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Macro-mechanical analysis of tensile strength of glass/carbon fiber reinforced plastics hybrid composites under hydrothermal environment

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**Abstract**

The material properties of composite materials are affected by changes in temperature and moisture. This study used the glass/carbon fiber reinforced plastic hybrid composite (G/CFRPHC) laminate as the research objects. The stiffness and strength of the composite lamina were expressed as a function of hydrothermal parameters. Based on classical lamination theory (CLT) and macro-mechanical analysis, using MATLAB programming, the tensile strength of G/CFRPHC laminates under a hydrothermal environment was studied. In addition, the influence of temperature, ply thickness, ply stacking sequence, and ply angle on the tensile strength of G/CFRPHC laminates under a hydrothermal environment was discussed. The results show that the tensile strength of G/CFRPHC laminates decreases with the increase of temperature and laying angle in the temperature range of 20°C ~ 110°C in the hydrothermal environment (moisture absorption rate \(C_1 = 0.5\%\)). Furthermore, for the G/CFRPHC laminates with laying modes of \((0_2G/90_mC)_S, (0_4G/90_mC)_S, (0_6G/90_mC)_S\) as \(m\) increases, their tensile strength gradually decreases. The tensile strength of G/CFRPHC laminates with the same ply angle but different ply stacking sequence is also not the same.

**1. Introduction**

In recent years, fiber hybrid composite materials have been widely used in aerospace, wind turbine blades, automobiles, civil infrastructure, and other fields due to their high designability. As a result, they have broad application prospects in the future [1–4]. However, as the composite material will be exposed to the hydrothermal environment for a long time during transportation and use, the mechanical properties of materials will decrease [5]. And then affect the strength of composites [6–8].

At present, many scholars at home and abroad have explored and studied the strength of composite materials under hydrothermal environments. Through experiments and finite element analysis, Zhao Y [9] established a prediction model for the tensile strength of resin-based fiber-reinforced composite laminates under hydrothermal conditions but only considered single fiber-reinforced composite materials. Barbero E J [10] established a model to predict the tensile strength of unidirectional e-glass fiber composites in a hydrothermal environment. However, this model is based on the curve fitting of data and is aimed at single fiber-reinforced composite materials. Xu H H [11] studied the tensile strength of multi-directional G/CFRPHC through experiments and finite element analysis but did not consider the influence of the hydrothermal environment on its tensile strength. Literature [12–17] found through hydrothermal aging experiments that the tensile strength of composite materials significant declined when exposed to a hydrothermal environment for a long time. Through experiments, Cao S et al [18] studied the tensile strength of carbon fiber reinforced composites, glass/carbon fiber reinforced plastic hybrid composite, and carbon fiber/basalt fiber reinforced...
plastic hybrid composites at high temperatures. The results show that the tensile strength of different fiber-reinforced polymer (FRP) laminates will decrease significantly with increasing temperature. Through experimental research, Naito K et al [19] found that the tensile strength of G/CFRPHC increased with the increase of carbon fiber volume fraction and decreases with temperature rise. The literature [18, 19] is based on experimental research, without detailed theoretical analysis, and does not consider the effect of moisture on its tensile strength. Ali J SM et al [20] analyzed the bending strength of composite laminates under thermal and mechanical coupling based on high-order shears deformation theory. Shen H S [21] studied the bending strength of composite laminates under thermal and mechanical coupling and elastic foundation. Although the literature [20, 21] analyzed the strength of composite materials based on theory, it only considered the influence of temperature and did not consider the impact of moisture changes.

Through reviewing relevant literature, it is found that many scholars at home and abroad have conducted relevant researches on the tensile strength of composites under hydrothermal environment. But it mainly focuses on experimental research, with relatively little theoretical research. Moreover, the influencing factors considered by various scholars also have their emphasis, and single fiber-reinforced composite materials are mainly studied. However, there are few reports on the effect of the hydrothermal environment on the tensile strength of G/CFRPHC.

The current theoretical research on the strength of composite materials under hydrothermal environment only considers the hydrothermal load caused by the hydrothermal environment while ignoring its impact on the properties of composite materials. This article starts from the perspective of macro-mechanics. For G/CFRPHC laminates, considering the hydrothermal load generated by the hydrothermal environment and the impact on the composite material performance, a prediction model of the tensile strength of G/CFRPHC under the hydrothermal environment is established. It optimizes the strength calculation theory of composite laminates. It discusses the influence of temperature, layer thickness, ply stacking sequence, and laying angle on the tensile strength of G/CFRPHC laminates under a hydrothermal environment. Thus, it has crucial theoretical guiding significance for the structural design, manufacturing, use, and strength prediction of G/CFRPHC laminates in hydrothermal environments.

2. Theoretical analysis

Assume that the room temperature is 20 °C and the working temperature is 20 °C ~ 110 °C. This study used the (G/CFRPHC) laminate as the research objects. The laminate thickness is T. The G/CFRPHC laminate is in a hydrothermal environment (the moisture absorption rate of the laminate is $C_1 = 0.5\%$), and an in-plane tensile load $N_x$ is applied to it. As shown in figure 1.

