Study on tensile properties of composite laminates with gap defects

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Abstract. The mechanical properties of composite laminates with gap defects are studied both experimentally and numerically. Based on the experimental research, a finite element model of composite laminates with gap defects is established. ABAQUS software, Hashin stress failure criterion and Camanho stiffness degradation model is used to analyse the mechanical properties of composite laminates with gap defects under tensile load. By comparing with the results of ideal composite laminates, the influence of the existence of defects on the matrix and fibre damage and interface damage of the laminates is discussed. The feasibility and effectiveness of the finite element method are verified by comparison with experiments. The results show that the existence of gap defects under the tensile load will lead to the stress concentration distribution of laminate and reduce the ultimate strength of the laminate.

1. Introduction
Composite material refers to a new material obtained by combining several different materials by a certain process technology. The composite material has many superior material properties than that of the original component materials. At present, the integrated design and manufacture of composite materials is a new direction of manufacturing technology. The advantage lies in that the integral of the components reduces the number of parts and the working time of the integral connection and assembly. Because of the reduction of the connecting parts, the total mechanical properties of structures and the load capacity can be improved.

Compared with traditional materials, composite materials have lower density, high specific strength and high specific stiffness, which make it increasingly applied to large complex structures. The application of automated fibre placement technology in the manufacturing process of composite materials provides the possibility of building large composite structure. However, there are process induced defects in the manufacturing process which makes the mechanical properties of the automated fibre placement composite structure uncertain. Since the defects of composite structure have always been an unavoidable problem in the manufacturing process, the automated fibre placement technology has to face the common defect forms existing in the composite material preparation process, at the same time, as a new automatic placement technology, it will inevitably bring new forms of defects.

Composite materials are prone to form defects during the manufacturing process, and the damage mechanism is very complicated. With the increasing application range of composite materials, the research methods and theories are becoming more and more prosperous. The study of the evolutionary behavior of defects such as porosity, impurities, cracks, looseness, fibre/matrix interfaces unboned,
layup or fiber orientation errors is usually combined with the strength criteria of the composite material. For unidirectional plates, Tsai-Hill, Hoffman and Tsai-Wu has established failure criteria respectively, and for comprehensively considering the failure between layers, there still have many failure criteria and failure models, such as Hashin, Chang-Chang, Hou, etc. [1]. Based on the deep study of the damage mechanism and failure mechanism of composite materials, the effects of micro component damage on the macroscopic overall performance of composite materials are summarized and combined with computer aided analysis technology, Tail et al. developed a method of stiffness degradation [2, 3]. It can describe the complex damage and failure process of laminated composite structures to a certain extent. The damage of the material components leads to a decrease of the ultimate strengths in the damage zone, some stiffness decrease and the stress redistribution cause the stress increase in the neighbor of the damage area, when the load continues to increase, the damage gradually expands, this is called the progressive damage and failure mechanism of composite laminate structures. The method of numerical simulation using the theory of stiffness degradation to analysis progressively damage of the composite structures has been widely used by scholars. It is difficult to measure the parameters required to characterize the damage quantitatively, such as crack width and crack density in the actual structure. At the same time, the remaining stiffness of the material is different to determine under different loading conditions, so there are multiple sets of stiffness degradation programs [4, 5], which leads to the strong empirical characteristics of the method. However, this method is simple to implement and has computational efficiency and can reflect the damage status of materials and characterize the residual stiffness of materials to a certain extent. This method has been adopted in many commercial finite element softwares. In the Reference [6], the effects of four main types of defects, such as gap, overlap, half gap/overlap and twisted tow, on the ultimate strength and failure mode of composite laminates were studied by experimental methods. Due to the complex damage patterns of composite materials, it has great engineering significance to analyze the failure mode and ultimate strengths of composite plates commonly used in engineering. The progressive failure analysis of composites is based on the strength analysis of laminates which are stacked from lamina, so the progressive failure analysis of laminates translates into strength analysis of a lamina. One of the lamina damage is not equal to the failure of the entire structure, usually at this time the laminate still has the load capacity, so the prediction of the ultimate strengths of the laminate is the layer-by-layer strength analysis of the laminate until the failure of the laminate. In this paper, the effects of defect forms on the failure modes of composite laminates were studied by using the composite laminates with defects, and the mechanical properties of composite laminates with defects were predicted by finite element simulation. The comparison of experimental results and that of finite element simulation provided useful references of engineering applications.

