Experimental and Numerical Study on Long-Life and Progressive Damage in Laminates in Open-Hole Compression Tests

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Abstract. The strength theory design accuracy of carbon fiber reinforced plastics (CFRP) composite structures are integral to CFRP composite structures product weights along with production costs. In order to further improve the CFRP composite structure strength theory design accuracy in this paper, it developed an ATM/SIFT analysis method by combining strain invariant failure theory (SIFT) and Accelerated testing methodology (ATM). The developed implementation scheme of ATM/SIFT includes: three parts of accelerating material strength test, component strength main curve characterization, structures life prediction, among which the material life prediction is achieved by using Python code to customize user material subroutines (VUMAT), through secondary development on the ABAQUS platform. Based on the developed ATM/SIFT method, it analyzed the compressive gradual failure mechanism and life of IM600/TDE-85 composite laminated plates open pore structures. Finally, it predicted the long-term static load compression life of IM600/TDE-85 composite laminate open-hole structures by using ATM/SIFT method and compared this prediction results with test results.

Keywords. Strain invariant failure theory, accelerated testing methodology, long-term life, VUMAT, open-hole structures.

1. Introduction
In the aircraft industry, carbon fiber reinforced polymer (CFRP) is frequently employed because of its excellent advantages of high specific strength and modulus, high resistance to corrosion, and a low thermal expansion coefficient, which reduces the weight of the structure by 20-30% [1]. Accurate theoretical design methods are essential to ensure the safety of CFRP composite structures in service. But at the moment, the most widely used strength theories of composite structure design are still the traditional macro strength theories [2-7], which are mainly based on mathematical approximations, having larger analysis errors in practical use. In addition, these traditional theories cannot provide a qualitative analysis of the specific location and mechanism of structural failures. It is critical to construct a composite strength theory in order to address the above shortcomings of standard macro strength theories based on failure physics, which is important to promote the wide application of CFRP composite in industry.
In this paper, it extended the strain invariant failure theory’s application [8], combining strain invariant failure theory (SIFT) with accelerated testing methodology (ATM), and established ATM/SIFT method, which is applied in analyzing the gradual failure evolution process and life of CFRP composite three-dimensional structures. The developed ATM/SIFT theory implementation method includes: three parts of material macroscopic strength variable temperature test, component strength characterization and structure life prediction, among which material macroscopic strength variable temperature test includes: microscopic strain analysis and structural component characteristic master curve; structure life prediction includes: specific structure modeling, macroscopic strain analysis, and amplification, component failure judgment, element material stiffness reduction and crack propagation. This process is the second time development on the ABAQUS platform, by using Python code to customize user material subroutines (VUMAT), has developed strength design method of laminate structures based on SIFT theory. Finally, using the developed ATM/SIFT method has evaluated gradual compressive failure and life of open-hole structures of IM600/TDE-85 CFRP laminated plates.

2. Strain Invariant Failure Theory

2.1. The SIFT of Failure Criteria

The SIFT divides the failure of fiber reinforced resin matrix composite into matrix failure and fiber failure. It’s a laminated plate strength theory based on physical failure modes. Its core idea is to establish a microscopic unit cell model at first and then use the microscopic model to connect components with unidirectional layers. Thus, the unidirectional layer performance can be calculated by using compositional properties. In return, microscopic strains on the components can be deduced from macroscopic strains on the unidirectional layers.

In the SIFT theory, the tensile and compressive deformation of fiber is characterized by using Von-Mises strains, while the tensile and compressive deformation of resin is characterized by respectively using the first strain invariant \( J_1 \) and Von-Mises strain. The failure is determined when the fiber or matrix in fiber-reinforced resin matrix composite reaches the critical value of the strain failure criterion. Strain invariant failure criterion is as follows:

The fibre failure \( \varepsilon_{vm}^f \geq \varepsilon_{vm,Crit}^f \)

Tensile matrix failure \( J_1^m \geq J_{1,Crit}^m \)

Compressive matrix failure \( \varepsilon_{vm}^m \geq \varepsilon_{vm,Crit}^m \) (1)

Where fiber and matrix are represented by the superscripts “f” and “m,” respectively; the maximum strain in the fiber direction is used to obtain the failure critical parameters of fibers, the failure of matrix critical parameters is extracted using the \( J_1 \) and \( \varepsilon_{vm} \). Within the matrix phase of the composite, these are two fundamental and independent measures of the deformation state.

