МІНІСТЕРСТВО ОСВІТИ ТА НАУКИ УКРАЇНИ
НАЦІОНАЛЬНИЙ АВІАЦІЙНИЙ УНІВЕРСИТЕТ
КАФЕДРА КОНСТРУКЦІЇ ЛІТАЛЬНИХ АПАРАТІВ

ДОПУСТИТИ ДО ЗАХИСТУ
Завідувач кафедри, д.т.н., проф.
__________ Сергій ІГНАТОВИЧ
«___» __________ 2022 р.

ДИПЛОМНА РОБОТА

ВИПУСКНИКА ОСВІТНЬОГО СТУПЕНЯ МАГІСТРА
ЗІ СПЕЦІАЛЬНОСТІ
«АВІАЦІЙНА ТА РАКЕТНО-КОСМІЧНА ТЕХНІКА»

Тема: «Модель прогресуючого пошкодження вуглецевого волокна»

Виконавець: __________ **Сяохуей У**

Керівник: к. т. н., доц. __________ **Володимир КРАСНОПОЛЬСЬКИЙ**

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Київ 2022

MINISTRY OF EDUCATION AND SCIENCE OF UKRAINE
NATIONAL AVIATION UNIVERSITY
DEPARTMENT OF AIRCRAFT DESIGN

PERMISSION TO DEFEND
Head of the department,
Professor, Dr. of Sc.
_________ Sergiy IGNATOVYCH
"___" _____________ 2022

MASTER DEGREE THESIS

ON SPECIALITY
"AVIATION AND ROCKET-SPACE ENGINEERING"

Topic: "Progressive damage model of Carbon Fiber"

Fulfilled by:	____________	**Xiaohui WU**
Supervisor: **PhD, associate professor**	____________	**Volodymyr KRASNOPOLSKII**
Labor protection advisor: **PhD, associate professor**	____________	**Victoria KOVALENKO**
Environmental protection adviser: **Ph.D. associate professor**	____________	**Tamara DUDAR**
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Kyiv 2022

НАЦІОНАЛЬНИЙ АВІАЦІЙНИЙ УНІВЕРСИТЕТ

Аерокосмічний факультет
Кафедра конструкції літальних апаратів
Освітній ступінь «Магістр»
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Освітньо-професійна програма «Обладнання повітряних суден»

ЗАТВЕРДЖУЮ
Завідувач кафедри, д.т.н, проф.
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«___» _____________ 2022 р.

ЗАВДАННЯ
на виконання дипломної роботи студента

Сяохуей У

1.Тема:«Модель прогресуючого пошкодження вуглецевого волокна», затверджена наказом ректора від 11 жовтня 2022 року № 2173/ст.

2. Строки дипломної роботи: з 11 жовтня 2022 р. по 31 грудня 2022 р.

3. Вихідні дані: Зразки були виготовлені у вигляді прямокутних зразків довжиною 150 мм, шириною 20 мм і товщиною приблизно 2,2 мм методом укладання [0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°] південної широти.

4. Зміст: Вступ; основна частина: Експериментальне проектування вуглепластиків, армованих вуглецевим волокном, аналіз міцності при розтягуванні на втому; спеціальна частина: охорона праці, охорона навколишнього середовища.

5. Необхідний матеріал: Скінченно-елементна імітаційна модель, розрахунковий код умат .

6. Календарний план-графік

№ пор.	Завдання	Термін виконання	Відмітка про виконання
1	Отримання завдання, обробка статистичних даних.	11.10.2022 – 11.10.2022	
2	Проектування та виготовлення вуглепластиків.	11.10.2022 – 18.10.2022	

3	Скінченно-елементне і математичне моделювання та проведення експериментів.	18.10.2022 – 24.10.2022	
4	Програмування, тестування та налагодження.	24.10.2022 – 28.10.2022	
5	Експериментальний аналіз і теоретична верифікація.	28.10.2022 – 01.11.2022	
6	Охорона праці .	01.11.2022 – 03.11.2022	
7	Охорона навколишнього середовища.	03.11.2022 – 06.11.2022	
8	Підготовка ілюстративного матеріалу, написання доповіді.	06.11.2022 –13.11.2022	
9	Перевірка редагування та виправлення пояснювальної записки.	13.11.2022 – 16.11.2022	

7. Консультанти з окремих розділів:

Розділ	Консультант	Дата, підпис	
		Завдання видав	Завдання прийняв
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Охорона навколишнього середовища	к.т.н, доцент Тамара ДУДАР		

8. Дата видачі завдання: 5 жовтня 2022 року

Керівник дипломної роботи ____________ Володимир КРАСНОПОЛЬСЬКИЙ
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Завдання прийняв до виконання ____________ Сяохуей У
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NATIONAL AVIATION UNIVERSITY

Faculty ____Aerospace______
Department __of Aircraft Design__
Educational degree __"Master"__
Specialty 134 "Aviation and space rocket technology"
Educational program __"Aircraft equipment"__

APPROVED BY
Head of department Dr. of Sc., prof.
__________ Serhii IGNATOVYCH
"___" ___________ 2022.