2.1. Degradation model of a composite lamina under hydrothermal environment

Reference [22], in this study, the lamina elastic parameters ($E_{11}, E_{22}, G_{12}, G_{23}$), coefficient of damp thermal expansion ($\beta_{11}, \beta_{21}, \alpha_{11}, \alpha_{21}$), in the hydrothermal environment has a linear relationship with the temperature change ($T_1$) and the moisture absorption rate ($C_1$), as follows
\[ E_{11} = E_{10}(1 + \alpha_{11}T_1 + E_{111}C_l) \]
\[ E_{22} = E_{20}(1 + \alpha_{21}T_1 + E_{211}C_l) \]
\[ G_{12} = G_{120}(1 + \alpha_{11}T_1 + G_{121}C_l) \]
\[ G_{13} = G_{130}(1 + \alpha_{11}T_1 + G_{131}C_l) \]
\[ G_{23} = G_{230}(1 + \alpha_{21}T_1 + G_{231}C_l) \]
\[ \alpha_1 = \alpha_{10}(1 + \alpha_{11}T_1), \quad \beta_1 = \beta_{10}(1 + \beta_{11}C_l) \]
\[ \alpha_2 = \alpha_{20}(1 + \alpha_{21}T_1), \quad \beta_2 = \beta_{20}(1 + \beta_{21}C_l) \]  

(1)

Where \( E_{111}, E_{211}, G_{121}, G_{131}, G_{231}, \alpha_{11}, \alpha_{21}, \beta_{11}, \) and \( \beta_{21} \) are constant coefficients of hydrothermal. On the other hand, \( E_{10}, E_{20}, G_{120}, G_{130}, G_{230}, \alpha_{10}, \alpha_{20}, \beta_{10}, \) and \( \beta_{20} \) are in the dry environment at room temperature of mechanical parameters of the material. Therefore, because Poisson’s ratio is little affected by the hydrothermal climate, it can be regarded as unchanged.

2.2. Stress analysis of G/CFRPHC laminate under hydrothermal environment

2.2.1. Calculation of the off-axis stiffness matrix of a lamina of different materials

Considering the lamina as an orthotropic material, according to the engineering elastic constant of the single layer, the positive axis stiffness matrix of the carbon fiber/epoxy lamina and glass fiber/epoxy lamina of any layer (assuming the kth layer) can be respectively calculated:

\[
\begin{bmatrix}
Q_{11} & Q_{12} & 0 \\
Q_{12} & Q_{22} & 0 \\
0 & 0 & Q_{66}
\end{bmatrix}_k =
\begin{bmatrix}
\frac{E_{11}}{1-\nu_{12}\nu_{21}} & -\frac{\nu_{12}E_{22}}{1-\nu_{12}\nu_{21}} & 0 \\
-\frac{\nu_{21}E_{22}}{1-\nu_{12}\nu_{21}} & \frac{E_{22}}{1-\nu_{12}\nu_{21}} & 0 \\
0 & 0 & G_{12}
\end{bmatrix}
\]  

(2)

According to the positive axis stiffness matrix, the off-axis stiffness matrix of any layer (assuming the kth layer) of the fiber-reinforced composite lamina can be calculated as follows:

\[ I[Q]_k = [T_k]^{-1}[Q]_k([T_k]^{-1})^T \]  

(3)

2.2.2. Calculation of flexibility matrix of G/CFRPHC laminate

Since the G/CFRPHC laminates studied in this paper are symmetrical, the coupling stiffness matrix is \( [B] = 0 \).

\[ A_y = \sum_{k=1}^n (\bar{Q}_y)\alpha(z_k - z_{k-1}) \]  

(4)

\[ D_y = \frac{1}{3} \sum_{k=1}^n (\bar{Q}_y)\alpha(z_k^2 - z_{k-1}^2) \]  

(5)

Since the G/CFRPHC laminate is studied in this paper, when \( k \) is the glass fiber/epoxy resin layer, \( Q_y \) is the off-axis stiffness of the glass fiber/epoxy lamina. When \( k \) is the carbon fiber/epoxy resin layer, \( Q_y \) is the off-axis stiffness of the carbon fiber/epoxy lamina. Because \( [B] = 0 \), the flexibility matrix of the G/CFRPHC laminate is calculated as follows:

\[
\begin{bmatrix}
A_{11} & A_{22} & 0 \\
A_{12} & A_{22} & 0 \\
0 & 0 & A_{66}
\end{bmatrix}^{-1}
\]  

(6)

\[
\begin{bmatrix}
D_{11} & D_{22} & 0 \\
D_{12} & D_{22} & 0 \\
0 & 0 & D_{66}
\end{bmatrix}^{-1}
\]  

(7)

2.2.3. Calculation of the off-axis hydrothermal expansion coefficient of the lamina of different layers and different materials

In actual engineering, each layer of composite laminates is mostly off-axis. Thus, for any \( k \)-layer G/CFRPHC laminates, the off-axis hydrothermal expansion coefficient is:

\[
\begin{bmatrix}
\alpha_k \\
\alpha_y \\
\alpha_{1y}
\end{bmatrix}_k = [T_k^T \begin{bmatrix}
\alpha_1 \\
\alpha_2 \\
0
\end{bmatrix}]
\]  

(8)
\[
\{ \beta \}_k = \begin{bmatrix} \beta_x \\ \beta_y \\ \beta_{xy} \end{bmatrix} = [T]_k^T \begin{bmatrix} \beta_1 \\ \beta_2 \\ 0 \end{bmatrix}
\] (9)

2.3. Calculation of the wet internal force and thermal internal force of G/CFRPHC laminates

The temperature and moisture environment of the G/CFRPHC laminates studied in this paper is uniformly changed, unchanged along the thickness direction, only the last amount of change is considered, and the change process is not considered. Calculate the wet internal force and thermal internal force of the G/CFRPHC laminate as follows

\[
\{ N^T \} = \sum_{k=1}^{n} \tilde{Q}_k \{ \alpha \}_k T_i (z_k - z_{k-1})
\] (10)

\[
\{ N^H \} = \sum_{k=1}^{n} \tilde{Q}_k \{ \beta \}_k G_i (z_k - z_{k-1})
\] (11)

Since this paper takes G/CFRPHC laminate as the research object, the \( \tilde{Q}_k \), \( \{ \alpha \}_k \) and \( \{ \beta \}_k \) of different material layers are different. First \( \{ N^T \} \) is the thermal internal force of the G/CFRPHC laminate. The second \( \{ N^H \} \) is the wet internal force of the G/CFRPHC laminate.