The constituent failure indexes are described as:

\[
\begin{align*}
    k &= \max \left( k^f, k^m_T, k^m_C \right) \\
    k^f &= \max \left[ \varepsilon_{vm}^f / \varepsilon_{vm,Crit}^f, \cdots, \varepsilon_{vm}^f / \varepsilon_{vm,Crit}^f, \cdots, \varepsilon_{vm}^f / \varepsilon_{vm,Crit}^f \right] \\
    k^m_T &= \max \left[ J_1^m / J_{1,Crit}, \cdots, J_1^m / J_{1,Crit}, \cdots, J_1^m / J_{1,Crit} \right] \\
    k^m_C &= \max \left[ \varepsilon_{vm}^m / \varepsilon_{vm,Crit}, \cdots, \varepsilon_{vm}^m / \varepsilon_{vm,Crit}, \cdots, \varepsilon_{vm}^m / \varepsilon_{vm,Crit} \right]
\end{align*}
\] (2)

Where the indices for the element’s failure index is \( k \), fibre failure is \( k^f \) and the matrix tensile and compressive failure are \( k^m_T \) and \( k^m_C \) respectively; \( i=1 \ldots n_1, j=1 \ldots n_2, n_1, n_2 \) represent the total numbers of the analyse points in the fibre and matrix respectively.
From equation (2), we can see that the corresponding mode of material failure can be determined once the material \( k \) value reaches 1. Therefore, in the SIFT theory, \( k^f \), \( k^m_T \) and \( k^m_C \) are the strength index of the fiber reinforced resin matrix composite laminate.

2.2. Macro and Micro Strain Analysis Methods

The SIFT theory is based on fiber and resin micro strain analysis, and the relationship between micro and macro strains can be established by the unit cell model. The SIFT theory transforms the analysis of laminate structures from macro to micro scale, which can much accurately analyze the failure modes and damage evolution of laminated plate structures to realize accurate prediction of final strength. The micro structure analysis of laminated plates is as shown in figure 1.

![Figure 1. Within the micromechanical representative unit cell model of carbon fibre reinforced resin scheme, locations for extracting strain amplification factors were located.](image)

The expression of the derived strain amplification factors is used to modify the strains from the macro-level to the micro-level as follows:

\[
\varepsilon_{\text{mech}}^{(i)} = M^{(i)} \varepsilon_{\text{mech}} + M^{(i)} \varepsilon_{\text{ther}} + A^{(i)} \Delta T
\]

where the micro-strain of the key pint \( i \) in fibre or matrix is denoted by \( \varepsilon_{\text{mech}}^{(i)} \), the macro-strain in CFRP lamina is denoted by \( \varepsilon_{\text{mech}} \), the thermal strain in CFRP lamina is denoted by \( \varepsilon_{\text{ther}} \), the strain amplification factors of the key point \( i \) either in fibre or matrix resin is denoted by \( M^{(i)} \), the thermal strain amplification factors for the key point \( i \) is denoted by \( A^{(i)} \), the temperature difference between environment temperature and the curing temperature is denoted by \( \Delta T \).

Literature [8] have introduced in detail the following contents: In SIFT analysis, the creation of a matrix element finite element model, the placement of critical spots on resin and fiber, the method of extracting the strain amplification coefficient on key points, and the extraction method of component strain invariant. All these contents will not be repeatedly discussed in this paper.

3. Mechanical Performance Test of CFRP Laminates

In this test, the select material system of IM600/TDE-85 prepreg (the fiber volume fraction was 60%) to make four kinds of laminated plates of different layers and angles, [0]_{10s}, [90]_{20s}, [45/-45]_{5s}, [45/0/-45/90]_{2s}, respectively. Table 1 shows the test scheme and sample size. The preparation process of laminated plates is as follows: Hold the temperature of 85°C for 30min; Then heat up to 135°C, hold this temperature for 60min and keep the pressure for 150min. Finally, take out the laminated plates after it dropped to room temperature.

