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A review of FMLs performance test methods and index evaluation

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ABSTRACT

With its excellent fatigue performance and high damage tolerance and other irreplaceable advantages, FMLs have gradually increased the demand in aerospace, rail transit, ship and other fields, and have put forward higher requirements for the speed and accuracy of its performance test and index evaluation. In this paper, the methods of performance test, analysis and index evaluation of FMLs are introduced from three aspects with carbon fiber and composite materials, mechanical properties and numerical simulation technology, details the common test methods, the latest technology and progress, and analyzes their advantages and disadvantages, so as to provide direction and reference for the performance test method and index evaluation of FMLs. Finally, the main development directions of the current performance testing methods and index evaluation of FMLs are briefly discussed.

Keywords: FMLs; Carbon Fiber Composites; Mechanical Properties; Numerical Simulation Technology; Outlook.

1. INTRODUCTION

Fiber metal laminate (FMLs) is an intermixed composite material made of metal sheet and fiber reinforced composite alternately laying and curing at a certain temperature and pressure, also known as super-mixed laminate. FMLs integrates the characteristics of traditional fiber reinforced composites and metal materials, with high specific strength, specific stiffness, excellent fatigue performance and high damage tolerance, and has great development potential of in aerospace, rail transit, shipping and other fields [1–3].

With the increasing requirements of large aircraft for lightweight, integration and damage tolerance capacity, carbon fiber reinforced composite material is widely used in FMLs for its irreplaceable advantages of high specific modulus, high specific strength, fatigue resistance, higher residual strength and higher impact strength [4–6]. The third generation of FMLs with epoxy resin-based carbon fiber reinforced aluminum alloy material, namely CARALL. However, research shows, there is a high potential difference between carbon fiber and aluminum alloy. The composite electrocouple corrosion of the two intensifies the lamina corrosion, and it is difficult to use in an environment of more than 120 °C, which has become the main obstacle that CARALL is still difficult to commercialize [7, 8]. In order to overcome the above problems, TiGr, namely the fourth generation of FMLs, came into being, which uses graphite fiber reinforced polyether ether ketone composite material combined with titanium alloy to form. TiGr does not have corrosion problems, but its low research maturity, high manufacturing cost, and poor fracture toughness limit its application [9–11].

In addition to the development of new material system, the researchers continue to enrich and improve the failure mechanism and damage mechanism through theoretical analysis and experimental research. In addition, as an important structural materials of aerospace, rail transit, FMLs need before the application of the system performance analysis and index evaluation, need great manpower, time, and material cost. In the background, to carry out fast and stable and reliable FMLs material performance test and index evaluation, called the focus of many scholars. Among them, the observation of appearance and microstructure, the detection of physical and chemical properties, the detection of mechanical properties, and other items that especially need to be tested, are all the focus of current research.

Commonly used standards in China including national standards (GB), aviation standards (HB) and the American materials association standard (ASTM D), etc., respectively for FMLs performance test and index evaluation method has carried on the detailed regulation, scholars on the basis of related experiments, and constantly optimize and improve the experimental equipment, method, in order to obtain more consistent with

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the engineering application effect [12–15]. Based on ASTM D standard, this paper introduces the method of common performance test and index evaluation of FMLs, focuses on the latest technology, method and progress, and analyzes its advantages and disadvantages, and briefly discusses the main development direction of current FMLs performance test method and index evaluation, FMLs performance test method and index evaluation provide reference and research direction.

2. TESTING AND INDEX EVALUATION OF CARBON FIBER AND COMPOSITE MATERIALS

The properties of carbon fiber and composites have an important influence on the mechanical properties of FMLs. For example, the surface of carbon fiber affects the excellent performance of the composite material. The infiltration of the resin to the fiber surface is the condition that the fiber and the resin form a close interface and combine, and the binding strength of the interface affects the overall performance of the composite materials [16–18].