2.4. Calculation of the spindle stress of each lamina in the G/CFRPHC laminate

The CLT of G/CFRPHC laminate in a hydrothermal environment is

\[
\begin{bmatrix} \varepsilon^0 \\ \kappa \end{bmatrix} = \begin{bmatrix} A^B \\ B^T D^T \end{bmatrix} \begin{bmatrix} N \\ M \end{bmatrix} + \begin{bmatrix} N^T \\ M^T \end{bmatrix} + \begin{bmatrix} N^H \\ M^H \end{bmatrix}
\] (12)

Since the G/CFRPHC laminate studied in this paper only bears the action of the in-plane force \( \{ N \} \), the components of the in-plane moment \( \{ M \} \) are zero, and all of the elements of \( \{ \kappa \} \) is also zero. In the state of plane stress, the relationship between wet internal force, thermal internal force and external load and midplane strain can be obtained from the composite material in a hydrothermal environment CLT as follows

\[
\{ \varepsilon^0_N \} = [A'] \{ N \}
\] (13)

\[
\{ \varepsilon^0_T \} = [A'] \{ N^T \}
\] (14)

\[
\{ \varepsilon^0_H \} = [A'] \{ N^H \}
\] (15)

Where \( \{ \varepsilon^0_N \} \) is the midplane strain caused by the external load, \( \{ \varepsilon^0_T \} \) is the midplane strain caused by temperature, \( \{ \varepsilon^0_H \} \) is the midplane strain caused by moisture.

Since the various components of \( \{ \kappa \} \) are zero, the strain \( \{ \varepsilon^N \} \) caused by the external load at any point in the lamina is equal to the midplane strain \( \{ \varepsilon^0_N \} \) caused by the external load, that is

\[
\{ \varepsilon^N \} = \{ \varepsilon^0_N \}
\] (16)

In the same way, the total hydrothermal strain \( \{ \varepsilon^S \} \) caused by temperature and moisture at coordinate \( z \) at any point of each lamina can be calculated as follows

\[
\{ \varepsilon^S \} = \{ \varepsilon^0_H \} + \{ \varepsilon^0_T \}
\] (17)

The lamina assumed in this paper is unconstrained, and the free wet-heat deformation \( \{ \varepsilon^f \} \) of the lamina of different materials can be calculated as follows

\[
\{ \varepsilon^f \} = \{ \alpha \} T_i + \{ \beta \} G_i
\] (18)

The total hydrothermal strain and the free hydrothermal strain of lamina of different materials can be calculated to obtain the residual strain \( \{ \varepsilon^R \} \) at each point in the G/CFRPHC laminate as follows

\[
\{ \varepsilon^R \} = \{ \varepsilon^S \} - \{ \varepsilon^f \}
\] (19)

The strain caused by the external load and the residual strain at each point in the laminate can be used to obtain the off-axis strain \( \{ \varepsilon \}_k \) of the lamina in a hydrothermal environment as follows

\[
\{ \varepsilon \}_k = \{ \varepsilon^N \}_k + \{ \varepsilon^R \}_k
\] (20)

According to the calculated off-axis strain of the lamina under the hydrothermal environment, the principal axis stress \( \{ \sigma \}_k \) of the lamina with different material layers can be obtained in the following

\[
\{ \sigma \}_k = [T]_k^{-1} [\bar{Q}] \{ \varepsilon \}_k
\] (21)
2.5. Calculation of tensile strength of G/CFRPHC laminate under hydrothermal environment

The strength of the laminated board is related to the strength of the lamina. Therefore, to consider the influence of the hydrothermal environment on the mechanical properties of the lamina, the power function of the dimensionless temperature $T^*$ proposed by Tsai [23] can be introduced to modify the strength of the lamina.

![Flow chart of calculating the tensile strength of G/CFRPHC under hydrothermal environment.](image)

**Figure 2.** Flow chart of calculating the tensile strength of G/CFRPHC under hydrothermal environment.

The single layer in the glass/carbon fiber reinforced plastic hybrid composite laminate is destroyed.

Whether all single layer is destroyed?

- Yes
- No

Output tensile strength. Make stiffness correction.
expressions are as follows

\[ X_i = \left( T^* \right) X_0^i \]  \hspace{1cm} (22)

\[ X_c = \left( \frac{G_{12}}{G_{11}} \right)_{614G} \left( T^* \right) X_0^c \]  \hspace{1cm} (23)

\[ Y_i = \left( T^* \right) Y_0^i \]  \hspace{1cm} (24)

\[ Y_c = \left( \frac{G_{12}}{G_{11}} \right)_{614G} \left( T^* \right) Y_0^c \]  \hspace{1cm} (25)

\[ S_{12} = \left( T^* \right) S_{12}^0 \]  \hspace{1cm} (26)

\[ T^* = T_g^0 - \frac{T_{pr}}{T_g^0 - T_{tm}} \]  \hspace{1cm} (27)

\[ T_g = T_g^0 - kC_1 \]  \hspace{1cm} (28)

The superscript 0 at formulas (22)–(28) represents the material’s mechanical properties in the dry state at room temperature. \( X_i, X_c, Y_i, Y_c \), and \( S_{12} \) are the longitudinal tensile, compressive strength, transverse tensile, compressive strength, and in-plane shears strength of the lamina in a hydrothermal environment. \( f-k \) is the hydrothermal degradation constant. The glass transition temperature of the material at room temperature is \( T_g^0 \). \( T_g \) is the glass transition temperature of the material at the working temperature.