TASK
for the master thesis

Xiaohui WU

1. Topic: «Progressive damage model of Carbon Fiber» approved by the Rector's order № 2173/ст from 11 October 2022.
2. Thesis terms: since 11 October 2022 till 31 December 2022.
3. Initial data: The specimens were designed as rectangular specimens of 150 mm in length, 20 mm in width, and approximately 2.2 mm in thickness with the lay-up method $[0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°]_s$.
4. Content: Introduction; main part: Experimental design of Carbon Fiber Reinforced Plastics, CFRP tensile fatigue strength analysis; special part: Labor protection, Environmental protection.
5. Required material: Finite element simulation model, umat design code.
6. Thesis schedule

№	Task	Time limits	Done
1	Task receiving, processing of statistical data.	11.10.2022–11.10.2022	
2	Design and Fabrication of Carbon Fiber Laminates	11.10.2022–18.10.2022	
3	Finite element modeling and mathematical modeling and conducting experiments	18.10.2022–24.10.2022	
4	Programming, testing and debugging	24.10.2022–28.10.2022	
5	Experimental analysis and theoretical verification	28.10.2022-01.11.2022	

6	Labor protection .	01.11.2022–03.11.2022	
7	Environmental protection.	03.11.2022–06.11.2022	
8	Preparation of illustrative material, writing the report.	06.11.2022–13.11.2022	
9	Explanatory note checking, editing and correction.	13.11.2022–16.11.2022	

7. Special chapter advisers:

Chapter	Adviser	Date, signature	
		Task issued	Task received
Labor protection	PhD, associate professor Victoria KOVALENKO		
Environmental protection	PhD, associate professor Tamara DUDAR		

8. Date: "05" October 2022

Supervisor _____________ Volodymyr KRASNOPOLSKII

Student _____________ Xiaohui WU

РЕФЕРАТ

Магістерська робота «Модель прогресуючого пошкодження вуглецевого волокна»

80 с., 35 рис., 13 табл., 77 джерел

Дана робота присвячена прогресивній моделі пошкодження для аналізу властивостей композитів, армованих вуглецевим волокном, яка може точно прогнозувати основні властивості та втомну довговічність композитів, армованих вуглецевим волокном.

Метод проектування заснований на методі аналізу кінцевих елементів та підпрограмі umat abaqus, основні параметри продуктивності отримані за допомогою експериментів на розтягнення та втому ламінованої пластини, числові значення підставляються в параметри моделювання abaqus, експериментальні дані та дані моделювання перевіряються в межах розумної похибки, а ефективне моделювання композитного матеріалу може бути реалізовано за допомогою методу аналізу кінцевих елементів.

Матеріали для отримання ступеня магістра та диплома можуть бути використані в процесі навчання авіаційної промисловості та авіаційної спеціальності.

Вуглепластикові композити, модель прогресуючого пошкодження, скінченно-елементний аналіз, руйнівне пошкодження

ABSTRACT

Master thesis "Progressive damage model of Carbon Fiber"

80 pages, 35 figures, 13 tables, 77 references

This thesis is devoted to a progressive damage model for analyzing the properties of carbon fiber reinforced composites, which can accurately predict the basic properties and fatigue life of carbon fiber reinforced composites.

The design method is based on the finite element analysis method and the umat subroutine of abaqus, the basic performance parameters are obtained through the tensile and fatigue experiments of the laminated plate, the numerical values are substituted into the simulation parameters of abaqus, the experimental data and the simulation data are verified to be within a reasonable error, and the effective simulation of the composite material can be realized through the finite element analysis method.

The materials for the master's degree and diploma can be used in the education process of aviation industry and aviation major.