2.1. Surface characteristic test of carbon fiber

The surface properties of carbon fiber include fiber surface roughness, fiber surface chemical properties, specific area of fiber surface, etc. The surface properties of carbon fiber directly affect the surface properties of composites, and thus affect their mechanical macroscopic properties [19, 20]. In general, the rougher the carbon fiber surface, the larger the specific surface area, the better the bonding of the interface; the more polar functional groups on the carbon fiber surface, the more favorable the adhesion of carbon fiber and resin; and the macroscopic mechanical properties of carbon fiber composites.

The common testing and evaluation methods of fiber surface characteristics mainly include SEM (Scanning Electron Microscope), TEM (Transmission Electron Microscope), EDX (Energy Dispersive X-Ray Spectroscopy), AES (Auger Electron Spectrometry), XRD (X-ray diffraction), AFM (Atomic Force Microscope), LRS (Laser Raman Spectrometer), XPS (X-ray photoelectron spectroscopy), BET (Specific surface area test), FTIR (Fourier Transform Infrared Spectrometer), etc. The main applications are shown in the Table 1.

SEM is often used for the observation of interface morphology, AFM can observe the interface morphology more intuitively and accurately, and quantitatively analyze the surface roughness of fiber; XPS and FTIR can analyze the chemical composition of carbon fiber surface; XPS can obtain the electronic structure, element composition and chemical state of the material surface, and has higher sensitivity [23–25].

2.2. Resin infiltration performance test and index evaluation

The infiltration of carbon fiber and resin indicates the difficulty of the resin immersed into the fiber bundle. If the infiltration is poor, the composite material will eventually contain pores and defects in the composite material, and affect the final macroscopic mechanical properties of the composite material [26–28]. Common tests and index evaluation of the infiltration properties of composite materials include contact angle, surface energy and adhesion work.

2.2.1. Contact angle

The contact angle is an important indicator to describe the ability of liquid to solid wetting. The better the carbon fiber bundle infiltration, the easier the resin is to soak in carbon fiber, the more conducive to the preparation of composite materials [29]. Measurement of the contact angle is difficult due to the fine and soft fibers. The methods used for fiber contact angle measurement are seat drop method, Wilhelmy and Washburn.

Base drop method, also known as droplet method, is the most commonly used contact angle testing method. The seat drop method is completed by using optical contact angle meter, from manual instrument to fully automatic system. In the seat drop method, the image of the droplet is taken by the high-resolution camera, and the air-liquid interface tangent is made through the junction of gas, solid and liquid, and then the angle is automatically measured by the software. Base method is a fast non-destructive method to characterize the chemistry of material surface, and it is also often used to calculate surface free energy [30, 31].

Table 1: Presents the test and evaluation methods of the common fiber surface properties [21, 22].

FIBRE SURFACE PROPERTIES	COMMON EVALUATION METHODS
configuration of surface	SEM, AFM, TEM, EDX
surface chemical property	XPS, FTIR, EDX, AES
state of aggregation	XRD, LRS
Surface adsorption	BET

Table 2: The comparation of contact angle method with IGC method [35–37].

METHOD	THE TEST PRINCIPLE	FABRIC METHOD	REPEATABILITY
Contact angle method	The infiltration theory	High precision requirements	mal
IGC law	Adsorption theory	Low accuracy requirements are required	good

The surface energy, dispersion and positive components described in 2.2.1 are calculated.

In Wilhelmy test, when a part of the solid is inserted into the liquid, the liquid will rise or fall along the vertical wall of the solid, and the contact angle is determined by measuring the tensile force (thrust) of the liquid on the solid, i.e., the wetting force. Wilhelmy Simple equipment, through the precision motor to accurately control the movement speed of the lifting table, precision balance can record the changes in the solid surface in the hand, the balance after zero measurement does not have to consider the influence of gravity, easy operation, do not need to do any correction [32].

The Washburn method is mainly based on the capillary siphon effect of the liquid in the porous material. During the test, the carbon fiber was loaded into the glass tube closed with the microporous diaphragm at the lower end, and dropped to the liquid level in parallel. The change curve of the infiltration weight gain to the infiltration time was measured, and the contact angle was obtained through the own software of the instrument. The contact angle using the balance method to measure the fiber-resin system has high requirements on the test conditions and cumbersome operation. It is necessary to ensure that the two measurement states are completely consistent [33, 34].