It is shown in the literature [24] that the Hoffman strength criterion is relatively close to the experimental measurement value. Therefore, the principal axis stress of each lamina obtained by formula (21) is substituted into the Hoffman strength criterion to calculate the strength of the G/CFRPHC laminate.

\[ \sigma_j^2 X_j X_c - \sigma_1^2 X_c X_j + \sigma_2^2 X_c X_j + \left( \frac{X_j - X_c}{Y_j Y_c} \right) \sigma_1^2 + \left( \frac{X_j - Y_j}{Y_j Y_c} \right) \sigma_2^2 + \frac{\tau_{12}^2}{S^2} = 1 \]  \hspace{1cm} (29)

\( \sigma_1, \sigma_2 \)-refers to the stress in the lamina’s first and second main directions. \( \tau_{12} \)-refers to the shear stress of the 1–2 plane of the lamina.

2.6. Stiffness correction of the lamina in a hydrothermal environment

As long as the strength of single or multiple layers in the composite laminates fails, the laminate will have stiffness reduction, and the stress of the single-layer will be redistributed. Therefore, it is necessary to calculate the residual stiffness of the laminate again to determine the internal force of the other lamina. This paper adopts the method of stiffness reduction correction of partial failure assumption. After the stiffness is corrected, continue applying the tensile load at the x-direction, performing stiffness correction, stress redistribution, Hoffman strength criterion checks, judging whether it fails, and iterating until all layers are destroyed. The ultimate strength obtained is the tensile strength of the G/CFRPHC laminate.

3. Program design and verification

It is highly complex to calculate the tensile strength of G/CFRPHC laminates based on the classical composite laminate strength theory. This paper expresses the rigidity and strength performance of the lamina as a function of hydrothermal parameters. It adopts a stiffness correction method based on CLT, macro-mechanical analysis, Hoffman strength criterion, and partial failure assumption. First, calculate the predicted values of the mechanical parameters of the lamina under different hydrothermal environments, and then calculate the tensile strength of the G/CFRPHC laminate. The program flow is shown in figure 2.

**Verification example 1** Tensile strength of G/CFRPHC in the dry state at room temperature.

| Laminate type | Results in present solution (\( R_p \))/MPa | Results in reference solution [11] (\( R_l \))/MPa | \( 100\%(R_p - R_l) / R_p \) |
|--------------|------------------------------------------|------------------------------------------|---------------------------------|
| 0\(^{0}\)/\(45\(^{0}\)/90\(^{0}\)/\(-45\(^{0}\)\)/0\(^{0}\)/\(45\(^{0}\)/0\(^{0}\)\) | 553.8 | 536.5 | 3.2 |
| 0\(^{0}\)/\(45\(^{0}\)/90\(^{0}\)/\(-45\(^{0}\)/0\(^{0}\)/\(45\(^{0}\)/\(-45\(^{0}\)/0\(^{0}\)\) | 431.0 | 466.0 | 7.5 |
| 45\(^{0}\)/0\(^{0}\)/\(-45\(^{0}\)/0\(^{0}\)/\(45\(^{0}\)/\(-45\(^{0}\)/0\(^{0}\)\) | 549.0 | 605.6 | 9.3 |
| 45\(^{0}\)/0\(^{0}\)/\(-45\(^{0}\)/0\(^{0}\)/\(45\(^{0}\)/\(-45\(^{0}\)/0\(^{0}\)\) | 560.9 | 544.6 | 3.0 |
| 45\(^{0}\)/0\(^{0}\)/\(-45\(^{0}\)/0\(^{0}\)/\(45\(^{0}\)/\(-45\(^{0}\)/0\(^{0}\)\) | 418.3 | 447.6 | 6.5 |
| 0\(^{0}\)/\(45\(^{0}\)/\(-45\(^{0}\)/0\(^{0}\)/\(45\(^{0}\)/\(-45\(^{0}\)/0\(^{0}\)\) | 427.0 | 468.9 | 8.9 |
The mechanical parameters of carbon fiber/epoxy single-layer board (T700/5528A) and glass fiber/epoxy lamina (QF210/5528A) in literature [11] are input into the strength prediction model of this paper. The hydrothermal conditions are average temperature and dry state. Then a tensile load at the x-direction is applied to the laminate, which is compared with the predicted value of tensile strength of the multi-directional hybrid composite material based on the hybrid effect coefficient in the literature [11]. The results are shown in table 1. The solution in this paper is similar to the finite element solution [11]. Therefore, the accuracy of the model in this paper is verified.

**Verification example 2.** Tensile strength of carbon fiber/polyamide resin composite laminate under hydrothermal environment

The mechanical parameters of carbon fiber/epoxy single-layer board (T700/5528A) and glass fiber/epoxy lamina (QF210/5528A) in literature [11] are input into the strength prediction model of this paper. The hydrothermal conditions are average temperature and dry state. (Moisture absorption rates $C_1 = 0$). Then a tensile load at the x-direction is applied to the laminate, which is compared with the predicted value of tensile strength of the multi-directional hybrid composite material based on the hybrid effect coefficient in the literature [11]. The results are shown in table 1. The solution in this paper is similar to the finite element solution in literature [11]. Therefore, the accuracy of the model in this paper is verified.

