Research on Biaxial Damage Evolution Characteristics of Flexible Woven Composite Film

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Abstract. The flexible braided composite film structures have been widely used in many fields such as near space aerostats, inflatable wings, flexible spacecraft due to their unique advantages such as small folding volume, light weight, high specific strength, excellent comprehensive performance, etc. However, the space environment is so harsh, and the flexible film structure composite material could be easily affected by various environmental factors such as long-term sunlight, ultraviolet radiation and space particle impact. So the weathering damage evolution characteristics directly determine the use life and working efficiency. The typical biaxial fiber reinforced laminated flexible composite material was studied with the damage mode, and the composite meso-mechanical theory was also used to construct the braided composite mechanics model during the damage process. The damage model of the warp and weft fiber bundles with the base film layer was introduced into the independent flexible film composite component damage degree, and the damage evolution model of the damage-containing composite material characterized by the mesoscopic component parameters was also established. Moreover, the load-bearing stress characteristics of each component under different damage conditions were calculated and analysed. The research results could provide an effective theoretical reference for the weathering optimization design and the improvement of the service life of flexible film woven composite structures.

1. Introduction

Recently, stratospheric aircraft such as stratospheric high-altitude airships, balloons, and adjacent space aerostats has become a hot spot due to the unique advantages [1-2]. However, the space working environment is extremely harsh, and the flexible film skin composite material that is the core material of the aircraft is prone to mechanical damage and result in the decrease of load bearing performance [3]. And flexible film materials needed to be in a harsh and complex stratospheric environment for a long time, which could cause the microstructure to deteriorate and eventually form macroscopic cracks or stress fatigue damage [4], and even result in the overall failure of the aircraft [5].

Nouri H et al. [6] studied the damage mechanical properties of skin materials under stress alternating fatigue conditions, which could be applied into the structural design of skin materials to estimate the damage evolution characteristics of the film material, while the high-performance Kevlar and Vectran fiber braided films in the microscopic direction could be studied with the damage evolution method [7-8]. For the damage failure mode of composite materials, Ahmed and Thostenson [9] established the corresponding damage model according to the damage failure mode. Furthermore, the damage behavior of airship skin materials was studied [10], and it was found that the damage, yield, fracture and failure process of fiber reinforcement was an energy-consuming process [11].
Based on the recent research, the structural characteristics of the flexible woven composite film skin were studied, and the damage evolution law of the skin film was also studied with the progressive damage mechanics theory of the composite material, which had an important meaning for the flight performance, flight safety reliability and the overall service life of the stratospheric aerostats [12].

2. Biaxial Damage Mechanics Model of Fiber Braided Skin Composite

The mechanical bearing characteristics of fiber woven flexible film composites directly affected the overall structural design, aerodynamic shape and skin bearing performance of near space aircrafts. At present, the research on the mechanical properties of laminated flexible skin-film composites mostly focused on the calculation of macroscopic strength and deformation stress, while the meso-structural features of the skin-skin composites, especially the meso-components of the skin composites were few studied considering the effects of mechanical properties of skin macroscopic damage.

2.1. Flexible Skin Film Material

The influence mechanism of the two main material contents of the film composites (waved high-performance fiber yarn bundle and matrix film layer) was considered on the mechanical properties of the skin macroscopic damage. And the flexible composite model was modeled and shown in Figure 1.

![Figure 1. Flexible skin film composite model](image1)

![Figure 2. Specimen geometry (unit: mm)](image2)

Based on the theory of fabric geometry and physics, the biaxial tensile stress-strain constitutive model was constructed with the typical constitutive Peirce model and Castigliano principle of plain weave fabric. According to the standard ASTM D1004-09 [13], the biaxial tensile specimens were sampled with a "+" shape. The length and warp and weft of the specimen were shown in Fig. 2. And the skin film composite was subjected to warp and weft biaxial tensile load.

2.2. Film Damage Mechanics Model

Based on the actual biaxial load conditions of the laminated composite skin, the mechanical properties of the biaxial stress-strain constitutive relationship of the warp and weft braided yarn bundles were constructed with the Peirce model and the sawtooth model [14, 15], and the physical structural unit model of fiber reinforced plain weave laminated skin was shown in Figure 3.

In this model, the subscript 1, 2 indicates the direction of the warp yarn bundle and the weft yarn bundle respectively, and C is the contact point and the mutual squeeze position point when the warp and weft yarn bundle is woven. And the parameters of each material component are shown in Table 1.
According to Castigliano energy deformation principle [3, 15], Warp and weft fiber bundles generated extrusion deformation, while fiber bundles bending and compression deformation were nearly considered in the actual plane stress state. So the total stretching elongation strain energy of fiber bundles could be obtained with the elastic deformation energy:

\[ U_f = 2U_{f_1} + 2U_{f_2} = \frac{l_1}{\alpha_1} (T_1 \cos \theta_1 + g_1 \sin \theta_1)^2 + \frac{l_2}{\alpha_2} (T_2 \cos \theta_2 + g_2 \sin \theta_2)^2 \]  

(1)