The tensile and compression tests of unidirectional laminated plates are carried out in accordance with ISO 527-5 [9] and ASTM D695-10 standards [10], and the test of open-pore compression structures of quasi-isotropic laminated plates was carried out in accordance with ASTM D 6484/6484-04 standard [11]. The experimental scheme is shown in table 1. We test the constant strain rate (CSR) of unidirectional laminated plates and quasi-isotropic laminated plates open-hole structures at different temperatures using Miyano and Nakada’s accelerated testing technique (ATM) [12].
### Table 1. The AS4/3501-6 laminates experimental scheme and specimen size.

| Test type                  | Temperature/℃ | Deflection rate V/mm/min | Specimen size/mm (L×W×H) |
|----------------------------|---------------|--------------------------|--------------------------|
| In-plane shear             | 25            | 2                        | 200×15×2                 |
| Longitudinal tensile       | 1             | 200×12.5×1               |                          |
| Longitudinal compressive   | 25,50,80,110,140 | 2                        | 78×10×2                 |
| Transverse tensile         | 2             | 100×15×2                 |                          |
| Transverse compressive     | 1             | 78×10×2                  |                          |
| Open-hole compressive      | 1             | 118×38.1×1.6             |                          |

### 4. Numerical Analysis Model Establishment

#### 4.1. Derivation of a Damage Model

In the mechanical performance analysis of composite laminate constructions, material damage analysis is critical. By lowering the material stiffness matrix during computation, Kachanov [13] pointed out that the influence of material degradation on the overall performance of composites might be realized. Based on McCarth, Schuecker, and other material damage strength estimation models [14-15] combined with and established on SIFT theory, we present a new gradual failure analysis model. Because of the elastic-brittle behavior of CFRP under force, we observed no significant failure-associated plastic deformation. Therefore, the plastic behavior of the CFRP material can be ignored during modeling establishment. The material’s stiffness matrix in the damage model is as follows:

$$\begin{bmatrix}
C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\
C_{22} & C_{23} & 0 & 0 & 0 & 0 \\
C_{33} & 0 & 0 & 0 & 0 & 0 \\
symm & C_{44} & 0 & 0 & 0 & 0 \\
C_{55} & 0 & 0 & 0 & 0 & 0 \\
C_{66} & 0 & 0 & 0 & 0 & 0
\end{bmatrix}

(4)$$

where

- $C_{ij} = E_{ij} (1-d_f) [1-(1-d_m)^n] (1-d_i) v_{i1} v_{j1} / A$
- $C_{22} = E_{22} (1-d_m) [1-(1-d_m)(1-d_i)v_{12} v_{21}] / A$
- $C_{33} = E_{33} (1-d_m) [1-(1-d_m)(1-d_i)v_{12} v_{21}] / A$
- $C_{12} = E_{12} (1-d_m)(1-d_i)[(1-d_m)v_{13} v_{23} + v_{13}] / A$
- $C_{13} = E_{13} (1-d_m)(1-d_i)[v_{11} v_{23} + v_{13}] / A$
- $C_{23} = E_{23} (1-d_m)^2 (1-d_i) v_{13} v_{23} / A$
- $C_{44} = G_{12} (1-d_m)(1-d_i)$
- $C_{55} = G_{13} (1-d_m)(1-d_i)$
- $C_{66} = G_{23} (1-d_m)(1-d_i)$
- $A = 1-(1-d_m)(1-d_i)v_{12} v_{21} - (1-d_m)^2 v_{23} v_{32} - (1-d_m)(1-d_i)v_{13} v_{31} - 2(1-d_m)^2 (1-d_i)v_{12} v_{23}$

where the fibre damage parameter is denoted by $d_f$; and the matrix damage parameter is denoted by $d_m$. 


The introduction of $d_f$ and $d_m$ into the stiffness matrix is needed by the SIFT theory. When key points of components of an element get failed, the material performance degradation treatment should be carried out according to the failure mechanism. $d_f$ and $d_m$ are just the performance degradation schemes to express the failure of components. Component damage factor is defined as follows:

The fibre failure ($\sigma_1^f > 0$)

If $k^f \geq 1$, then $d_f = 0.99$ \hspace{1cm} (6)

Tensile matrix failure

If $k^m_{11} \geq 1$, then $d_m = 0.99$ \hspace{1cm} (7)

Compressive matrix failure

If $k^m_{\varepsilon eq} \geq 1$, then $d_m = 0.99$ \hspace{1cm} (8)