2. Experiments

2.1. Sample description
Automated fiber placement tensile specimens with and without gap defect are prepared, and the defect position is as show in Figure 1. In the design of the defect position, in order to prevent the occurrence of the bending moment effect and to ensure the symmetry, the defect position is set in the center of the two layers in the middle of the stack direction, and the boundary of the defect aligned.

![Figure 1. Gap defect configuration.](image)

For the convenience of comparison, the perfect composite laminate is selected as the benchmark specimen, and the layout and size of the perfect composite laminate is the same as that of the laminate
with defect. The tensile specimen has a length of 250 mm, a width of 25 mm, a gap defect width of 5 mm, and a 14-layer symmetric layer of the laminate, and the thickness of the lamina is 0.125 mm, as shown in Figure 2. The direction of the laminate is shown in Table 1, where T-Baseline represents a perfect tensile specimen and T-Gap is a specimen containing a 0° direction gap defect. The strengthening plates are attached at both ends 75mm of the specimen to ensure sufficient strength to be connected to the tensile clamp of the testing machine.

![Figure 2. Specimen size(mm).](image)

**Table 1.** Composite laminate ply angle.

| Type    | Ply angle                  | Number |
|---------|----------------------------|--------|
| T-Baseline | [45/-45/0/-45/0/45/0]s | 3      |
| T-Gap   | [45/-45/0/-45/0/45/0]s   | 3      |

2.2. Testing process

The tensile test is performed on a microcomputer control electronic universal testing machine WDW-300 according to the ASTM D3039 experimental standard, as shown in Figure 3a. The experiment is loaded by displacement control. The specimen was fixed with the upper end and the lower end applied downward displacement, the specimen is installed as shown in Figure 3b, the loading rate is 0.5mm/min, the sample is broken with the maximum load applied. The broken load and failure form of the test piece are recorded, and multiple specimens are carried out to reduce the error caused by the fabrication of the specimen. The damage form of the specimen is shown in Figure 3c.

![Figure 3. Tensile experiments: (a) Test machine, (b) Installation test, (c) Failure mode](image)

The load values recorded by the experiment are shown in Table 2.

**Table 2.** Ultimate load.

|                  | T-Baseline | T-Gap | Comparison |
|------------------|------------|-------|------------|
| Mean maximum load(KN) | 44.219     | 40.943| 7.409%     |
3. Numerical analysis

3.1. Finite element model

The strength theories commonly used in composite design and failure analysis are maximum stress theory, maximum strain theory, Cai-Hill strength theory and Cai-Wu tensor theory. Other representative criteria are Hashin criteria [7], Puck guidelines [8] and so on. In this paper, the Hashin criterion based on stress description is adopted. The criterion expression is simple and can predict each failure mode. The expression is:

Fiber tensile failure:
\[
\left( \frac{\sigma_{11}}{X_T} \right)^2 \geq 1 \quad (\sigma_{11} \geq 0)
\]  

(1)

Fiber compression failure:
\[
\left( \frac{\sigma_{11}}{X_C} \right)^2 \geq 1 \quad (\sigma_{11} \leq 0)
\]  

(2)

Matrix tensile failure:
\[
\left( \frac{\sigma_{22}}{Y_T} \right)^2 + \left( \frac{\sigma_{12}}{S_{12}} \right)^2 + \left( \frac{\sigma_{13}}{S_{13}} \right)^2 + \left( \frac{\sigma_{23}}{S_{23}} \right)^2 \geq 1 \quad (\sigma_{22} \geq 0)
\]  

(3)

Matrix compression failure:
\[
\left( \frac{\sigma_{22}}{2Y_T} \right)^2 + \left( \frac{\sigma_{12}}{S_{12}} \right)^2 + \left( \frac{\sigma_{13}}{S_{13}} \right)^2 + \frac{\sigma_{23}}{S_{23}} \left[ \frac{Y_C}{2S_{23}} \right]^2 - 1 \geq 1 \quad (\sigma_{22} \leq 0)
\]  

(4)

Fiber matrix shear failure:
\[
\left( \frac{\sigma_{11}}{X_C} \right)^2 + \left( \frac{\sigma_{12}}{S_{12}} \right)^2 + \left( \frac{\sigma_{13}}{S_{13}} \right)^2 \geq 1 \quad (\sigma_{11} \geq 0)
\]  

