore, in the multiple-bolted joints of metal materials, the hole which took a larger load firstly undergoes bearing plastic deformation, on the one hand, the stress concentration in the pin-hole was notably reduced; on the other hand, the load of each pin was redistributed so that the loading proportion tended to be uniform. At the same time, since the composite material was a typical brittle material and plastic deformation hardly occurs, which was not conducive to stress redistribution.

Consequently, the pin-load distribution would not change significantly with the change of external load.

5. Conclusion

Based on the theory of cumulative damage of composite laminates, this paper studied the problem of pin-load distribution of multiple-bolted in composite mechanical joints, and finally made the following conclusions:

(1) Considering the cumulative damage of composite material, the pin-load distribution varies with the change of external load, but the change is slight.

(2) Implementing the cumulative damage analysis technique of composite materials, it is found that pin-load distribution shows " Bolts at both ends bearing a greater load, the middle bolts bearing a smaller load ". The result is analogous to traditional analysis method that does not consider the effect of material damage on pin load.

(3) In order to consider the objective process of damage accumulation, iterative calculating is required in conducting FEM analysis of complicated structures, which leads to larger scale and more time-consuming computations by executing the strength calculation of composite joints. Under the condition that the accuracy of the two algorithms is similar, the algorithm which does not consider the material damage is more efficient and the calculation scale is small. To quickly determine the pin-load distribution in engineering applications, the effect of the cumulative damage of the material on the pin-load distribution should not be considered.

6. References

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