The goal of gradual failure analysis of laminated plates is to adjust component damage factors through determining every element in laminated plates’ component failure index and then applying every element of the structures’ specified degradation scheme by reducing the stiffness of each element. With the load increase, the failure index and damage factors of key points in all elements are constantly updated, and the stiffness matrix of all element materials is resolved until the laminate structures fails to bear the load and finally fails completely. The update equation of the stiffness matrix is shown in equation (4). From equation (4), we can see that either fiber failure or resin failure will affect the elastic parameters of the stiffness, greatly reducing the elastic constant of stiffness matrix. When there is a component failure in the element, the corresponding component damage factor is assigned to 0.99, and then the stiffness matrix of the material is adjusted to carry out stiffness degradation treatment of element material. Then, in the next step of load analysis, the stress is calculated based on the degraded stiffness matrix. This process was all compiled on the ABAQUS platform by using Fortran code for user-defined material subroutines. It should be noted that, in this paper, the gradual failure analysis model of the developed composite materials, analyzes every element of the composite structures one by one in the process of composite structure failure analysis. When the fiber or resin in a element is damaged, the stiffness of the element will be greatly reduced. At this time, the stiffness matrix used in stress calculation of other elements without component failure will not be reduced. Material performance is listed in table 2-4.

Table 2. Properties of AS4/3501-6 laminates.

| Material properties                              | Ply  | Fiber | Matrix |
|-------------------------------------------------|------|-------|--------|
| Fiber volume fraction $V_f/%$                   | 60   | 100   | 0.0    |
| Longitudinal modulus $E_1/GPa$                  | 126  | 208   | 3.0    |
| Transverse modulus $E_2=E_3/GPa$                | 11   | 42    | 3.0    |
| Shear modulus $G_{12}=G_{13}/GPa$               | 4.6  | 23    | 1.06   |
| Shear modulus $G_{23}$                          | 3.9  | 15    | 1.06   |
| Poisson’s ratios $\mu_{12} = \mu_{13}$          | 0.28 | 0.23  | 0.38   |
| Poisson’s ratio $\mu_{23}$                      | 0.4  | 0.41  | 0.38   |
| Longitudinal coefficient of thermal expansion $a_1/10^6 K^{-1}$ | -0.34 | -0.87 | 60     |
| Transverse coefficient of thermal expansion $a_2=a_3/10^6 K^{-1}$ | 75   | 40    | 60     |

$E_i (i=1,2,3)$: Young’s modulus; $G_{ij} (i,j=1,2,3)$: shear modulus; $\alpha_i (i=1,2,3)$: thermal expansion coefficient; $\mu_{ij} (i,j=1,2,3)$: Poisson’s ratio.
### Table 3. The failure stress and strain of AS4/3501-6 laminate.

| Laminates               | Failure stress /MPa | Failure strain /% |
|-------------------------|---------------------|------------------|
| Longitudinal tensile    | 2100                | 1.67             |
| Longitudinal compressive| 1960                | 1.56             |
| Transverse tensile      | 92                  | 0.83             |
| Transverse compressive  | 196                 | 1.78             |

### Table 4. Critical strain invariants of AS4/3501-6 laminate.

| Critical strain invariants                  | Values /% |
|---------------------------------------------|-----------|
| Fiber failure $\varepsilon_{vm,Crit}^f$     | 0.021     |
| Matrix expansion deformation failure $J_{m,Crit}^m$ | 0.0301 |
| Matrix deformation failure $\varepsilon_{vm,Crit}^m$ | 0.198 |

4.2. **Geometric Model of Open-Hole Structures**

The [45/0/-45/90]$_2s$ stacking sequence is used to create an open-hole structure and established based on ABAQUS kernel language Python. Each layer of the laminated structure is 0.1mm. The geometrical size, boundary constraints, and mesh division of the open-hole structure are shown in figure 2, among which the geometrical dimension is determined according to ASTM D 6484/6484-04 [11] standard. The structured meshing technique is used in meshing finite elements. With the aim of ensuring solution accuracy, the mesh elements are refined around the small pores where the stress is concentrated, while the mesh division is sparse in non-stress concentrated areas where are far away from pores, which both consider the accuracy of calculation and ensures the timeliness of calculation. The element is all hexahedral in shape, and its type is reduced integral element C3D8R. Its characteristic is that each element has only one integral point, which is convenient for variable display after microscopic strain amplification in the process of post-processing. After mesh division of the open-hole structure model, the total number of generated elements and nodes is 58368 and 64872, respectively. Implicit solver is used in calculation and solution. The displacement control method is adopted as the loading method in the process of finite element analysis.

![Figure 2](image.png)  
**Figure 2** Open-hole compressive specimen FEM model Mesh for with boundary conditions and a stacking sequence [45/0/-45/90]$_2s$.

