MECHANICAL CHARACTERISTIC AND STRENGTH PREDICTION OF FILLED-HOLE COMPOSITE LAMINATE UNDER COMPRESSION LOADING

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0 Introduction

Mechanical connection method is commonly used in composite primary structures. However, the fastener would introduce the complicated stress field around the bolt hole, which would reduce the carrying capacity of the structure. And failure often occurs in the joint. At present, most of the existing composite aircraft structure design is still based on the allowable value of open-hole compressive strength. The results of a large number of experiments\(^1\) show that the hole of 6mm (tensile load for OHC laminates, compression load for FHC laminates) can represent the initial defects in composite structure, such as porosity, delamination, etc., which are allowed in manufacturing inspection. The corresponding allowable values of the tensile and compressive strength can be obtained by the specimens with typical stacking sequences containing the hole of 6mm. With regard to mechanical connection, it is too conservative to regard fastener hole as open-hole. The local stress field of filled-hole is the better representative of the fastener hole, which represents the special state in mechanical connection where the bolt does not carry loads. The load-carrying capacity of the structure can be improved by the allowable value of filled-hole compressive strength\(^2\). Therefore, the research on the mechanical response of FHC laminates under compressive loading has great significance.

With regard to FHC laminates, the stress distribution cannot be obtained by classical elastic mechanics method due to the contact surface of the filling bolt and laminate is not continuous, and their contact relationship would change with the deformation of the hole in the loading process. P. Berbinau et al\(^3\) simplify the FHC laminate as orthotropic plate containing a foreign circular inclusion based on the assumption of tight junction and no clearance between the inclusion and the laminate in loading process. Then the stress distribution of the laminate under biaxial tension-compression loading is obtained based on the stress distribution form deduced by S. G. Lekhnitskii\(^4\). Hindman and Horn\(^5\) has conducted research on the mechanical properties of FHC laminates under uniaxial tensile load from both aspects of theory and experiment. The calculation results of the laminate stress field obtained respectively by the finite element method and the Lekhnitskii’s analytical method\(^4\) are in quite good agreement with each other. Tsai\(^6\) extends the point stress criterion to the laminate containing the inclusion, for estimating its tensile strength. According to his experience, Tsai assumed that the characteristic length \(d_0\) in criterion is the same as that of open-hole laminate, so as to predict the ultimate bearing capacity of filled-hole laminate. Tan\(^7\) studies on the mechanical response of filled-hole orthotropic laminates under multi-axial loading. He obtained the laminate stress distribution based on the S.G. Lekhnitskii\(^4\) stress analysis method to determine the best filling scheme; in addition, Tan also used the point stress criterion and the average stress criterion to get laminate ultimate strength.

Both domestic and foreign scholars have conducted a lot of experiments on the mechanical properties of FHC laminates. B. Castanié et al\(^8\) have observed the progressive failure process of the filled-hole composite laminates under compression load by the high-speed camera, and found that the factors, such as stacking sequence, bolt material, bolt pre-torque, etc, can affect the ultimate strength and the failure mode of laminates. Adam J. Sawicki and Pierre J. Minguet\(^9\) analyzed the influence of different stacking sequences, clearances, and bolt pre-torques on the ultimate strength of the T800/3900-2 laminates. Experimental results indicate that the clearance can obviously affect the ultimate strength of laminates. For the filled-hole laminates with the same geometry, the clearance of 1.2% can reduce the laminate ultimate strength by 5%~10%, while the bolt pre-torque slightly affects the ultimate strength only about 1%. 


A predictive method, defining the carrying capacity proportion with load distribute factor, is proposed to estimate the compressive strength of filled-hole composite (FHC) laminates based on the load distribution between the composite plate and the bolt filled in the plate. The load distribute factor is derived respectively by the complex variables function and the finite element analysis methods. Based on the works above, the influences of the clearance and the pre-torque on the mechanical properties and the ultimate compressive stress of the composite laminates are verified. And finally, the state that the clearance and the pre-torque simultaneously act on the laminate is also considered. The experiments for the T700/LT-03A CFRP laminates with three different stacking sequences are taken to obtain the OHC and FHC strength. Comparison is also applied between the results from the proposed method and the experimental results of the T800/3900-2 shown in Ref. [9]. The proposed method could well predict the FHC strength with accuracy, and has certain significance in engineering.