**Verification example 2.** Tensile strength of carbon fiber/polyamide resin composite laminate under hydrothermal environment

The mechanical parameters of the carbon fiber/polyamide resin lamina (T300/BMP316) in the literature [9] are input into the strength prediction model of this paper. Then compared with the experimental value of the tensile strength of the laminate in the literature [9], the results are shown in table 2. It can be seen that the solution in this paper is the similar to the experimental value solution in literature [9], which again verifies the effectiveness of the strength prediction model in this paper.

The above two verification examples prove that the program written by Matlab for calculating the tensile strength of G/CFRPHC under a hydrothermal environment is reliable. And the present theoretical model based on CLT, macro-mechanical analysis method, stiffness reduction correction, and Hoffman strength criterion in solving the tensile strength of G/CFRPHC in a hydrothermal environment has high calculation accuracy.

### Table 2. Tensile strength of T300/BMP316 unidirectional laminate under hydrothermal environment.

| Laminate type | Temperature/°C | Results in present solution (Rp)/MPa | Results in reference [9] solution (Rt)/MPa | $\frac{R_p - R_t}{R_t} \times 100\%$ |
|---------------|----------------|-------------------------------------|------------------------------------------|---------------------------------|
| ($0_\circ$)$_{16}$ | 22             | 1835.90                             | 1852.21                                  | 0.19                            |
|                | 80             | 1842.20                             | 1839.15                                  | 0.16                            |
|                | 120            | 1832.50                             | 1827.20                                  | 0.29                            |
| ($90_\circ$)$_{16}$ | 22             | 62.06                               | 63.31                                    | 1.97                            |
|                | 80             | 53.01                               | 56.57                                    | 6.29                            |
|                | 120            | 46.35                               | 50.98                                    | 9.08                            |

### Table 3. Material parameters of composite laminas.

| Basic strength | Glass/Epoxy | Carbon/Epoxy | Engineering elastic constant | Glass/Epoxy | Carbon/Epoxy |
|----------------|-------------|--------------|-----------------------------|-------------|--------------|
| $X_t$/MPa      | 1100        | 1350         | $E_{11}$/GPa                | 45          | 105          |
| $X_c$/MPa      | 675         | 1000         | $E_{22}$/GPa                | 10          | 7.5          |
| $Y_t$/MPa      | 35          | 35           | $G_{12}$/GPa                | 5           | 3.5          |
| $Y_c$/MPa      | 120         | 160          | $\nu_{12}$                  | 0.3         | 0.3          |
| S/MPa          | 80          | 55           |                             |             |              |

Figure 3. The effect of temperature on the tensile strength of G/CFRPHC in the hydrothermal environment.

(a) $(0_\circ/90_\circ)_{4S}$
(b) $(45_\circ/0_\circ/90_\circ/45_\circ/0_\circ/90_\circ/45_\circ/45_\circ)_{8}$
Table 4. Hydrothermal degradation constants.

| f  | g  | h  | i  | j  | k  |
|----|----|----|----|----|----|
| 0.03 | 0.11 | 0.69 | 0.25 | 0.318 | 4800 |

Table 5. Hydrothermal coefficients.

| $E_{11}$ | $E_{22}$ | $G_{12}$ | $G_{23}$ | $\alpha_{11}$ | $\alpha_{22}$ | $\beta_{11}$ | $\beta_{22}$ |
|---------|---------|---------|---------|-------------|-------------|-------------|-------------|
| $-0.5 \times 10^{-3}$ | $-0.2 \times 10^{-3}$ | $-0.2 \times 10^{-3}$ | $0.5 \times 10^{-3}$ | $0.5 \times 10^{-3}$ | $0.5 \times 10^{-3}$ | $0.5 \times 10^{-3}$ |

4. Calculation and discussion of the strength of G/CFRPHC laminate

This article studies the ultimate tensile strength of G/CFRPHC laminates after being subjected to a tensile load at the x-direction in a hydrothermal environment. It can analyze the effects of different temperatures, layer thicknesses, ply stacking sequence, and laying angles on the tensile strength of G/CFRPHC laminates.

In this research, the commonly used temperature, layer thickness, ply stacking sequence, and laying angle are used in engineering to explore the tensile strength law of G/CFRPHC laminates in the hydrothermal environment. The material parameters are taken from the material database in the composite material analysis and design software ESAcomp. Carbon fiber/epoxy lamina parameter thickness $t_c = 0.425$ mm, fiber volume fraction $V_f = 40\%$, $\alpha_{11} = 5.5 \times 10^{-6}\, ^\circ C$, $\alpha_{22} = 25 \times 10^{-6}\, ^\circ C$, $\beta_{11} = 0$, $\beta_{22} = 0.6 \times 10^{-2}\, ^\circ C$, $T_{g} = 210\, ^\circ C$. Glass fiber/epoxy lamina parameters $t_c = 0.19$ mm, $V_f = 60\%$, $\alpha_{11} = 5.5 \times 10^{-6}\, ^\circ C$, $\alpha_{22} = 25 \times 10^{-6}\, ^\circ C$, $\beta_{11} = 0$, $\beta_{22} = 0.6 \times 10^{-2}\, ^\circ C$, $T_{g0} = 170\, ^\circ C$. See table 3 for other parameters. The material’s hydrothermal performance degradation constant [25] is shown in table 4. The hydrothermal constant coefficient in the lamina performance degradation model under hydrothermal environment [22] is shown in table 5.