5. **Results and Discussion**

5.1. **The Unidirectional Laminate Master Curves of Strength**

Figure 3(a) illustrates the TDE-85 matrix resin creep compliance master curves, with the transverse direction creep compliance $D_c$ for the unidirectional laminate against time $t$ with different temperatures.
Figure 3. (a) Creep compliance master curves for the 3501-6 matrix resin, (b) The factor of time-temperature shift of creep compliance for AS4/3501-6 unidirectional laminates in a transverse direction.

The master of CSR for the unidirectional laminate of the IM600/TDE-85 was obtained based on the factors of time-temperature shift $\alpha_{ts}$, illustrated in figure 4. Equation (9), whose parameters are shown in table 5, was used to fit these CSR master curves.

$$\log \sigma_s = \log \sigma_{s0} (t_0', T_0) + \frac{1}{\alpha_s} \log[-\ln(1-P_f)] - \log[1 + \left(\frac{t_1'}{t_0'}\right)^n]$$

(9)

where, constant strain rate strength at the initial reduced time $t_0'$ at a reference temperature $T_0$ is denoted by $\sigma_{s0}$, the transient reduced time at $T_0$ is denoted by $t_1'$, the gradient in the rubbery region of the CSR strength master curve is denoted by $n_r$, the failure probability is denoted by $P_f$, and the shape parameter in constant strain rate strength is denoted by $\sigma_s$.

Figure 4. Static strength master curves for AS4/3501-6 unidirectional laminate in various load directions (a) longitudinal tensile, (b) longitudinal compressive, (c) transverse tensile, (d) transverse compressive.
Table 5. Parameters of AS4/3501-6 for SIFT/ATM analysis.

| Parameter | Value |
|-----------|-------|
| $T_0/\degree C$ | 25 |
| $D_{C0}/1/GPa$ | 0.34 |
| $t_0/min$ | 1 |
| $m_g$ | 0.022 |
| $m_r$ | 0.415 |
| Resin $t_g/\min$ | 3.98×10^{10} |
| $\Delta H_1/KJ/mol$ | 153 |
| $\Delta H_2/KJ/mol$ | 701 |
| $T_g/\degree C$ | 134 |

| CFRP $\alpha_s$ | 22.6 | 20.5 | 19.2 | 18.7 |
| $n_r$ | 0.16 | 0.18 | 0.20 | 0.23 |
| $t_g/\min$ | 2.9×10^{17} | 4.5×10^{10} | 8.8×10^{7} | 1.6×10^{5} |

Longitudinal tensile Longitudinal compressive Transverse tensile Transverse compressive

5.2. Compressive Strength Analysis of Open-Hole Structures under Static Load

The SIFT method is used to predict the layup sequence [45/0/-45/90]_2s of IM600/TDE-85 laminate and the compressive strength under a static load of the open-hole structures. Then compare the predicted results with the analysis results of Tsai-Wu and Hashin theories. Figure 5 shows the three theoretical analyses of IM600/TDE-85 laminated plates with a layup sequence of [45/0/-45/90]_2s, and compares the static compressive load-displacement curves of open-hole structures with the experimental test curves. From figure 5, we can see that the load-displacement curve predicted by SIFT method is the best one matching the test result. And the predicted compressive load is 17.4kN with a relative error of 4.9% compared with the test; The compressive load predicted by Hashin theory is 16.5kN, with a relative error of 9.8% compared with the test; as predicted by the Tsai-Wu theory, the compressive load is 14.7kN, with a relative maximum error of 19.7% compared with the test.

Figure 5 The static loading compressive load-displacement curves of the AS4/3501-6 open-hole compressive constructions with a stacking sequence of [45/0/-45/90]_2s were compared between experiments and predictions.

Based on SIFT method, it analyses static load compressive failure mechanism of open-hole structures with a layup sequence of [45/0/-45/90]_2s, and IM600/TDE-85 laminate. Figure 6 shows the distribution cloud map of the failure indices for the first four layers of IM600/TDE-85 laminated plate open-hole structure under initial compressive failure. According to the SIFT theory, the failure of components can be determined when the maximum value of the three failure indices reaches 1. Figure 6 shows that the fiber failure index $k_f$ of the 0° layer is the first to reach 1 among the static load
compressive failure indices of the open-hole construction. This suggests that the failure of an open-hole structure under static compressive load is caused by the $0^\circ$ layer fiber at the pores’ edges failing.

Figure 6. The distribution of the initial failure indices of the first four layers of an open-hole compressive structure constructed of AS4/3501-6 laminate stacked in the order $[45/0/-45/90]_{2s}$ via static compression.