1 Stress analysis and strength prediction method of laminated plate

The filled-hole composite laminate under uniaxial compression load is shown in Figure 1. The stress state of section m-n of OHC laminate is obviously different from that of FHC laminate: Under open-hole condition, load P is borne by the net cross-sectional area (W-d) t of section m-n; Under filled-hole condition, the filling bolt limits the hole deformation induced by compression loading, and prevents Point A, B on the hole center close to each other. The bolt has to bear self-balanced force P1, while the net cross-sectional area (W-d) only bears load P2=P-P1, as shown in Figure 2. Therefore, the filling bolt increases the load transfer path of the center section of the hole, reduces the stress level of the hole center section, and improves the ultimate bearing capacity of the laminate.

The load distribute factor α is used to measure the stress relaxing effect of the filling bolt on the center section of the hole in the laminate, which is perpendicular to the loading direction, reaches the ultimate strength of the corresponding OHC laminate, the FHC laminates reaches its ultimate strength. In other words, when \( P_2 \) in Figure 2(b) reaches the ultimate strength of the OHC laminate, the FHC laminate with the same stacking sequence fails. The compressive ultimate strength of the FHC laminate can be obtained by Formula (2):

\[
\sigma_{0}^{\text{FHC}} = \sigma_{0}^{\text{OHC}} / \alpha
\]

It should be noted that in this section the hole in the laminate are tightly filled with the bolts and there is no clearance or interference fit between the bolt and the hole. Simultaneously, only the uniaxial compression loading is considered. Filling bolts don’t transfer loads to other structural elements.

2 Calculation Methods for the load distribution factor

The load distribution factor (LDF) can be derived respectively by the complex variables function and the finite element analysis methods.

2.1. Complex variables function method\(^{3,4}\)

By means of the complex variable function method for solving the LDF of filled-hole composite laminate, the laminate is simplified as an orthotropic plate containing a foreign circular inclusion. The plate thickness is the same as the inclusion but the material is not the same. The inclusion and the plate are tightly connected without positive or negative tolerance. It is assumed that \( \Phi(z_1) \) and \( \Phi(z_2) \) are the stress functions under the open-hole condition, and \( \sigma_{s}^{0}, \sigma_{y}^{0}, \tau_{xy}^{0} \) are arbitrary remote loads. Then the stress field and the displacement field of an orthotropic plate containing a foreign circular inclusion can be expressed as:

\[
\begin{align*}
\sigma_{s} &= \sigma_{s}^{0} + 2 \text{Re}\{\mu_{1}z_{1}\Phi(z_{1}) + \mu_{2}z_{2}\Phi(z_{2})}\) \\
\sigma_{y} &= \sigma_{y}^{0} + 2 \text{Re}\{\phi_{1}(z_{1}) + \phi_{2}(z_{2})\) \\
\tau_{xy} &= \tau_{xy}^{0} - 2 \text{Re}\{\mu_{1}\phi_{1}(z_{1}) + \mu_{2}\phi_{2}(z_{2})\) \\
u &= u^{0} + 2 \text{Re}\{a_{1}\phi_{1}(z_{1}) + a_{2}\phi_{2}(z_{2})\} \quad w_{y} + w_{0} \\
v &= v^{0} + 2 \text{Re}\{b_{1}\phi_{1}(z_{1}) + b_{2}\phi_{2}(z_{2})\} \quad w_{x} + v_{0}
\end{align*}
\]

In which, \( u^{0}, v^{0}, w \) are the constants for rigid body displacement, and the complex parameters \( \mu_{1}, \mu_{2} \) of orthotropic plate in Formula (3) is the characteristic root of Equation (5):
\[ a_{11} \mu^4 - 2a_{10} \mu^2 + (2a_{12} + a_{20}) \mu^2 - 2a_{20} \mu + a_{22} = 0 \]  
(5)

As shown in Figure 3, the boundary conditions at the contact surface can be written as:

\[ X_a = -X_{core}, Y_a = -Y_{core} \]  
\[ u = u_{core}, v = v_{core} \]  
(6)

Considering the addition effect, the stress functions \( \Phi_1(z) \) and \( \Phi_2(z) \) of the laminate, which is obtained by S. G. Lekhnitskii \[ [4] \], can be expressed as:

\[
\phi_1(z_i) = \frac{1}{2(\mu_2 - \mu_1)}[(A - p)i - (B - q)\mu_2a + (C - r)(\mu_2b - a)]  \\
\phi_2(z_i) = -\frac{1}{2(\mu_2 - \mu_1)}[(A - p)i - (B - q)\mu_2a + (C - r)(\mu_2b - a)]
\]  
(7)