2.2.2. Surface energy

The surface free energy of carbon fiber is an important physical quantity to describe and determine the surface properties of the fiber. At present, the commonly used methods to test the surface energy mainly include contact angle method and reverse gas chromatography (IGC method). The advantages and disadvantages of the two are shown in the Table 2.

The IGC method takes the carbon fiber as the probe molecule, and the known small molecule liquid is used as the probe molecule. Under certain conditions, the gasified probe molecule is used to bring the gasification probe molecule into the chromatographic column. The surface energy of the stationary phase is studied by testing the retention time of the probe molecule through the chromatographic column. The contents of IGC detection mainly include: dispersion and polar surface energy, BET, specific surface area, adsorption heat, surface acid/alkaline analysis, etc. [38–42].

2.2.3. The adhesive work

After the infiltration of resin and carbon fiber, the surface disappears and then the interface between resin and carbon fiber is produced. When the resin surface per unit area and the surface of carbon fiber adhere, the maximum attack is called adhesion work. The greater the greater the adhesion work, the better the infiltration, the more conducive to the formation of composite materials [43]. The adhesion work is the calculated value, the Young-Dupre method calculates the adhesion work by measuring the contact angle, and the Wu method measures the relevant surface energy, dispersion component and polar component to calculate the adhesion work by the IGC method [44–46]. It is shown that the results measured by the Wu method are higher than that measured by the IGC method, because the contact angle test reflects the average effect on the fiber surface, while the probe molecules are easier to interact with the high energy points on the fiber surface [47, 48].

2.3. Interfacial binding strength test of carbon fiber composites

Interface is an important combination part of carbon fiber composite materials, which has an important influence on the mechanical properties of carbon fiber composites [49–51]. It is of great significance to accurately measure and express the binding strength of the interface. Methods for characterizing interface binding strength are mainly in macroscopic and microscopic ways.

2.3.1. Macroscopic test and evaluation of the interface binding strength

The macroscopic testing methods of interface binding strength of carbon fiber composites mainly include tensile method, three-point bending method, shear method, Nuo ear ring (NOL), etc. [52–54]. Carbon fiber composite interface combined strength test method and the FMLs mechanical properties test method is almost the same, will be detailed in the FMLs mechanical properties test and evaluation index, it is worth noting that in the tensile performance test, although the lateral tensile to the interface bonding strength is very sensitive, it is difficult to get stable data, but is still the only effective method to characterize the interface tensile properties of composite materials [55, 56]. The ring test method can not only evaluate the bonding performance of the interface, but also evaluate the tensile strength, which is currently widely used [57, 58].

2.3.2. Microscopic test and evaluation of the interface binding strength

The microscopic test of the interface binding strength of carbon fiber composites generally adopts the single fiber method, including the single fiber fracture method, the single fiber extraction method, and the single filament embedding method, etc.

The single fiber fracture method places a single fiber in the resin matrix for curing, and the sample is stretched along the fiber direction. Under the condition that the matrix is broken, the single fiber breaks and reaches the saturation state, and then the interface binding strength is calculated through the formula.

The single fiber extraction method requires that the single fiber should be wrapped straight in the resin matrix. The test principle is shown in the figure. By recording the force of the fiber deadhesion moment, the debonding force of the fiber is calculated by the formula. During the experiment, it should be noted that the interface binding strength increases linearly as the fiber embedding length increases [59].

Single fiber pressing method presses the fiber out of the fiber from the resin at the end of the fiber with very sharp diamond. This method requires that the fiber is perpendicular to the interface with the composite material, and the test method is relatively complex, and the data collation and analysis is mainly realized through finite element analysis [60].

3. MECHANICAL PROPERTIES TEST AND INDEX EVALUATION

Mechanical testing of the structure of FMLs is a prerequisite for their design, structure optimization, etc. [61]. For common mechanical properties, mainly include interlayer shear failure, bending failure, fatigue failure, etc., for specific working conditions, including high and low speed impact, high temperature resistance, salt spray and other performance tests, this paper only considers the most basic mechanical properties.