4.1. The influence of temperature on the tensile strength of G/CFRPHC in a hydrothermal environment

The influence of temperature in the hydrothermal environment on the tensile strength of G/CFRPHC laminates cannot be ignored. This article explores the impact of temperature on the tensile strength of two types of G/CFRPHC laminates ($0_{G}/90_{C})_{4S}$ and ($45_{C}/0_{C}/90_{C}/−45_{C}/0_{C}/90_{C}/45_{C}/−45_{C})_{3S}$ under hydrothermal environment. The size of the laminate is 150 mm $\times$ 60 mm $\times$ 4.96 mm. And compare it with the strength calculation results that ignore the influence of hydrothermal environment on the mechanical properties of the lamina, as shown in figures 3(a), (b). Among them, A represents the calculation result that does not consider the influence of the hydrothermal environment on the mechanical properties of the lamina, and B represents the calculation result that thinks over the effect of the hydrothermal environment on the mechanical properties of the lamina.

Figures 3(a) and (b) show that the tensile strength of G/CFRPHC laminates decrease with increasing temperature in a hydrothermal environment. For example, in a hydrothermal environment of 20 $^\circ C$ ~ 110 $^\circ C$, the tensile strength of ($0_{G}/90_{C})_{4S}$ is better than ($45_{C}/0_{C}/90_{C}/−45_{C}/0_{C}/90_{C}/45_{C}/−45_{C})_{3S}$. Among them, the tensile strength calculated without considering the influence of hydrothermal environment on the mechanical properties of the lamina at a temperature of 110 $^\circ C$, and the tensile strength calculated by considering the impact of the hydrothermal environment on the mechanical properties of the lamina, differs respectively by 44.78 MPa, 30.00 MPa. Because, in a hydrothermal environment, the diffusion of moisture in the lamina matrix is promoted due to the increase in temperature. The generated osmotic pressure causes micro-cracks inside the matrix, which increases the distance between the macromolecular structures of the matrix and plasticizes the matrix [26]. Therefore, affect the tensile strength of the lamina. It can be seen that in the calculation of tensile strength of G/CFRPHC laminates, the influence of the hydrothermal environment on the mechanical properties of single-layer laminates cannot be ignored.

In the temperature range of 20 $^\circ C$ ~ 110 $^\circ C$ in a hydrothermal environment, from the curve B in figure 3(a), we can see that the ($0_{G}/90_{C})_{4S}$ as the temperature increases, its tensile strength is compared with 20 $^\circ C$ decreases respectively by 1.00%, 3.71%, and 9.10%. The curve B in figure 3(b) shows that the tensile strength of ($45_{C}/0_{C}/−45_{C}/90_{C})_{3S}$ compared with that at 20 $^\circ C$ decreased by 1.51%, 3.90%, and 9.86%. In a hydrothermal environment, the increase in temperature promotes the diffusion of moisture in the lamina matrix, and the matrix is plasticized, resulting in faster degradation of the matrix performance. At the same time, the mismatch of the hydrothermal expansion coefficient of carbon fiber/epoxy lamina and glass fiber/epoxy lamina under the hydrothermal environment will reduce the interface bonding performance of each lamina. The rate of moisture infiltration into the interface microcracks is accelerated, causing further degradation of the interface.
performance. Therefore, as the temperature increases, the tensile strength of G/CFHC laminates decreases more and more. Consistent with the conclusion of [27–29].

4.2. The influence of layer thickness on the tensile strength of G/CFRPHC under hydrothermal environment

Laminate thickness is a critical physical parameter in a hydrothermal environment. Due to the different thicknesses of the laminate, its tensile strength may also be dissimilar. This article uses three types of G/CFRPHC laminates (0_2G/90_0mC)_S, (0_4G/90_0mC)_S, (0_6G/90_0mC)_S, all of which are 150 mm × 60 mm × a mm in size. According to the different values of m, to explore the tensile strength law of G/CFRPHC laminate in a hydrothermal environment (moisture absorption rates C_1 = 0.5%).

It can be seen from figures 4(a)–(c) that for three different types of G/CFRPHC laminates in a hydrothermal environment of 20 °C~110 °C, the G/CFRPHC laminates increase with the thickness of 90° layup. As a result, its tensile strength gradually decreases. The possible reason is that the local stress concentration near the fiber in the 0° layer becomes more and more severe due to the matrix cracking in the 90° layer as the thickness of the single-layer increases. Consistent with the conclusion of [30]. Therefore, when designing the G/CFRPHC laminate project in the hydrothermal environment, the number of layers overlapping the same laying angle should be as small as possible. The reason is that this can slow down the tension-shear coupling between the individual layers of the G/CFRPHC laminate, reduce the interlayer stress, and improve the tensile strength of the laminate. Furthermore, it can be seen from figure 4(d) that the tensile strength of the G/CFRPHC laminate also is increased by increasing the number of the 0° main bearing layer of the G/CFRPHC laminate.