Thus, the stress distribution form \( \sigma_z(0, y) \) of the orthotropic plate containing the foreign circular inclusion under uniaxial compression load can be derived. Load \( P_2 \) for the laminate during the loading process can be derived by Formula (8).

\[
P_2 = \left( \int_{-R}^{R} \int_{-w/2}^{w/2} \sigma_z(0, y) dy + \int_{R}^{w/2} \sigma_z(0, y) dy \right) t
\]  
(8)

In which, \( R \) is the diameter of the hole; \( W \) is the width of the plate; \( t \) is the thickness of the plate.

If the uniformly distributed uniaxial compression load is set up as \( p \), the total load for the laminate can be derived:

\[
P = pwt
\]  
(9)

According to the definition, the LDF can be expressed as:

\[
\alpha = \frac{P_2}{P} = \frac{1}{w} \left( \int_{-R}^{R} \sigma_z(0, y) dy + \int_{R}^{w/2} \sigma_z(0, y) dy \right)
\]  
(10)

Then the compressive ultimate strength of the FHC laminate can be obtained according to the compressive ultimate strength of the OHC laminate.

### 2.2. Finite element method

The 3D model of the FHC laminate is established by the finite element analysis software ABAQUS. Considering the symmetry of the structure and the load, a 1/2 model of the laminate and filling bolt is established, using 3D eight node reduced integration element (C3D8R) to simulate the laminate and filling bolt. The laminate is divided into 2 layers along the direction of its thickness, and 20 UD plies with different material orientations are assigned to each layer unit according to the laminate stacking sequence in the "Composite Layups" under the "Part", so as to accomplish the simulation of the laminate stacking sequence. The connection relationship between the laminate and the filling bolt is stimulated by the contact type “Surface to Surface”. The established finite element model is shown as Figure 4.

The displacement is applied to the end of the model. In the subsequent processing, the support reaction force values of the laminate and bolt are extracted from the symmetry plane to sum up, so as to derive their sharing load. Then the LDF can be obtained.

### 3. Tests and Validation of strength prediction method

#### 3.1. Test process

In order to verify the accuracy of the strength prediction method, the compressive ultimate strength tests for OHC and the FHC laminates are conducted according to ASTM D6484 \[ [10] \] and ASTM D6742 \[ [11] \]. The test machine is MTS SANS 100KN.

The composite laminates are made of T700/LT-03A. Considering the influence of laminate stiffness on the compression performance of FHC, three kinds of stacking sequences are selected. The corresponding stacking sequences are shown in Table 1. The geometry size of specimens is shown in Figure 5. Inclusions were made of 30CrMnSiA, whose nominal diameter was 6mm.

The experimental setup is shown in Figure 6. Load is applied to the test piece at both ends by two rigid upper and lower plates. The experiment is controlled by displacement with the rate of 2mm/min. The extensometer gauged at 25mm is fixed on the side of the specimen to record the data of deformation.

#### 3.2. Experiment results

The compressive ultimate strength values of the OHC and the FHC laminates are summarized in Table 2. Considering the influence of different material systems, a set of data of the compression strength tests for the T800/3900-2 OHC and FHC laminates in Ref. [9] are cited. The laminates are numbered as OHC-4/FHC-4, whose test results are listed in Table 2.

Compared with the open-hole compressive ultimate strength, the bolt has provide another transfer path of load, significantly improved the ultimate strength of filled-hole laminates, increased by 28.29%, 30.67%, and 32.80% respectively.

#### 3.3. Validation of strength prediction method

Taking the FHC-2 composite laminate as an example, the load-displacement curve of the finite element
analysis model established above is compared with the test results, as shown in Figure 7. The finite element model can well simulate the load-displacement relationship of the laminate subjected to the compressive load. The finite element model has quite high accuracy.

According to the relevant material properties, the LDFs of the laminates with the corresponding stacking sequences can be respectively obtained by the complex variable function method and the finite element analysis method. According to the open-hole compressive strength test values and Formula (2), the compressive ultimate strength of the FHC laminate with the corresponding stacking sequence can be predicted. Comparison results are shown in Figure 8. It can be noted that the compressive ultimate strength values obtained by both methods are quite conservative, in which the error of complex variable function method are respectively -3.8%, -7.2%, -8.8%, -4.1%; the error of finite element method are respectively -3.5%, -6.5%, -8.1%, -1.8%. Therefore, the proposed prediction method can quite accurately predict the compression ultimate strength of FHC laminates, and the predicted values are quite conservative.