Through the SIFT method, we can analyse the final failure’s failure index distribution of each layer of open-hole structures under static load compression for laminate IM600/TDE-85, using a $[45/0/-45/90]_{2s}$ layup sequence and draw three failure index distribution cloud maps of every layer. By using SIFT method, figure 7 provides failure index distribution cloud maps of layers 1 to 4 for the open-hole laminated plate structure’s final failure under static load compression.

Figure 7. Under static compression, the final failure indices distribution of the first four layers of an open-hole compressive structure built of AS4/3501-6 laminate with stacking sequence $[45/0/-45/90]_{3s}$. 
We observed that the maximum value of the failure index on each layer shows a trend of linear expansion from the transverse edge of the pores to both sides of the plates, among which only the fiber failure occurred on both sides of the pores in the 0° layer (figure 7). The forms of failures that occurred on other layers are resin failures, among which the failure mechanism of ±45° layer includes both resin expansion failure and resin twist failure, and only resin twist failure occurred on the 90° layer. At the same time, it was noted that the resin expansion failure area on the 0° layer extended from the center line to 45°, which indicated that the resin expansion failure on the 0° layer was not only caused by the fiber failure but also caused by the influence of shear action, which resulted in the resin damage.

Figure 8 shows the scanning observation of the failure modes around the pores and the macro failure morphology of the whole structure when the open-hole structure of IM600/TDE-85 laminate fails initially under static load. From figure 8 (a), we can find that cracks appear in the 0° layer during the open-hole structure’s initial failure with load compression, which is consistent with the results of SIFT analysis. From figure 8 (b), it is found that cracks propagate linearly from both sides of the pores to both sides of the plates in the direction perpendicular to the load during the open-hole structure’s static load compressive failure, which is also consistent with the simulation results.

Figure 8. Failure mode of an open-hole compressive structure under static loading, the AS4/3501-6 laminate with stacking sequence [45/0/-45/90]_2s (a) Initial failure location observation (b) Macroscopic fracture surface.

5.3. Analysis of Open-Hole Structures’ Long-Term Static Compressive Life

According to the main strength curve of unidirectional laminated plated and the analysis of strain invariant theory, the strength of components varying with time can be obtained. The specific implementation method is as follows: Combine the strain amplification coefficient of the key points on the fiber and resin of IM600/TDE-85 unidirectional laminated plate, which was obtained by finite element analysis with macro strength of IM600/TDE-85 unidirectional laminated plates under the given time log t, and substitute them into equation (3), so as to get the micro strain of key points on fiber and resin in micro-unit cell model under 7 kinds of loads under the time log t. According to equation (1), we can calculate the maximum strain critical value at each key point of the components at this time. The failure strength of the component at this time can be obtained by stress-strain transformation.

The SIFT/ATM method predicts the long-term life of open-hole structures built of IM600/TDE-85 laminates with a stacking sequence of [45/0/-45/90]_2s, under static load compression, as illustrated in figure 9 under static load compression. The projected life matches the experimental data rather well. The developed SIFT/ATM method can forecast the CFRP laminate constructions’ long-term static strength.
Figure 9. The long-term static strength of the open-hole compressive structures is made of AS4/3501-6 laminates with a stacking sequence of [45/0/-45/90]s.

6. Conclusions
(1) The SIFT/ATM composite structures life analysis method has been developed through a combined and accelerated testing methodology (ATM) and strain invariant failure theory (SIFT) approaches. This method can efficiently and accurately predict the creep life of composite structures, which provides a new idea for the life design of composite structures.

(2) On the ABAQUS platform, we wrote VUMAT by using Fortran language and developed composite gradual failure procedures based on SIFT theory. These failure procedures combine SIFT theory with the model of element material stiffness degradation of laminated plates, which is related to composite component failure, and determines the failure category of composite components in the process of loading. Then according to the above, these failure procedures reduce the element material stiffness matrix of laminated plates, realizing dynamic track of the gradual damage process of laminated plates.

(3) By using SIFT method, we analyzed the gradual failure and load of IM600/TDE-85 laminate open-hole structures under static load compression, and compared these results with the analyzed results of theories of Hashin and Tsai-Wu. The results show that in terms of strength prediction, the SIFT method is the highest, with an average error of 4.9%. At the same time, the initial failure mechanism and failure mode of laminated plate open-hole structures under static load compression, which is predicted by SIFT method, are consistent with the experimental results.

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