3.1. Layer plate shear failure and index evaluation

In the process of assembly and service, if FMLs are subjected to lateral load or torsion force, it is easy to produce local interlayer debonding, and then layer expansion, leading to the overall failure of the structure [62–64]. Therefore, appropriate methods are needed to characterize the interlayer shear resistance of FMLs.

The interlayer shear strength (ILSS) is the interlayer shear stress when the sample fails or the load reaches the maximum value, which characterizes the interlayer shear strength of the materials [65]. At present, the test methods for evaluating the interlayer shear performance of composite materials mainly include compression experiment, short beam method, double groove tensile shear method, V-groove shear method, etc. Researchers at home and abroad aim for the shear strength test of fiber metal laminate, mainly by short beam method, and the main test standards and parameters are shown in the Table 3.

It is worth noting that, compared with the short beam method, the double beam method has a pure shear stress point, which alleviates the influence of bending stress on the shear strength between layers to a certain extent [71, 72]. At the same time, considering the application of double-beam shear method to resin-based composites, it has some specificity compared with the traditional interlayer shear performance test, and is gradually widely used in the shear performance test of FMLs [73–75].

Table 3: Test standards and parameters of short beam method [66–70].

TEST METHOD	ASTM D 2344-2000	SRM 8R-1994	JC/T 773-2010 (ISO)	BS EN 2563-1997	BS EN 2377-1989
The style requires	any structure	any structure	0 ° unidirectional	carbon fiber unidirectional	glass fiber cloth laminate
Standard size/mm (width × thick)	12 × 6	6.35 × 2	6 × 2	10 × 2	10 × 3
Recommended size/mm (width × thick)	2 h × h		5 h × h		3.3 h × h
Span thickness ratio	4	4	5	5	5

3.2. Bending failure and index evaluation

In the process of service, if FMLs are subjected to a large bending moment, they will produce bending deformation. The most commonly used method to evaluate the bending performance is the three-point bending experiment. At present, there is no relevant standard for FLs bending performance test at home and abroad. Most of the bending performance evaluation directly uses the traditional experimental method of the polymer matrix composite material, and the commonly used standards are ISO 14125-1998, ASTM D 790 and GB 1449-2005. The specific experimental method is described in 3.1 and will not be described.

3.3. Fatigue performance test and index evaluation

During the service of FMLs, the repeated action of fatigue loads will lead to the damage and failure of structural materials. Compared with traditional metal materials, the biggest characteristic of FMLs is its better damage fatigue and damage tolerance performance [76]. FML fatigue injury includes the expansion of metal layer, matrix cracking, interface debonding, interlayer delamination and fiber fracture, and the crack expansion of metal layer and fiber layer layer coupling and influence each other [77–80].

At present, there is no relevant standard for the fatigue crack extension test of FMLs at home and abroad. The scholars generally adopt the fatigue test standard ASTM E647 of metal materials, the central crack (MT) test, and the fatigue crack extension test through MTS fatigue test machine and related environmental test box. They use the sine wave cycle loading with stress ratio R = 0.1, frequency f = 10Hz, and observe the fatigue crack expansion through digital microscope. After the experiment, the damage of the lamina can be detected by ultrasonic C scan [81–83].

3.4. Nondestructive testing technology and index evaluation

Although FMLs has been widely used in engineering companies, but in its production process, due to the process of instability, pores, layer, inclusion, damage, in the use process of defects, also can produce knife marks, scratch, corrosion pit, layered and layered offline damage [84–87], so the FMLs damage detection and testing is particularly important, also gradually caused the researchers and application of extensive attention. For the nondestructive testing methods of FMLs, they mainly include infrared thermal wave detection, ultrasonic detection, acoustic emission detection and microwave nondestructive testing. Various methods have their own characteristics and defects, and they play their own advantages in their respective suitable fields.

3.4.1. Infrared thermal wave detection method

Infrared hot wave nondestructive testing process, need to the detection material heating, detection material internal thermal properties differences and heat conduction discontinuity of the physical surface area form temperature gradient, infrared radiation capacity changes with different temperature, with the aid of infrared thermal imager is measured practice detection and according to the radiation distribution of detection to infer the test of the internal defects [88].