Similarly, the fiber bundle could be subjected to compression and shear elastic energy:

\[ U_M = 2U_{M_1} + 2U_{M_2} = \frac{l_1^3}{24\beta_1} (T_1 \sin \theta_1 - g_1 \cos \theta_1)^2 + \frac{l_2^3}{24\beta_2} (T_2 \sin \theta_2 - g_2 \cos \theta_2)^2 \]  

(2)

\[ U_f = 4\left(\frac{d_1^2}{\gamma_1} + \frac{d_2^2}{\gamma_2}\right) \]  

(3)

When the biaxial stretching of warp and weft fabric was performed, the elongation of fiber bundles would induce themselves to slip along the surface of the adjacent fiber bundle. Then the slipping friction energy could be produced from the compressive force:

\[ U_{f_s} = 2U_{f_{1s}} + 2U_{f_{2s}} = 2Y(T_1) \cdot u_1 f_1 \cdot \frac{T_1}{\alpha_1} l_1 + (\frac{\gamma_1}{\gamma_1 - f_1})^2 - 1)l_1) + 2Y(T_2) \cdot u_2 f_2 \cdot \frac{T_2}{\alpha_2} l_2 + (\frac{\gamma_2}{\gamma_2 - f_2})^2 - 1)l_2) \]  

(4)

So the total deformation energy could be comprised of elongation energy, compression strain energy, bending strain energy, and the friction energy, which could be superimposed below:
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Furthermore, according to Castiglano theory of deformation energy, then it could become:

\[ \partial U / (2f_1) + \partial U / (2f_2) = \partial U / (g_1) + \partial U / (g_2) = 0 \]  

(6)

From the interaction principle of biaxial fiber compression force of warp and weft bundles: \( f_1 = f_2 = f_2 = 2g_1 = 2g_2 = 2g \), then the compression force could be obtained:

\[
g = g_1 = g_2 = \sum_{i=1}^{2} \left( \frac{l_i}{12\beta_i} - \frac{l}{\alpha_i} \right) T_i \sin \theta_i \cos \theta_i \right) \]  

(7)

The deformation constitutive relation under biaxial load could be further deduced as equation (8).

\[
\varepsilon_i = F_{ii} \frac{l}{W_y} \left( \cos^2 \theta + \sin^2 \theta \right) - \frac{(F_{ii} + F_{ii})^2}{2W_y} \left( \frac{l_i}{12\beta_i} - \frac{1}{\alpha_i} \right) \sin^2 \theta \cos^2 \theta
\]

\[
+ \frac{2\mu_i^2}{\alpha_i} \left( 2a_i + a_i \right) W_y \left( F_{ii} + F_{ii} \right) \frac{l}{\alpha_i} \left( \frac{l_i}{12\beta_i} - \frac{1}{\alpha_i} \right) \sin \theta \cos \theta
\]

\[
= \varepsilon_i (F_{ii}, F_{ii}) \quad i = 1, 2
\]

(8)

Considering that the elastic modulus of the base film layer was smaller than that of the fiber yarn bundles, in order to simplify the analysis model, the influence of the damage of the base film layer was not considered on the overall bearing mechanical properties of the flexible skin film composite. According to the continuum damage theory and the non-damaged linear elastic stress-strain constitutive relation [3,13-15], the damage variation of the elastic modulus could be introduced to characterize the damage degree of the material under the stress fatigue load. The degree of damage of tensile elongation and bending of the warp and weft braided yarn bundle could be further expressed as:

\[
D_{i,a} = \frac{\alpha_i - \alpha_i}{\alpha_i} = D_{i,j} = \frac{\gamma_i - \gamma_i}{\gamma_i} \quad (i = 1, 2)
\]

(9)

In order to simplify the computational research model, the warp and weft yarn bundles were synchronously damaged under fatigue load among the theoretical analysis, and the damage degree of tensile and shear modulus was considered to be equal, while the compressive modulus was considered to have little influence and remains unchanged. For the damage constitutive equation of the fiber reinforced braided stratospheric airbag material, the above equation would transform the damage problem of the skin material into the damage degree of the mesoscopic component of the airship skin material (the warp and weft braided reinforcing fiber yarn bundles, the base material). Then the damage evolution constitutive equation could be obtained.

\[
\varepsilon_{ii} = F_{ii} \frac{l}{W_y} \left( \cos^2 \theta + \sin^2 \theta \right) - \frac{(F_{ii} + F_{ii})^2}{2W_y} \left( \frac{l_i}{12\beta_i} - \frac{1}{\alpha_i(1-D_i)} \right) \sin^2 \theta \cos^2 \theta
\]

\[
+ \frac{2\mu_i^2}{\alpha(1-D_i)} \left( 2a_i + a_i \right) W_y \left( F_{ii} + F_{ii} \right) \frac{l}{\alpha(1-D_i)} \left( \frac{l_i}{12\beta_i} - \frac{1}{\alpha(1-D_i)} \right) \sin \theta \cos \theta
\]

\[
= \varepsilon_{ii} (F_{ii}, F_{ii}) \quad i = 1, 2
\]

(10)
3. Results and Discussion

According to the constructed damage evolution model of the fiber woven flexible skin film, the tensile loading was carried out according to different proportional loads in the warp and weft direction (1:1, 1:2, 2:1), and the damage degree of different material components was considered \((D=0, 0.1, 0.3, 0.5)\), and the warp and weft fiber yarn bundle damage degree was consistent, and the calculated strain of the warp and weft flexible film material changes with the biaxial tensile load shown in Figure 4-6.