4 The influence of clearance and pre-torque

ASTM [11] clearly points out that the clearance between the hole and the fastener has special influence on the results of the compressive ultimate strength for the FHC laminates. The clearance of 25 μm may change the failure mode observed, and have the effect on the strength, which can reach 25%. [12] In addition, the pre-torque of the fastener can also influence the test results. Under the tension and compression condition, changes in the pre-torque of the fastener can change the failure load and the failure mode of the laminate obviously. Critical pre-torque conditions (the magnitude of clamping force) would change according to loading type, material system, laminate stacking sequence and test environment. Therefore, this paper analyzes the influence of clearance and pre-torque on the compressive ultimate strength of filled-hole structure from the aspect of load distribution.

4.1. The influence of clearance

Adam J. Sawickiet et al [9] have taken the compressive strength tests for the FHC laminates with different clearance to study on the compressive ultimate strength of the laminates. The compressive strength tests for the FHC laminates with two kinds of stacking sequences have been respectively conducted, whose clearance is 0.4% and 1.2% respectively, to analyze the influence form of clearance on their ultimate strength. The stacking sequences of laminates in Ref. [9] are shown in Table 3.

4.1.1 The FEM analysis of the influence of clearance

According to the parameters of the geometry dimensions and the mechanical performance of the laminates in the reference, the finite element model was established, and the mechanical response of the laminate under compression load has been obtained. And then the load distribution factors of the laminates with different clearances have been derived, and are used to estimate the laminate compressive ultimate strength. Comparison of predicted values and experimental values is shown in Table 4. Because defects such as porosity inevitably introduced during the manufacturing process in the specimen, the laminate stiffness is smaller than the theoretical value. So the load which the laminate actually bears is smaller than that obtained by finite element analysis; and the test values of ultimate strength are greater than prediction values. The ultimate strength predicted is conservative. The predicted results are less than the test results within 10%. Therefore, the proposed strength prediction method can quite accurately predict the compressive ultimate strength of the FHC laminates with the consideration of the clearance.

Concerning the clearance of 0.5%, the LDFs of the laminates with 3 kinds of stacking sequences change with the load during loading process, as shown in Figure 9. Taking the FHC-2 laminate as an example, when the load is less than 14.5% of the total load in the initial loading, the laminate and the filling bolt are not contacted, and the LDF stayed 1; With the increase of the load, the contact area between the laminate and the bolt increases, the proportion of the load borne by the laminate to the total load decreases, and the laminate reaches the ultimate strength and fails in the subsequent loading process. When the contact relation between the filling bolt and the laminate is stable, the LDF of the laminate is arranged in accordance with the stiffness in the loading direction of the laminate (FHC-1 < FHC-2 < FHC-3).

For the laminates with the same ply stacking sequence, the clearance increasing means that the
higher load is needed to make the laminate deform more so as to let the laminate and the filling bolt contact. But before this, the total load is borne by the laminate, LDF changes of laminate FHC-2 with different clearance during the loading process is as shown in Figure 10, the greater the clearance is, the less load the filling bolt shares. If the clearance is too large, the laminate does not contact with the bolt until it reaches the failure load, then the ultimate compressive strength is the open-hole ultimate compressive strength rather than the filled-hole ultimate compressive strength.

4.1.2. The influence factor of clearance

The influence factor of clearance $\alpha_{hc}$ is led into the strength prediction Formula (2), whose subscript HC is the abbreviation of Hole Clearance. So the LDF $\alpha$ changes into:

$$\alpha = \alpha_{hc}\alpha_{base} \quad (11)$$

In which, $\alpha_{base}$ is the LDF under no clearance condition.

The influence factors of the clearances can be obtained by FEM analysis, as shown in Table 5. It is found that the influence factors are all greater than 1. Therefore the existence of clearances can only reduce the compressive strength of the laminates. The larger the clearance is, the greater the influence factor is, which results in lower ultimate strength.

Moreover, for the composite laminates with the same clearance but different stacking sequences, the influence factors are not constant. The magnitude of influence factor is related to stacking sequences and others.