Infrared hot wave test technology can conduct nondestructive testing of internal defects such as cracks and stratification of FMLs, but the detection process requires heating and heat transfer to form a temperature gradient, and then produce radiation [89, 90]. Therefore, it needs a certain time in the detection process, and rapid scanning and detection cannot be carried out.

3.4.2. Ultrasound detection method

Ultrasound detection is one of the most commonly used nondestructive testing methods in the industry. When the ultrasonic wave enters the object, if the defect is encountered, a part of the sound waves will reflect, the receiver analyzes the reflected wave, and can accurately measure its internal defects, and can show the position and size of the internal defects.

However, ultrasonic detection is a kind of contact detection, which requires to add the coupling agent at the probe to reduce the attenuation of the signal when the ultrasonic signal enters the detection material, which will cause pollution to the surface of the test parts, and the rapid scanning detection cannot be carried out, especially for large parts [91, 92].

3.4.3. Acoustic emission detection method

The AE detection method is a detection method to assess the material performance and structural integrity by receiving and analyzing the AE signals of a material. The essence of AE is the stress wave phenomenon caused by the rapid release of strain caused by crack expansion, plastic deformation or phase change in the material.

The acoustic emission detection technology can effectively detect the internal defects and damage types of the composite material, but the position and direction of the defects do not affect the detection effect of the acoustic emission, that is, the acoustic emission detection technology cannot detect the position of the defect and the size of the defect [93, 94].

3.4.4. Microwave nondestructive testing method

Microwave without detection is a new non-contact, the pollution of rapid detection and monitoring technology, through the microwave reflection, scattering, diffraction, transmission, Doppler effect and other physical characteristics and the dielectric constant and loss of detected material to change the electromagnetic characteristics to measure the change of microwave basic parameters, the performance of the material, the defect of the power detection.

According to the different principles of microwave detection, microwave detection can be divided into microwave penetration method, microwave scattering method, microwave reflection method, etc. Li, and other scholars elaborated on the principles, advantages and defects of various methods in [95–98].

4. APPLICATION OF NUMERICAL SIMULATION TECHNOLOGY IN PERFORMANCE ANALYSIS AND INDEX EVALUATION

FMLs performance test time is long, the sample index cost is high, in order to reduce the test cost, improve the reliability of the test, the scholars constantly explore through the finite element simulation technology analysis of the mechanical properties of FMLs, and through the stress analysis combined with appropriate strength failure criterion and damage criterion and damage evolution law to judge the material damage process [99, 100]. Since the metal layer of FMLs is elastic-plastic, while the fiber layer is considered to be approximately linear elastic, the traditional classical theoretical model of carbon fiber laminates is not suitable for the mechanical property model after the combination of the two, so the research on the failure behavior of FMLs needs to be further improved.

The comprehensive performance of FMLs is not only related to the properties of fibers, matrix and metal, but also closely related to the arrangement of fibers, the interface binding strength of fiber layer/metal layer, shear strength, etc. [101–104]. The related test methods are introduced in detail in the mechanical properties test, and this section only introduces the constitutive model and failure criteria.

4.1. Conductive model of metal layer and failure criteria

FMLs, the metal layer mostly using aluminum alloy, titanium alloy ductility good metal, therefore, the metal layer using isotropic elastic-plastic model, applied stress-strain model to show strain reinforcement behavior, using delay damage rule to judge the initial damage [105, 106], namely the material in the loading process of plastic deformation, cause internal microporous and micro crack initiation, extension and bureau level, is the material stiffness is reduced, performance degradation. Then, based on the mechanical theory of continuum medium damage, the damage process was analyzed, and the stiffness damage variable changed from 0 to 1, representing the process from initial injury to complete fracture.

4.2. Constitutive model of the fiber layer, and the failure criterion

The commonly used failure models of carbon fiber composites are Tsai-Hill strength criteria, Tsai-Wu failure criteria, Hashin model, Linde model, etc. The Tsai-Hill strength criterion takes the longitudinal strength, transverse strength and shear strength as the failure criteria, and no composite materials with different tensile properties are considered [107–109]. LINDE *et al*. [110] modified the Hashin model for the fiber layer.