Figure 4. The influence of layer thickness on the tensile strength of G/CFRPHC under hydrothermal environment.
4.3. The influence of the ply stacking sequence on the tensile strength of G/CFRPHC under a hydrothermal environment

Ply stacking sequence in a hydrothermal environment may also affect the tensile strength of G/CFRPHC laminates. The laying angles are 0°, 45°, −45°, and 90°. The four types of G/CFRPHC laminates with the same...
laying angle but different ply stacking sequences are $\{90^\circ/45^\circ/-45^\circ/0^\circ\}_{2S}$, $\{0^\circ/45^\circ/90^\circ/-45^\circ\}_{2S}$, $(45^\circ/0^\circ/-45^\circ/90^\circ)_{2S}$, and $(0^\circ/45^\circ/-45^\circ/90^\circ)_{2S}$. The size of the laminate is 150 mm × 60 mm × 4.92 mm. Then, calculate the moisture absorption rate $C_1 = 0$ (dry state) and $C_1 = 0.5\%$ (wet condition). In both cases, the tensile strength of laminates with temperature changes is shown in figures 5(a) and (b).

Figures 5(a) and (b) show the influence of the ply stacking sequence on the tensile strength of the G/CFRPHC laminate in the wet state and the dry form, respectively. It can be seen that the tensile strength of G/CFRPHC laminates with the same laying angle but different ply stacking sequence in a dry and wet environment from 20 °C ~ 110 °C is also dissimilar. Among them, the tensile strength of $(0^\circ/45^\circ/-45^\circ/90^\circ)_{2S}$ and $(45^\circ/0^\circ/-45^\circ/90^\circ)_{2S}$ is better than the other two laminates. The possible reason is that the $\pm 45^\circ$ layers are adjacent in the $(90^\circ/45^\circ/-45^\circ/0^\circ)_{2S}$ and $(0^\circ/45^\circ/-45^\circ/90^\circ)_{2S}$ are adjacent. Therefore, it will cause the tension-shear coupling coefficient of G/CFRPHC laminates to be inconsistent and cause interlaminar shear stress, resulting in lower tensile strength. Consistent with the conclusion of [30]. Thus, in the hydrothermal environment, designing the G/CFRPHC laminate structure, the $45^\circ$ layer and the $-45^\circ$ layer should be laid at intervals to reduce the interlaminar shear stress, thereby increasing the tensile strength of the G/CFRPHC laminate.

4.4. The influence of laying angle on the tensile strength of G/CFRPHC under hydrothermal environment

Under a hydrothermal environment, the ply angle is one of the critical factors affecting the tensile strength of G/CFRPHC laminates. For example, we can choose $(\theta_1/\theta_2)_{1S}$ laminated board, and the size is 150 mm × 60 mm × 4.92 mm. Among them, $\theta$ takes seven different laying angles: $0^\circ$, $15^\circ$, $30^\circ$, $45^\circ$, $60^\circ$, $75^\circ$, and $90^\circ$. Let’s explore the influence of the laying angle on the strength of G/CFRPHC in the wet state and compare it with the tensile strength of the dry environment.

Figures 6(a)–(b) shows the comparison of the tensile strength of G/CFRPHC laminates with the laying angle under four temperature environments of 20 °C, 50 °C, 80 °C, 110 °C. It can be seen from figures 6(a)–(d) that the strength curve of the wet environment is lower than the strength curve of the dry state. Therefore, the tensile strength of G/CFRPHC laminates after moisture absorption under four temperature environments reduce.

Consistent with the conclusion of [14]. From figures 6(a)–(d), it can be found that under the high-temperature environment of 80 °C and 110 °C, when the laying angle of G/CFRPHC laminate is $90^\circ$, when the environment transitions from the dry state to the wet form, its tensile strength decreases respectively 19.29% and 23.32%. Thus, it can be seen that in a high-temperature environment, moisture has a more significant impact on the tensile strength of the G/CFRPHC laminate with a $90^\circ$ laying angle. From figures 6(a)–(d), it can be seen that in a dry and wet environment, when the laying angle of G/CFRPHC laminates increases from $0^\circ$ to $90^\circ$, its tensile strength decreases continuously. Consistent with the conclusion of [31, 32]. Therefore, when designing G/CFRPHC laminates in the hydrothermal environment, the off-axis angle should be strictly controlled to prevent huge deflection angles from causing too low tensile strength of G/CFRPHC laminates.

5. Conclusions

In this research, the macro-mechanical analysis of the tensile strength of G/CFRPHC under the hydrothermal environment is carried out. Furthermore, the influence of temperature, layer thickness, ply stacking sequence, and layering angle on the tensile strength of G/CFRPHC laminates under a hydrothermal environment was studied. Based on the above research, the following conclusions can be drawn:

In the hydrothermal environment, the tensile strength of G/CFRPHC laminates after being subjected to a tensile load at the x-direction decreases more and more as the temperature increases. In the G/CFRPHC engineering design, the number of layers overlapping the same laying direction should be as small as possible. Because this can slow down the tension-shear coupling between the layers of the G/CFRPHC laminate, reduce the interlayer stress, and improve the tensile strength of the laminate. With the increase of the $0^\circ$ main bearing layer, the tensile strength of G/CFRPHC laminates also increases. In the hydrothermal environment, in the G/CFRPHC laminate design, the $45^\circ$ layer and the $-45^\circ$ layer should be laid apart to reduce the interlayer shear stress and increase the tensile strength of the G/CFRPHC laminate. When the laying angle of G/CFRPHC laminates is from $0^\circ$ to $90^\circ$, as the laying angle increases, its tensile strength decreases continuously. Among them, in a high-temperature environment of 80 °C and 110 °C, moisture significantly impacts the tensile strength of the G/CFRPHC laminate with a $90^\circ$ laying angle.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).
Declarations of conflicting interests