4.2. The influence of pre-torque

4.2.1. The FEM analysis of the influence of pre-torque

In accordance with the geometry dimension and the mechanics parameters of the laminates in Ref. [9], the composite laminate model is established with the consideration of pre-torque. Lacinate modeling method is the same as the above. The washer and the bolt made of 30CrMnSiA are simplified as I-shaped part, shown in Figure 11. The friction coefficient between CFRP laminates and the washer is set as 0.3.

In the finite element analysis software ABAQUS/Standard, bolt pre-torque is simulated by the “Bolt Load” in the Load module, which is applied on the pre-torque section. The bolt is set as the entity unit, divided by the cross section perpendicular to the bolt axial direction. And the pre-torque is applied on this section.

In the finite element simulation, the pre-torque is a force value, unit N. Therefore, the pre-torque has to be transformed into force from moment before calculation. The boundary constraints of the connecting bolt pre-torque is transferred into uniform load in Ref. [13], and applied on the surface contacted with the laminate joints and the upper/lower covers. Uniform load q can be calculated as:

$$q = \frac{M}{0.2 \times d \times A} \quad (12)$$

In which, M is pre-torque, A is the area of the surface contacted with the laminate and the single washer, d is the diameter of the bolt hole.

Thus, the bolt pre-torque can be obtained by Formula (13):

$$F = q \times A = \frac{M}{0.2 \times d} \quad (13)$$

This section analyzes the mechanical response of the laminates under different pre-torques by using the finite element software; and then the different LDFs are obtained, the compressive ultimate strengths of laminates are estimated. The comparison between the prediction values and the experimental values are shown in Table 5.

The compressive stress was generated between the laminate and the washer along the plate thickness direction under the pre-torque. The load borne by the laminate is transferred to the bolt by the friction between the washer and the laminate in the loading process. Compared with the bolt without pre-torque, the bolt with pre-torque bears heavier load. In addition, due to the effect of pre-torque, laminate generates the compressive stress along the direction of its thickness. Laminate would generate the in-plane tensile pre-stress due to the Poisson effect. The laminate would generate the compressive stress only if the in-plane tensile pre-stress is offset in the sequent loading process. Therefore, comparing the laminate with the filled pin, the preloaded bolt bears higher load in the loading process, the load distribution coefficient of the laminate is correspondingly reduced and increases the compressive ultimate strength of the laminate.

It is pointed out in Ref. [9] that under the same pre-torque, reducing the diameter of the washer would improve the pre-tress between the laminate and the gasket. Then the laminate would generate greater in-plane tensile pre-stress, therefore the tensile ultimate strength of the laminate reduces with
the decreasing diameter of the gasket. When the laminate is subjected to compressive load, the tensile pre-stress takes positive effect on its strength. The increasing tensile pre-stress can improve its compressive ultimate strength. It is also known by Formula (12) that the increasing diameter of the gasket can improve the compressive ultimate strength of the laminates under the same pre-torque.

The size of the washer is not given in reference. So the washer diameter is considered as two times as the diameter of the hole, namely 12.7mm (0.5in). On the basis of this hypothesis, the predicted value of compressive ultimate strength of laminated is less than the experimental value, and the error is about 10%.

In addition, the finite element model for the T700/LT-03A laminates with 3 kinds of stacking sequences is established, considering the mechanical response of the CFRP laminates under the bolt pre-stresses of 0KN, 3KN, 6KN (corresponding to the pre-torque of 0N\cdot M, 3.5N\cdot M, 7N\cdot M, in which the pre-torque of 0N\cdot M means that the hole is filled with the bolt, and the slight force is applied just to keep the contact relationship between washer and laminate, not to generate any pre-stress), so as to analyze the influence of different pre-torques on the LDFs and the compressive ultimate strength of the laminates. The results are listed in Table 6.

The simulation results are consistent with the above conclusion: increasing the bolt pre-torque can improve the compressive ultimate strength of laminates. But the pre-torque does not contribute a lot to the compressive ultimate strength. Taking the FHC-1 as an example, the compressive ultimate strength of the laminate under the 7N\cdot M pre-torque is 1.2% higher than that under the 0N\cdot M pre-torque.

In addition, although the 0N-M pre-torque does not provide the pre-stressing force for the laminates, however, during the subsequent loading process, laminates generate the deformation in the thickness direction under the in-plane compression loads. The washer limits the deformation of the laminate in thickness direction, which generates the in-plane tensile stress of laminate, so as to relieve the stress of laminate. Therefore, the compressive ultimate strength of the FHC laminate under the 0N-M pre-torque is slightly higher than that of the laminate with filling pin.