4.2.1. Tsai-Wu destruction criteria

The Tsai-Wu damage criterion is the most comprehensive description of composite material destruction in the existing criteria [111]. Other damage criteria and models can be obtained by simplifying the Tsai-Wu under specific loading and stress conditions [112–115].

The Tsai-Wu criterion reduces the disruption to a higher-order tensor polynomial, expressed as

$$F_i\sigma_i + F_j\sigma_j + F_k\sigma_k + F_{ij}\sigma_i\sigma_j + F_{ji}\sigma_j\sigma_i + F_{ii}\sigma_i^2 + F_{ijk}\sigma_i\sigma_j\sigma_k + \cdots = 1 \quad (i, j, k = 1,2,\ldots 6) \tag{1}$$

Where, $\sigma_i, \sigma_j, \sigma_k$ is the stress vector and F_i, F_{ij}, F_{ijk} is the strength tensor coefficient of material characterization.

The more items that are included in the polynomial of the Tsai-Wu destruction criterion, the higher the computational accuracy, but the greater the cost of determining the tensor coefficient. Therefore, in the finite element analysis using the Tsai-Wu intensity criterion, it is easier to achieve damage analysis by using the degradation criteria of CHANG *et al.*, DUTTON *et al.*, and SHOKRIEH *et al*. [116–120].

4.2.2. Hashin model

Hashin The model specifies the destruction criteria of fiber composites under planar stress. The model considers that the composite material is orthogonal anisotropic material. The injury initiation is based on four main failure modes, namely, fiber tensile fracture, fiber compression buckling, matrix tensile fracture and shear failure of matrix fiber, which are specifically expressed as follows:

Fiber tensile fracture ($\varepsilon_{11} \leq 0$)

$$F_1^2 = \left(\frac{\varepsilon_{11}}{\varepsilon_{11}^{\mathrm{f,t}}}\right)^2 + \left(\frac{\varepsilon_{12}}{\varepsilon_{12}^{f}}\right)^2 + \left(\frac{\varepsilon_{13}}{\varepsilon_{13}^{f}}\right)^2 \quad (2)$$

Fiber compression in flexion ($\varepsilon_{11} < 0$)

$$F_1^2 = \left(\frac{\varepsilon_{11}}{\varepsilon_{11}^{\mathrm{f,c}}}\right)^2 \geq 1 \quad (3)$$

Basrix tensile fracture ($\varepsilon_{22} + \varepsilon_{33} \geq 0$)

$$F_2^2 = \left(\frac{\varepsilon_{22} + \varepsilon_{33}}{\varepsilon_{22}^{\mathrm{f,t}}\varepsilon_{33}^{\mathrm{f,t}}}\right)^2 - \frac{\varepsilon_{22}\varepsilon_{33}}{(\varepsilon_{23}^{f})^2} + \left(\frac{\varepsilon_{12}}{\varepsilon_{12}^{f}}\right)^2 + \left(\frac{\varepsilon_{13}}{\varepsilon_{13}^{f}}\right)^2 + \left(\frac{\varepsilon_{23}}{\varepsilon_{23}^{f}}\right)^2 \geq 1 \quad (4)$$

Basal fiber shear failure ($\varepsilon_{22} + \varepsilon_{33} < 0$)

$$F_2^2 = \left(\frac{\varepsilon_{22} + \varepsilon_{33}}{\varepsilon_{22}^{\mathrm{f,c}}\varepsilon_{33}^{\mathrm{f,c}}}\right)^2 + \frac{\varepsilon_{22} + \varepsilon_{33}}{\varepsilon_{22}^{\mathrm{f,c}}} + \left(\frac{\varepsilon_{22}^{\mathrm{f,c}}}{2\varepsilon_{12}^{\mathrm{f,c}}} - 1\right) - \frac{\varepsilon_{22}\varepsilon_{33}}{(\varepsilon_{13}^{f})^2} + \left(\frac{\varepsilon_{12}}{\varepsilon_{12}^{f}}\right)^2 + \left(\frac{\varepsilon_{13}}{\varepsilon_{13}^{f}}\right)^2 + \left(\frac{\varepsilon_{23}}{\varepsilon_{23}^{f}}\right)^2 \geq 1 \quad (5)$$