Carbon fiber composites, progressive damage model, finite element analysis, fracture damage

CONTENT

INTRODUCTION

In this paper, T700 carbon fiber reinforced epoxy resin matrix composite is taken as the research object. Through understanding the basic theory of each component of composite material, CFRP laminates are prepared, and the basic performance data of the material are measured by static strength tensile test. Based on the performance data, the fatigue test of composite laminates was designed to simulate the fatigue cyclic loading test of aircraft wing under different stress ratios. The fatigue failure modes of the composites were analyzed based on the failure morphology. Then, the finite element model is established, and the UMAT user subroutine is compiled. The static strength, fatigue strength and damage strength under load are simulated by progressive damage analysis method, and the test results are compared with the simulation results and cross-validated, and the progressive damage analysis model under fatigue load is established. Finally, the model is used to analyze the static strength and fatigue strength of a carbon fiber composite aircraft wing structure under displacement, which verifies that the finite element analysis method can be used to optimize the aircraft design.

PART 1. ANALYSIS OF CFRP PRESENT SITUATION

1.1 Background and significance of thesis research

With the continuous development of science and technology, in all aspects of materials are constantly developing, composite materials with its unique properties by the aerospace field, automotive field and the construction of ships on the use. The development of composite materials has become the measure of a country's industrial level. Advanced aerospace vehicles and their important structural components, such as aircraft (including civil and military), aero-engines, rockets and engines, and other aerospace products have become a symbol of the comprehensive national power of each country. New materials research and development and industrial product design have always been inextricably linked, from the first aircraft produced by mankind, "Aviator I", one of the goals of the design of various aircraft structures is to meet the strength and rigidity while reducing weight as much as possible. When the research and development of advanced materials is flourishing, the design of various types of aerospace vehicles is also the pursuit of high speed, light weight and high load-bearing capacity. Studies have shown that every 1 kg weight reduction of a vehicle will significantly improve the economic efficiency, and with the increase of the flight speed of the vehicle, the improved efficiency increases significantly, as shown in fig. 1.1 [1]. The use of advanced materials is one of the effective ways to achieve weight reduction of aerospace vehicles. From the aerospace field, structural materials have entered the development stage of mainly composite materials since the turn of the century. The emergence of new advanced composite materials has largely promoted the development of weight reduction in the structure of aerospace vehicles, and at the same time, the amount of composite materials has gradually become an indicator for judging the advanced level of aerospace vehicle design.

In recent years, Carbon Fibre Reinforced Plastics(CFRP) are used more and more widely in the aerospace field, CFRP are usually a combination of two or more materials of fiber and matrix, carbon fiber is an inorganic high-performance fiber with carbon content higher than 90%, which is transformed from organic fibers through heat treatment, and has the inherent characteristics of carbon materials, but also has the softness and processability of textile fibers, and the matrix can be polymer, metal or ceramics. There is a clear phase boundary between the carbon fiber reinforcement and the matrix material, which determines the non-homogeneity of Carbon Fibre Reinforced Plastics. Since the fiber reinforcement is mainly subjected to axial loads and has a weak load carrying capacity for other types of loads, CFRP also have significant anisotropy. In addition, it is possible to design the fiber direction and number of single-layer materials, as well as the number of layers and lay-up sequence of multi-layer composites to improve structural efficiency and reduce weight. It can be seen that CFRP have structural designability.

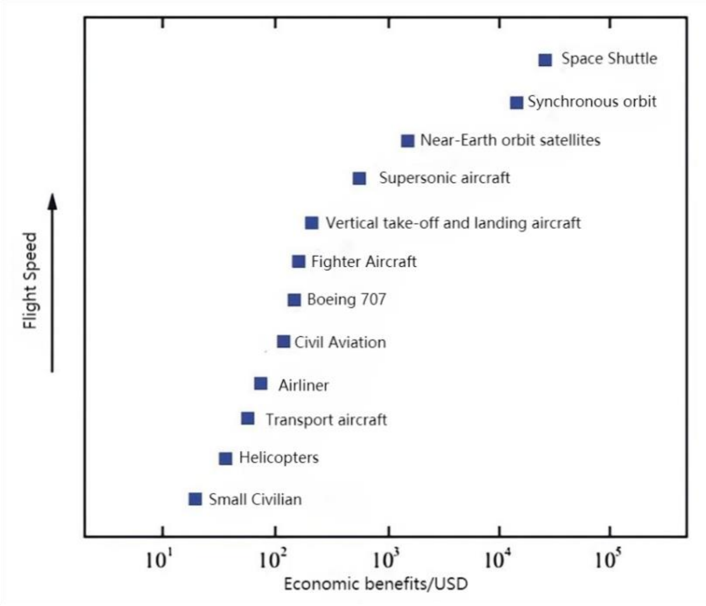


Fig 1.1. Economic benefits achieved per 1kg weight reduction of the vehicle as a function of flight rate.