The change of the load distribution factors of Laminate FHC-1 under the various pre-torques with the change of the external load is shown in Figure 12. Because of the existence of tension pre-stress, the laminates under 3.5N\cdot M and 7N\cdot M pre-torque have to offset the pre-torque at the initial stage of the load, the LDF is small; with the loading proceeding, the proportion of the pre-torque to the total load gets smaller and smaller which can be neglected. And the load distribution factor increases to a stable value.

4.2.2. The influence factor of pre-torque

The influence factor of pre-torque \( \alpha_{pr} \) is led into the strength prediction Formula (2), whose subscript \( PT \) is the abbreviation of pre-torque. So the LDF \( \alpha \) changes into:

\[ \alpha = \alpha_{pr} \alpha_{base} \] (11)

In which, \( \alpha_{base} \) is the load distribution factor under no pre-torque condition.

The influence factors of the pre-torques can be obtained by FEM analysis, as shown in Table 8. It is found that the influence factors are all less than 1, therefore the existence of pre-torques can increase the compressive strength of the laminates. The larger the pre-torque is, the less the influence factor is, which results in higher ultimate strength.

Moreover, for the composite laminates with the same pre-torque but different stacking sequences, the influence factors are not constant. The magnitude of influence factor is related to stacking sequences and others.

4.3. The influence of clearance and pre-torque simultaneously acting on the composite laminates

4.3.1. Basic hypothesis

The influence factors of clearance and pre-torque are respectively obtained above. Now it is assumed that when clearance and pre-torque simultaneously act on the composite laminates, the load distribution factor can also be used to predict the compressive strength. And the influence factor under this condition can be derived by superimposing the influence factors of them two alone. In the other words, during the loading process, the coupling between clearance and pre-torque can be ignored.

The load distribution factor \( \alpha \) in Formula (2) can be expressed as:

\[ \alpha = \alpha_{IC} \alpha_{pr} \alpha_{base} \] (14)

In which, \( \alpha_{base} \) means the LDF with no clearance or pre-torque, \( \alpha_{IC} \) means the LDF related to clearance, and \( \alpha_{pr} \) means the LDF related to pre-torque.

4.3.2. The experiments and the FEM analysis
A. J. Sawicki et al.[9] have conducted the compressive strength tests for the FHC laminates, in order to analyze the changes of the FHC-4 compression strength with the clearance of 0.4% or 1.2% and under the pre-torque of 0.56N·m (manual condition) or 9.6 N·m (mechanical condition). The results of the tests are shown in Table 9. With the same pre-torque, the increase of the clearance will reduce the compressive strength of the laminates. However, the influence of the pre-torque on the laminates with the same clearance doesn't have regular trends.

The FEM models were established according to the geometry dimensions and mechanical parameters in Ref. [14]. The modeling method for the bolt and plate is similar to that in the Section 4.2.1., expect that the influence of clearance is also considered. The LDFs under the conditions above are obtained respectively by Formula (14) and the FEM analysis, which can be used to predict the compressive strength of the laminates. The prediction results shown in Table 9.

Because of the spacer dimension, the prediction compression strength obtained by both the analytic method and the FEM analysis is lower than the test one, whose maximum error is about 15%.

However, the predictive results are closed to each other. Therefore, the coupling between clearance and pre-torque can be ignored. And the influence factor under this condition can be derived by superimposing the influence factors of clearance and pre-torque alone respectively.

5 Conclusions

A predictive method for the compressive ultimate strength of the filled-hole composite laminates has been proposed, based on the load distribution between the bolt and the laminate under uniaxial compressive load. The LDF has been derived respectively by the complex variables function and the finite element analysis methods. And the compressive strength has been predicted. Compared with the test results, the proposed method can well predict the FHC strength with accuracy.

The test for the compressive ultimate strength of the T700/LT-03A OHC and FHC laminates with three kinds of stacking sequences has been conducted. The test results indicate that the filling bolt effectively increases the carrying capacity. The compressive strength of FHC laminates is 30% higher than that of the OHC laminates.

The influence of clearance and pre-torque of on the ultimate compressive ultimate strength of FHC laminate is analyzed. The existence of clearance can obviously reduce the ultimate carrying capacity of laminates; while the pre-torque applied on the filling bolt can slightly increase the ultimate carrying capacity of the laminates.