(5)

\[
\left( \frac{\sigma_{12}}{S_{12}} \right)^2 + \left( \frac{\sigma_{13}}{S_{13}} \right)^2 \geq 1 \quad (\sigma_{11} \geq 0)
\]  

(6)

Where \( \sigma_{ij} \) is the stress component of a point in the structure in the corresponding layer material coordinate system. 1 represents the fiber direction, 2 represents the normal direction of the fiber direction in the plane, and 3 represents the normal direction of laminate. X, Y, and S represent the longitudinal, transverse, and shear strengths of the material coordinate system respectively, T and C represent tensile and compression.

The research on the performance degradation of composite materials is mainly to determine the degradation coefficient by combining experiments. In this paper, the modified Camanho degradation [9] model is used to select the reduction coefficient of the elastic parameters based on the experiment, which can simulate the material damage easily and effectively. A constitutive relationship with damage analysis is constructed to describe the degradation of material properties.

3.2. Finite element model

In this paper, commercial software ABAQUS is used to study the mechanical properties of composites with gap defects. In order to accurately simulate the experimental process, the reinforcement zone is considered as the holding zone, and the off plane displacement is constrained. One end is fixed and
another end is applied with a displacement loading, and only the degree of freedom of the loading direction is retained. The composite parameters used are shown in Table 3.

| $E_{11}$ (GPa) | $E_{22}$ (GPa) | $G_{12}$ (GPa) | $\nu_{12}$ |
|----------------|----------------|----------------|------------|
| 114            | 8.61           | 4.16           | 0.3        |

The laminate is modeled by solid elements, the mesh size is 1mm. The established finite element mesh is shown in Figure 4. For the model with gap defects, the gap region is filled with resin.

### 3.3. Numerical analysis results

The load-displacement curves of the perfect laminate and the gap containing defect laminate under tensile load are shown in Figure 5:

|                  | T-Baseline | T-Gap | Comparison |
|------------------|------------|-------|------------|
| Experimental     | 44.219     | 40.943| 7.41%      |
| Finite element   | 47.187     | 44.224| 6.28%      |

Figure 5. Load-displacement curves of laminate under tensile load.

The maximum loads of the defect-free laminate and the gap-containing laminate are shown in Table 4:
Figure 5 shows the load displacement curves of the perfect laminates and the gap containing defect laminates under tensile load. It can be seen from the figure that the maximum load and integral stiffness of the laminate with gap defects are reduced. It can be seen from Table 4 that the strength of the defect containing laminate is reduced by about 6% compared to the perfect laminate. From the Misses stress distribution in Figure 6, it is found that the stress distribution of the containing gap defect laminate is more concentrated than that of the perfect laminate.

![Figure 5: Load displacement curves](image)

**Figure 6.** Mises stress diagram of laminate under tensile ultimate load.

During the stretching process of the laminate, the tensile failure of the matrix mainly occurs at the 45° layer, and the tensile failure of the fiber mainly occurs at the 0° layer. When the matrix and the fiber begin to break, the damage appear at both ends and gradually expands to the middle part, at this time, the damage expands slowly. When the applied load is close to the maximum load, the speed of damage propagation of the fiber and the matrix increases, indicating that the stress distribution in the laminate changes sharply with the destruction of the fiber and the matrix during this process. Figure 7 shows the tensile failure of the laminate at the 45° layer under the maximum load.

![Figure 7: Tensile failure of laminate](image)

(a) Perfect laminate  (b) Gap-containing laminate

**Figure 7.** Matrix compression failure of 45° layer under maximum load.

4. Conclusions

Through experimental research and finite element simulation on perfect laminates and containing gap defect laminates, the following conclusions can be drawn:

1) It is found through experiments that the tensile failure form is laminate delamination and fiber broken.

2) The finite element model together with the Hashin criterion and the modified Camanho degradation model are used to simulate the failure mode of the composite laminate and the simulations are consistent with experiments results.

3) The presence of gap defects reduces the ultimate tensile strength of the laminate to 6%, and the presence of gap defects changes the stress distribution within the laminate.
Acknowledgement
The authors thank the National Natural Science Foundation of China (Nos. 11572070, 11772081, 11472070, 11422219), the Fundamental Research Funds for the Central Universities of China (DUT18ZD209).

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