![Figure 4](image_url) **Figure 4.** Biaxial strain changing when the warp and weft load ratio is 1:1 with the damage degree

![Figure 5](image_url) **Figure 5.** Biaxial strain changing when the warp and weft load ratio is 1:2 with the damage degree

As shown in Fig. 4, when the tensile load in the warp and weft loading was 1:1, because the flexible skinned film composite was modeled and calculated using the warp and weft fiber bundles with the same VECTRAN material and the same material properties. Under the same tensile load condition, the strain in the biaxial direction was consistent, and under the same damage degree, the strain value changed almost linearly with the change of the load. However, when the degree of damage of the skin film material increased, the tensile modulus and shear modulus decreased gradually, and the strain value increased significantly with the increasing of the load. Furthermore, the larger the tensile load, the more obvious the strain changing. However, the strain values of warp direction \(\varepsilon_1\) and weft strain \(\varepsilon_2\) showed the same change trend, and the more severe the damage of elastic modulus was, the strain change of biaxial direction appeared as the law of acceleration change.

When the warp and weft tensile load was 1:2, which was shown in Fig. 5, the tensile load in the weft direction was twice than that in the warp direction, and the same material was calculated for the warp and weft fiber yarn bundles. It could be found that, under the same condition of tensile load and elastic modulus damage degree, the strain value changed approximately linearly with the increasing of the load, and the biaxial strain change trend remained consistent. Moreover, the weft strain was significantly larger than the warp strain value under the same ratio of tensile load. Under the same damage degree, the weft strain value changed almost linearly with the changing of the load, but the change speed was obviously larger than that of the warp direction, which indicated that with the increasing of the damage degree of the flexible film, if the tensile load was increased, the fiber bundle would undergo greater elastic deformation, so the breakage failure would first occur.

Moreover, as the degree of damage of the film material increases, the tensile modulus and the shear modulus decreases gradually, and the larger the ratio of the load in the biaxial direction, the more obvious the rate and tendency of the strain value change. However, the strain value of the weft \(\varepsilon_2\) is advantageous for alleviating the change of the warp direction \(\varepsilon_1\) strain, which is manifested by the fact that the uniaxial deformation of the bearing load ratio value is improved.
When the tensile load in the warp and weft loading was 2:1, as shown in Fig. 6, the tensile load in the warp direction was twice that in the latitudinal direction, so that it can be found under the same tensile load and elastic modulus damage degree. The strain value still changes approximately linearly with the increasing of the load, and the biaxial strain change trend remains consistent. However, the warp strain value is significantly larger than that of the weft strain value. And the curves indicates that as the degree of damage of the biaxial elastic modulus of the flexible film increases, the uniaxial direction with the greater tensile load is subjected to greater elastic deformation of the fiber bundle, which would lead to the first occurrence of fiber yarn bundles and the fracture failure of the bundle, which affects the overall bearing mechanical properties of the flexible skin film composite.

However, as the degree of damage of the skin film material increases, the tensile elastic modulus and the shear modulus decrease gradually, and the biaxial load ratio value is larger, in the uniaxial direction of subjecting larger load ratio value, if When the load carrying capacity is small, the speed and trend of the strain value are relatively weakened. The change of the strain value of the flexible skin film is closely related to the bearing biaxial tensile load, the ratio value and the damage degree of the fiber bundle elastic modulus. Moreover, the uniaxial strain value of the same bearing load ratio (longitude $\varepsilon_1$) varies significantly with the increasing of the elastic modulus damage degree, and the warp deformation would aggravate the biaxial mechanical properties of the flexible skin film deterioration. Therefore, if the biaxial fiber bundle of the flexible skinned plain weave composite material is the same material, the tensile load ratio of the warp and weft directions should be kept consistent as much as possible among the design of the flexible skin film bearing structure.

4. Conclusion
When the ratio of the tensile load is the same in the warp and weft loading, and the fiber bundle is the same material property, the strain value changes almost linearly with the changing of the load under the same damage degree. And with the increasing of the load, the strain changes significantly, and the degree of damage of the elastic modulus is more serious, and the strain change of the biaxial axis appears as an acceleration change law.

When the tensile load is different in the warp and weft direction, under the same tensile load and elastic modulus damage degree, the strain value changes approximately linearly with the increasing of the load, and the biaxial strain change trend remains consistent. However, the greater the tensile load, the greater the elastic deformation of the bundle of fiber yarns, so that the fracture failure of the fiber bundle would firstly occur, but the deformation could be improved in the other direction.

The change of the strain value is closely related to the bearing biaxial tensile load, the ratio and the damage degree of the fiber bundle elastic modulus. If the biaxial fiber bundle of the flexible skinned plain weave composite is the same material, the tensile load ratios in the warp and weft directions should be as consistent as possible while designing the flexible film load-bearing structure.
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6. References
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