Without the consideration of the coupling between clearance and pre-torque when they act on the laminates simultaneously, the quantitative analysis is conducted. The LDF of clearance and pre-torque is led into the strength prediction formula, in order to predict the compressive ultimate strength. Compared with the test results in the reference, the method has quite high accuracy.

References


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Table 1 Specimen number and stacking sequence

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Stacking Sequence</th>
<th>0/±45/90 Proportion</th>
<th>Numbers of Layers</th>
<th>Material</th>
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<tr>
<td>OHC-1/FHC-1</td>
<td>$[\pm 45/90/\pm 45/\pm 45/\pm 45]_{\text{as}}$</td>
<td>10/80/10</td>
<td>40</td>
<td>T700/LT-03A</td>
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<td>OHC-2/FHC-2</td>
<td>$[45/0/-45/90]_{\text{as}}$</td>
<td>25/50/25</td>
<td>40</td>
<td>T700/LT-03A</td>
</tr>
<tr>
<td>OHC-3/FHC-3</td>
<td>$[45/0/-45/90/0]_{\text{as}}$</td>
<td>40/40/20</td>
<td>40</td>
<td>T700/LT-03A</td>
</tr>
</tbody>
</table>

Table 2 Test result of OHC & FHC ultimate strength

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>OHC Test Value, MPa</th>
<th>FHC Test Value, MPa</th>
<th>Ultimate Strength increasing rate, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>OHC-1/FHC-1</td>
<td>255.2</td>
<td>327.4</td>
<td>28.29</td>
</tr>
<tr>
<td>OHC-2/FHC-2</td>
<td>301.3</td>
<td>393.7</td>
<td>30.67</td>
</tr>
<tr>
<td>OHC-3/FHC-3</td>
<td>340.0</td>
<td>444.5</td>
<td>32.80</td>
</tr>
<tr>
<td>OHC-4/FHC-4</td>
<td>394.1</td>
<td>478.0</td>
<td>21.29</td>
</tr>
</tbody>
</table>

Table 3 Stacking sequence of composite laminate

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Stacking Sequence</th>
<th>0/±45/90 Proportion</th>
</tr>
</thead>
<tbody>
<tr>
<td>OHC-4/FHC-4</td>
<td>$[45/90/-45/0, /\pm 45/0, /\pm 45]$</td>
<td>50/42/08</td>
</tr>
<tr>
<td>OHC-5/FHC-5</td>
<td>$[45/90/-45/0, /45/0, /-45]$</td>
<td>62/29/09</td>
</tr>
<tr>
<td>OHC-6/FHC-6</td>
<td>$[45/90/-45/\pm 45/0, /\pm 45]$</td>
<td>33/56/11</td>
</tr>
</tbody>
</table>

Table 4 Comparison between predicting result and test result of filled-hole compressive ultimate strength

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>OHC or FHC</th>
<th>Diameter /mm</th>
<th>Clearance /%</th>
<th>Compressive Strength (Test Value) /MPa</th>
<th>Load Distribution Factor</th>
<th>Compressive Strength (Predicted Value) /MPa</th>
<th>Error /%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>OHC</td>
<td>6.35</td>
<td>—</td>
<td>394.8</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>OHC-4/FHC-4</td>
<td>FHC</td>
<td>6.35</td>
<td>—</td>
<td>480.4</td>
<td>0.835</td>
<td>471.9</td>
<td>-1.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.43</td>
<td>0.4</td>
<td>489.1</td>
<td>0.859</td>
<td>458.6</td>
<td>-6.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.43</td>
<td>1.2</td>
<td>458.6</td>
<td>0.893</td>
<td>441.4</td>
<td>-3.8</td>
</tr>
<tr>
<td></td>
<td>OHC</td>
<td>6.35</td>
<td>—</td>
<td>473.1</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>OHC-5/FHC-5</td>
<td>FHC</td>
<td>6.38</td>
<td>0.4</td>
<td>577.6</td>
<td>0.862</td>
<td>548.6</td>
<td>-5.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.43</td>
<td>1.2</td>
<td>523.9</td>
<td>0.891</td>
<td>530.7</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>OHC</td>
<td>6.35</td>
<td>—</td>
<td>330.9</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>OHC-6/FHC-6</td>
<td>FHC</td>
<td>6.38</td>
<td>0.4</td>
<td>396.2</td>
<td>0.857</td>
<td>386.1</td>
<td>-2.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.43</td>
<td>1.2</td>
<td>362.8</td>
<td>0.898</td>
<td>368.4</td>
<td>1.6</td>
</tr>
</tbody>
</table>
### Table 5 Influence factor of composites ultimate strength with clearance