Carbon fiber composites have higher specific strength and specific modulus compared to other aerospace metal alloys, with five times the specific modulus and three times the specific strength compared to aluminum and steel, and the specific gravity of carbon fiber is about 1/5 that of steel and 1/2 that of aluminum [2], with lighter weight, better corrosion resistance and fatigue life resistance, larger payloads (personnel, avionics, munitions, etc.) for longer range and fuel savings. The high temperature resistance of carbon fiber composites is very good, and the machine parts can withstand the effects of high temperatures during use to reduce unnecessary losses, and its properties and nature do not change easily under high temperature conditions, providing a guarantee for the smooth operation of aviation equipment [3]. The difference between the fatigue damage mechanism of CFRP and metallic materials is that composites generally do not have main cracks, while the formation and expansion of a large number of microcracks consumes a lot of energy, which determines the fatigue resistance of CFRP better than metallic materials. This has laid a solid foundation for the wide application of carbon fiber composites in the aviation and aerospace fields. CFRP are most commonly used in aircraft. Earlier, CFRP were mainly used in non-load-bearing parts of aircraft, such as aircraft radome, hatch, fairing, etc. As the composite material preparation process becomes more and more mature and the structural design level becomes higher and higher, CFRP start to be used in the main load-bearing parts of aircraft.

1.2 Current status of applications in the aviation field

Composites are the most important aerospace and aviation materials besides aluminum. Due to their light weight, they have accounted for more than 15% of the structural weight of civil aircraft and more than 50% of the structural weight of helicopters and fighter jets in the last 40 years, and are widely used in different aerospace equipment.

1.2.1 Application in the field of civil aircraft

Take Airbus as an example, composite materials were first applied to the A320 horizontal tail and vertical tail, and later also applied to the A400M large military transport aircraft wings. After entering the 21st century, A380 carbon fiber composite materials accounted for 25%, mainly applied to the center wing and tail wing, in addition, the A380 fuselage skin using fiber metal laminate (GLARE laminate). The 787 is Boeing's first aircraft to use composite materials on a large scale, and its fuselage, wings and tail are all made of composite materials, and the proportion of composite materials to the weight of the structure reaches 50%. Under the pressure of Boeing, the Airbus A350 changed its plan several times and increased the application of composite materials to a large extent, finally increasing the proportion of composite materials to about 52%. The use of composite materials in China is also a gradual process. 2% of composite materials are used in the new ARJ21 regional aircraft, mainly in the rudder and wingtip winglets, etc. The C919 large passenger aircraft has reached a level of 11%-12%, and the tail and rear pressure frame are basically composite materials. A350 and Boeing 787 belong to the same level.

Table 1.1

Some civil airliners and the CFRP they use

Company	Model	Part	Material type (carbon fiber/substrate resin)
Boeing	B787	fuselage, wing	T800S/3900-2B
Airbus	A350	fuselage, wing	IMA/M21
Airbus	A220	Wing	IMS65/Cytec890

1.2.2 Applications in the military aircraft field

In the early 1970s, the U.S. military F-14 fighter jet partially used carbon fiber composite materials as the main bearing structure; and later, CFRP materials in the tail of military aircraft, such as vertical tail, horizontal tail and other components began to gradually use, such as F-15, F-16, Mig-29, Mirage 2000, F/A-18 and other military aircraft. June 9, 1974, F-18 military aircraft The first flight was successful, becoming the only naval fighter on the U.S. aircraft carriers, of which the amount of composite materials accounted for 10% of the total mass of structural materials, mainly concentrated in the main wing, fuselage and other parts; in September 1985, the F-22 fighter began development, its structural quality factor of 27.8%, the amount of carbon fiber composite materials has reached more than 25%. As early as during the Sixth Five-Year Plan, Shenyang Aircraft Research Institute used composite materials to develop the drogue wall panel of the fighter, which reduced the weight by 30% compared with the original aluminum alloy structure; the Chinese J-10 fighter used composite materials for the duck wing, drogue tail, flap aileron, ventral fin and other parts; in 2011, the Falcon L-15 high education aircraft used composite materials as nose cowl, rudder and drogue [4]. The extensive use of composite materials in military aircraft can reduce the weight and thus significantly improve their combat capability. Table 1.2 shows the use of composite materials in some military aircraft.