4.2.3. Linde model

Linde The model takes the ultimate strain as the criterion for damage, and believes that both the tensile and compression properties of the material are broken. The model assumes that the material has continuous damage, mainly considers the damage of the fiber and the matrix, so that the destruction process of the fiber and the matrix is described by two injuries [121, 122], the matrix is expressed as:

Damage and failure of the fibers

$$\varepsilon_f = \sqrt{\frac{\varepsilon_{11}^{\mathrm{f,t}}}{\varepsilon_{11}^{\mathrm{f,c}}}(\varepsilon_{11})^2 + \left[\varepsilon_{11}^{\mathrm{f,t}} - \frac{(\varepsilon_{11}^{\mathrm{f,t}})^2}{\varepsilon_{11}^{\mathrm{f,c}}}\right]\varepsilon_{11}} > \varepsilon_{11}^{\mathrm{f,t}} \quad (6)$$

Damage failure of the matrix

$$\varepsilon_m = \sqrt{\frac{\varepsilon_{22}^{\mathrm{f,t}}}{\varepsilon_{22}^{\mathrm{f,c}}}(\varepsilon_{22})^2 + \left[\varepsilon_{22}^{\mathrm{f,t}} - \frac{(\varepsilon_{22}^{\mathrm{f,t}})^2}{\varepsilon_{22}^{\mathrm{f,c}}}\right]\varepsilon_{22} + \frac{(\varepsilon_{22}^{\mathrm{f,t}})^2}{\varepsilon_{12}^{\mathrm{f,c}}}(\varepsilon_{12})^2} > \varepsilon_{22}^{\mathrm{f,t}} \quad (7)$$

4.3. Establishment of the interface model and the damage criterion

FMLs are laminated structure, and stratification is one of the main forms of failure. The weak binding force at the interface between metal layer and fiber layer is the key factor controlling the failure of lamina, which is closely related to the macroscopic mechanical properties and interfacial properties of FMLs [123–125].

The interfacial layer of FMLs is relatively thin, the nature of the thickness direction cannot be ignored, and the stress and strain analysis is relatively difficult. In addition, the continuity assumption is no longer applicable to the stratification and expansion of inter-layer destruction. Scholars initially tried to use zero thickness unit to solve the problem of unit division in the thickness direction [126, 127], and then tried to equivalent the interface layer to normal and tangential orthogonal springs to simulate the debonding problem of composite materials [128, 129], and achieved certain results, but did not reflect the interaction between normal and tangential when the interface damage.

Cohesin model is widely used as a composite damage model by researchers to simulate the multilayer interface. It is on the basis of elastic, interface element model developed a thickness of interface unit, the interface unit by defining the appropriate interface stiffness, failure strength and fracture toughness between the material mechanical properties parameters, and describe the metal layer and fiber layer on the surface of the cohesion and separation of the relative only relationship, and study the interface damage evolution law and the influence on the overall performance of composite materials [130–132]. In the cohesive model, the stress-strain behavior is the traction-separation mode, and the area surrounded by the traction-separation curve and the displacement coordinate is the interlayer fracture toughness, as shown in Figure 1.

In the cohesion model, the secondary nominal strain criterion (quade damage) was used to determine the onset of injury. The energy-based Benzeggagh-Kenane fracture criterion (B-K law) is more accurate in predicting the evolution of hierarchical damage in the interface.

In the modeling process of FMLs, it is generally used to establish a thin layer of finite thickness between the metal layer and the fiber layer, assign the cohesive material properties, and realize the unit common nodes and transfer loads. This method can better simulate the layered damage failure than establishing the surface-surface cohesive contact [133].