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Clearance of 0.5%</th>
<th>Clearance of 1.0%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LDF</td>
<td>$\alpha_{HC}$</td>
</tr>
<tr>
<td>FHC-1</td>
<td>0.807</td>
<td>1.053</td>
</tr>
<tr>
<td>FHC-2</td>
<td>0.819</td>
<td>1.042</td>
</tr>
<tr>
<td>FHC-3</td>
<td>0.832</td>
<td>1.032</td>
</tr>
</tbody>
</table>

### Table 6 Ultimate strength of composites OHC-4/FHC-4 under different pre-torque

<table>
<thead>
<tr>
<th>OHC or FHC</th>
<th>Compressive Strength (Test Value)/MPa</th>
<th>Load Distribution Factor</th>
<th>Compressive Strength (Predicted Value)/MPa</th>
<th>Error/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>OHC</td>
<td>394.8</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Hole Filled with Dowel</td>
<td>480.4</td>
<td>475.0</td>
<td>0.831</td>
<td>-1.1</td>
</tr>
<tr>
<td>Pre-torque of 0.56N·M</td>
<td>529.5</td>
<td>475.8</td>
<td>0.830</td>
<td>-10.2</td>
</tr>
<tr>
<td>Pre-torque of 9.6N·M</td>
<td>526.0</td>
<td>479.0</td>
<td>0.824</td>
<td>-8.9</td>
</tr>
</tbody>
</table>

### Table 7 Predictive ultimate compressive strength of composites with pre-torque

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>OHC Test Value /MPa</th>
<th>Hole Filled with Dowel</th>
<th>Pre-torque of 0N·M</th>
<th>Pre-torque of 3.5N·M</th>
<th>Pre-torque of 7N·M</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Load Distribution Factor</td>
<td>Predicted Value /MPa</td>
<td>Load Distribution Factor</td>
<td>Predicted Value /MPa</td>
<td>Load Distribution Factor</td>
</tr>
<tr>
<td>FHC-1</td>
<td>255.2</td>
<td>0.807</td>
<td>316.1</td>
<td>0.802</td>
<td>318.0</td>
</tr>
<tr>
<td>FHC-2</td>
<td>301.3</td>
<td>0.819</td>
<td>368.0</td>
<td>0.815</td>
<td>369.7</td>
</tr>
<tr>
<td>FHC-3</td>
<td>340.0</td>
<td>0.832</td>
<td>408.4</td>
<td>0.829</td>
<td>410.3</td>
</tr>
</tbody>
</table>

### Table 8 Influence factor of composites ultimate strength with pre-torque

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>No Pre-torque</th>
<th>Pre-torque of 3.5N·M</th>
<th>Pre-torque of 7N·M</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LDF</td>
<td>LDF</td>
<td>$\alpha_{FT}$</td>
</tr>
<tr>
<td>FHC-1</td>
<td>0.802</td>
<td>0.796</td>
<td>0.993</td>
</tr>
<tr>
<td>FHC-2</td>
<td>0.815</td>
<td>0.810</td>
<td>0.994</td>
</tr>
<tr>
<td>FHC-3</td>
<td>0.829</td>
<td>0.825</td>
<td>0.995</td>
</tr>
</tbody>
</table>

### Table 9 Ultimate compressive strength prediction of composites FHC-4 with clearance and pre-torque

<table>
<thead>
<tr>
<th>Clearance and Pre-torque</th>
<th>Test Results</th>
<th>Predictive Values by Analytic Method</th>
<th>Predictive Values by FEM Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sigma_{FHC}$/MPa</td>
<td>$\alpha$</td>
<td>$\sigma_{FHC}$/MPa</td>
</tr>
<tr>
<td>0.4% 0.56N·M</td>
<td>538.1</td>
<td>0.860</td>
<td>459.1</td>
</tr>
<tr>
<td>0.4% 9.6N·M</td>
<td>530.1</td>
<td>0.840</td>
<td>470.0</td>
</tr>
<tr>
<td>1.2% 0.56N·M</td>
<td>481.5</td>
<td>0.874</td>
<td>451.7</td>
</tr>
<tr>
<td>1.2% 9.6N·M</td>
<td>495.7</td>
<td>0.853</td>
<td>462.8</td>
</tr>
</tbody>
</table>