Table 1.2

Use of composite materials in some military aircraft

Model	F-15A	F-16A	AV-8B	J-20	F-35
Composite material ratio/%	2	2	26	27	35

1.2.3 Application in the field of helicopter

The biggest difference between helicopters and fixed-wing aircraft is the difference in structure and flight dynamics. Traditional helicopters provide lift and propulsion through the rotation of the rotor blades, and fly at relatively low altitudes and speeds, making them a low- to medium-altitude, low-speed aircraft. The main application environment of helicopter is wet, hot, drought, sand, dust, rain and other harsh environmental conditions, which put forward higher requirements for the weather resistance and corrosion resistance of helicopter structure, at the same time, the helicopter rotor has high requirements for material fatigue resistance. So the composite material with comprehensive excellent performance will be the inevitable choice for the design of helicopter environmental adaptability.

The amount of foreign helicopter composite materials [5] (see fig. 1.2) has increased year by year, and has accounted for 35% to 50% of the structural mass fraction by the 1980s. As a typical representative of all-composite fuselage helicopters, NH90 composite materials account for 95% of the total mass, and only the power cabin platform and its bulkhead use metal parts, which brings the advantage of 20% reduction in the number of parts and 15% mass reduction, and its rotor parts use carbon fiber and glass fiber reinforced dimensional composites; RAH-66 helicopter fuselage structure uses carbon fiber/epoxy (IM7/ 8552) composites, accounting for a percentage of the total mass. 8552) composite materials, accounting for 51% of the weight of the structure, its front fuselage components, tail beam, main propeller and a large number of carbon fiber composite materials; V-280 helicopter for the first time used a full carbon fiber composite tilt rotor blades; Airbus Helicopters developed the H160 helicopter is the world's first all-composite civil helicopter, the central part of its propeller hub using carbon fiber reinforced polyether ether ketone resin-based The H160 helicopter developed by Airbus Helicopters is the world's first all-composite civil helicopter, and its propeller hub centerpiece is designed and prepared with carbon fiber reinforced polyether ether ketone resin-based composite material, which greatly reduces the fuselage mass, improves the damage tolerance and reduces the rate of structural fatigue crack expansion [6]. The V-280 tilt-rotor helicopter developed by Bell also used a large number of composite materials, including thermoplastic materials, on the basis of the V-22, and the main structural components are composite materials [7]. The Chinese straight 10 and straight 19 helicopter gunships also make extensive use of CFRP in the fuselage frame structure, helicopter rotors, wing skins, and helicopter tail components [8].

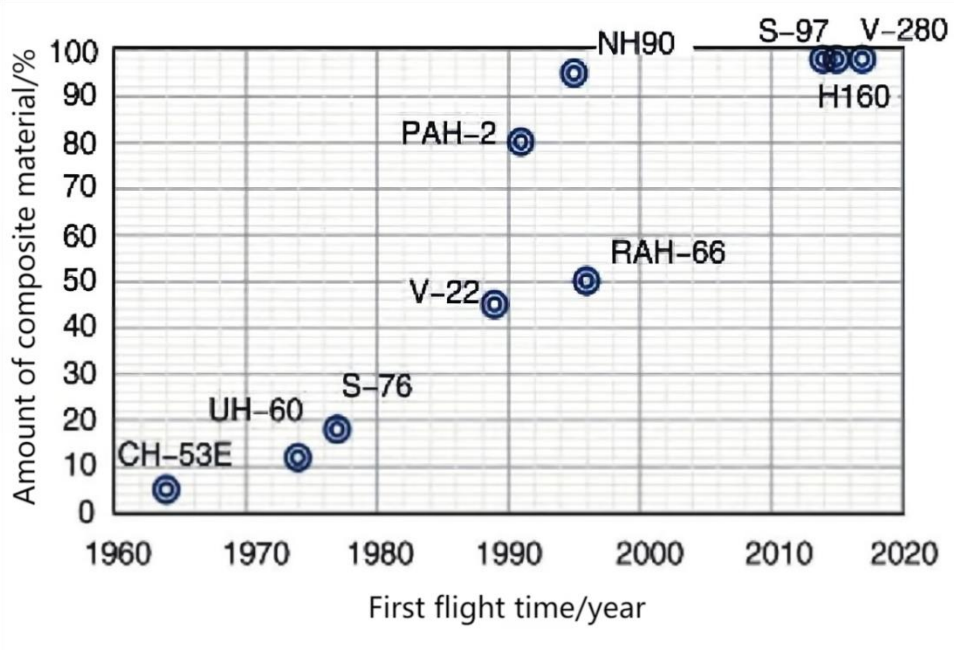


Fig 1.2. Foreign helicopter advanced composite materials applications.