4.4. Macroscopic and detailed view simulation

The damage evolution process of the composite material is multi-scale and cross-level, and its structural properties and damage failure mechanism not only depend on the material performance of each component of the composite material, but also depend on its fine structural characteristics [134–136]. A single macroscopic or fine-scale simulation method is difficult to accurately reflect the damage and failure characteristics of composite composites.

The macroscopic simulation does not discuss the difference between fiber and matrix, but mainly discusses the mechanical problems of stretching, bending, flexion and fatigue under the influence of FMLs structure. According to the main problems of the macroscopic simulation study, a variety of strength failure theories are also put forward. However, the macroscopic simulation does not involve the micro mechanism of material failure, but predicts the failure behavior of the composite material structure through the material failure criteria [137–139]. Therefore, the macroscopic simulation is widely used in engineering practice and plays an important role.

However, the mechanical properties of FMLs are their unique anisotropy, and there is a strong correlation between their failure form and its anisotropy, especially the carbon fiber reinforced composite material, which is composed of fiber and matrix, and the accumulation of microscopic defects and cracks determines the characteristics of macroscopic failure [140–142]. In the process of finite element simulation, the researchers use the single cell model under the fine scale, and build the internal fiber bundle of the material and woven or woven geometry parameters, pretreatment through CAD modeling and the finite element meshing software, and adopt appropriate failure criteria based on different failure modes to calculate the stress and strain distribution after damage on the mesoscale [143–146].

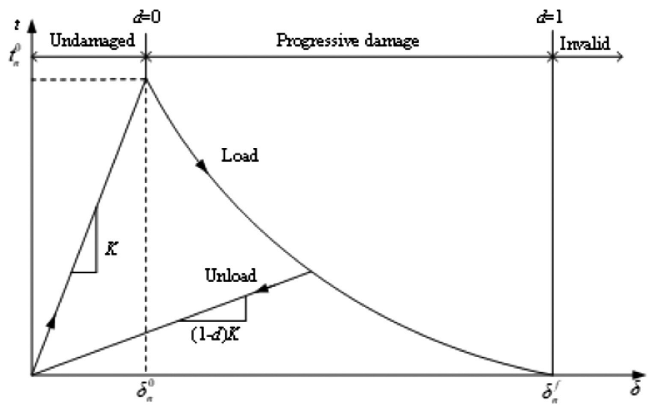

Figure 1: The constitutive model of cohesive force element.

5. FORECASTING AND OUTLOOK

With the increasing consumption of FMLs in aerospace, rail transit and ships and the continuous improvement of application requirements, the requirements for FLs test methods and index evaluation have also brought challenges, and the requirements for high efficiency and reliability of performance testing are getting higher and higher. The future work can be carried out in the following aspects.

(1) Carry out the performance test and study of FMLs of large size, large thickness, large curvature and complex structures. In the fields of aerospace, rail transit, shipping and other, the demand for large size, large thickness and complex structure FMLs is increasing, and the requirements for their reliability are also getting higher and higher. The relevant FLs, performance testing, related mechanism research and engineering application research will become the focus of research and application in recent years.

(2) Conduct performance tests under extreme conditions. FMLs has more extensive requirements in high temperature, high pressure, high speed, high frequency, low temperature, extreme humidity and other fields. Common performance testing equipment, systems, schemes, and standards cannot meet the requirements of performance testing under the above extreme conditions, so it is necessary to accelerate the research and standard formulation of FMLs testing equipment under extreme conditions.

(3) Carry out rapid ND destructive research with high sensitivity. The commonly used nondestructive testing technology such as infrared, ultrasonic, penetration, acoustic emission, microwave can meet the requirements of internal defects detection, but with the application of FMLs is more and more widely, high value-added products of detection content, detection accuracy, detection cycle requirement is more and more high, need to carry out high sensitivity of rapid nondestructive testing technology research.

(4) Carry out numerical simulation research on molecular scale. At present, the macro and micro scale resin simulation of the mechanical properties and damage of FMLs has certain limitations. With the increasing demands of the industry on the comprehensive properties of FMLs, it is imperative to develop a more complete constitutive model of FMLs and analyze the mechanical properties and damage mechanism of FMLs at the molecular scale.

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