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References

[1] Mishnaevsky L Jr and Dai G 2014 Hybrid carbon/glass fiber composites: Micromechanical analysis of structure–damage resistance relationships Comp. Mater. Sci. 81 630–40
[2] Papa I et al 2021 Mechanical behavior and damage degree of hybrid glass/carbon composites at low temperature Polym. Compos. 42 2432–44
[3] Jawaid M and Khalil H P S A 2011 Cellulose/synthetic fibre reinforced polymer hybrid composites: a review Carbohydr. Polym. 86 1–18
[4] Meng Q and Wang Z 2017 Modeling analysis of fiber hybridization in hybrid glass/carbon composites under high-velocity impact Polym. Compos. 38 2536–43
[5] Behera A et al 2020 Effect of hygrothermal aging on static behavior of quasi-isotropic CFRP composite laminate Compos. Commun. 17 51–5
[6] Chen F et al 2013 Effects on the structures and properties of APMOC fiber from hydrothermal aging Adv. Mater. Res. 744 288–92
[7] Almeida J et al 2016 Carbon fibre-reinforced epoxy filament-wound composite laminates exposed to hygrothermal conditioning. J. Mater. Sci. 51 4697–708
[8] Wang W et al 2020 Water absorption and hygrothermal aging behavior of wood-polypolypropylene composites Polymers 12 782
[9] Zhao Y 2011 Research on stiffness and strength of resin matrix composite laminated structures under hygrothermal environment M. S Thesis Nanjing University of Aeronautics and Astronautics (China)
[10] Barbero E J and Damiani T M 2003 Phenomenological prediction of tensile strength of E-glass composites from available aging and stress corrosion data J. Reinfl. Plast. Comp. 22 373–94
[11] Xu H H 2014 Study on tensile properties of glass/carbon fiber reinforced plastics hybrid composites M. S Thesis Nanjing University of Aeronautics and Astronautics (China)
[12] Haddar N et al 2014 Effect of hygrothermal ageing on the monotonic and cyclic loading of glass reinforced polyamide Polym. Compus. 35 501–8
[13] Bao Y 2018 Hydrothermal aging behaviors of CMR/PLA biocomposites J. Thermoplast Compus. 31 1341–51
[14] Wang S et al 2012 Hygrothermal behavior of T700 and T300 BMU used for advanced polymeric composite Advanced Materials Research. 476–478 632–5
[15] Akil H M et al 2014 Environmental effects on the mechanical behaviour of pultruded jute/glass fibre-reinforced polyester hybrid composites Compos. Sci. Technol. 94 62–70
[16] Yang S et al 2019 Influence of hygrothermal ageing on the durability and interfacial performance of pultruded glass fiber-reinforced polymer composites J. Mater. Sci. 54 2102–21
[17] Scida D et al 2013 Influence of hygrothermal ageing on the damage mechanisms of flax–fibre reinforced epoxy composite Compos Part. B Eng. 48 51–8
[18] Cao S, Zhi W U and Wang X 2009 Tensile properties of CFRP and hybrid FRP composites at elevated temperatures J. Compos. Mater. 43 315–30
[19] Naito K, Oguma H and Nagai C 2020 Temperature–dependent tensile properties of hybrid carbon/glass thermoplastic composite rods Polym. Compos. 41 3985–95
[20] Ali J M, Bhaskar K and Varadan T K 1999 A new theory for accurate thermal/mechanical flexural analysis of symmetric laminated plates Compos. Struct. 45 227–32
[21] Shen H S 2000 Non-linear bending of shear deformable laminated plates under lateral pressure and thermal loading and resting on elastic foundations J. Strain. Anal. Eng. 35 93–103
[22] Kumar R et al 2012 Hygrothermally induced buckling analysis of elastically supported laminated composite plates with random system properties J. Compos. Mater. 46 2711–30
[23] Tsai S W and Hahn H T 1980 Introduction to composite materials Lancaster, PA: Technomic Publishing Co., Inc. 362 377–419
[24] Shen G L, Hu G K and Liu B 2019 Mech. Compos. Mater. 2nd Edition (Beijing: Tsinghua University Press) 67
[25] Xie W and Dou Pengpeng X Z 2019 Research and application of the constitutive model of composite laminates in hydrotthermal environments Advances in Aeronautical Science and Engineering 10 62–72
[26] Tsereps K, Tratzadakis V and Katsiropoulos C 2019 Effect of hygrothermal ageing on the interlaminar shear strength of carbon fiber-reinforced resin-based epoxy bio-composites Compos. Struct. 226 111211
[27] Tsai Y L et al 2009 Influence of hygrothermal environment on thermal and mechanical properties of carbon fiber/fiberglass hybrid composites Compos. Sci. Technol. 69 432–7
[28] Yu H Y, Wu H Y and Shi H R 2021 Strength degradation and aging life prediction for carbon fiber reinforced polymers laminates in hygrothermal environment Materials For Mechanical Engineering 45 40–5
[29] De Sousa F K A, Ujike I and Kadota A Influence of the different hygrothermal conditions on the tensile strength of composites materials reinforced with fiberglass System 26
[30] Wang F, Zhang J Q and Ding J 2005 Strength prediction of symmetrical composite laminates Journal of Chongqing University (Natural Science Edition) 28 4
[31] Lim W K, Jeong W K and Tschegg E K 2010 Failure of fibrous anisotropic materials under combined loading Compos. Part B-Eng. 41 94–7
[32] Qiao S J et al 2017 Effect of layer parameters on off-axis tension properties of hybrid composites Journal of Guangxi University (Nat. Sci. Ed) 42 10