1.3 Current status of research on the strength of carbon fiber composites

1.3.1 Main research methods of composite mechanics

The mechanics of composites is a mechanical theory with both macroscopic and fine-scale properties. There are two main approaches to the study of composite mechanics: one is the macromechanical approach and the other is the fine-scale mechanical approach [9].

The macroscopic mechanical method is considered from an image-only point of view, ignoring the interaction between the components of the composite material and considering the reinforcement and the matrix as one, so that the composite material is a macroscopic homogeneous medium. In the macromechanical method, only the macroscopic stress and strain fields of the composite can be obtained, and the real stress and strain of the matrix phase and the reinforcement phase at a fine scale cannot be obtained. However, in fact, the catastrophic damage exhibited by macroscopic is often the result of the interaction of multiple damage mechanisms at both macroscopic and fine levels. Therefore, the disadvantage of the macroscopic mechanics method is that it is difficult to reflect the deep physical mechanism of the composite material and thus it is difficult to analyze the damage and destruction in depth.

The fine-mechanics method establishes the relationship between the fine-scale properties and macroscale properties to reveal the deformation and damage law of composite structures under certain working conditions, and its methods can be divided into analytical method and fine-mechanics finite element method. Among them, the fine-scale mechanical finite element method is used mainly to derive the fine-scale stress and strain fields of representative volume elements of composite materials at the fine-scale level. With this fine-scale volume, we can carry out analysis such as damage or plastic yielding of composites, and also derive macroscopic intrinsic structure relationship of composites based on homogenization method to quantitatively analyze the relationship degree between macroscopic properties such as strength and modulus of composites and their fine-scale structure.

EShelby et al [10-12] did a lot of fundamental work on the fine-scale mechanical methods for composites as early as 60 years ago. Based on EShelby's equivalent inclusions theory, Liang Jun et al [13] analyzed the mechanical properties of plastic matrix composites with different inclusions shapes and different fiber volume fractions under multi-axial tensile loading. Huang Zengming et al [14] found that the bridge-linkage theory can predict the strength of laminates under arbitrary loads based on the accurate parameters of the original property data of fibers and matrix, which is of great significance for the design of composites from components to structures. However, the fine-scale mechanics method also has many limitations in practical applications, such as the computational analysis can be limited by the fact that the structural network delineated for the composite is too fine and requires computer performance far beyond the level of current computers due to the large scale difference from fine-scale to macroscale.

1.3.2 Current Status of Progressive Failure Analysis Research

The failure process of composite laminates is a gradual failure process from damage sprouting, expansion to final destruction. The weak points of the structure fail first, and the material properties at the failure point degrade, leading to a reduction in the load-bearing capacity of the structure and stress redistribution, and finally various damage modes accumulate and couple until the whole plate loses its load-bearing capacity. Accurate prediction of the final failure strength of composite structures can maximize the performance of composite materials. The progressive damage analysis method for composites is one of the hot methods to study the failure of composites by selecting a material property degradation model to simulate the damage evolution process of composites so as to predict the maximum load carrying capacity of the structure [15].

Chang et al [16-20] and Tan et al [21, 22] used the progressive damage analysis method earlier and successfully predicted the damage initiation, evolution and ultimate strength of pore-containing fiber-reinforced laminates under uniaxial tensile, compressive and shear loading, and it was in good agreement with the experimental results. In recent years, Chenghua Wang et al [23] proposed a new stiffness degradation model that can be used for progressive damage strength analysis of laminated and solid-type composites, and wrote a subroutine based on the Tsai-Wu criterion to numerically analyze the two structures to verify the reliability of the model. Rupeng Li et al [24] used the three-dimensional Hashin criterion to determine the damage of composite open-hole plates and compared the analysis with the experimental results to verify the effectiveness of the progressive damage analysis method. Zhu Jianhui et al [25] simulated the laminate failure load based on the Camanho degradation model using the three-dimensional Hashin criterion with shear nonlinearity, and the failure mode and failure occurrence location matched with the test.

1.3.3 Current status of fatigue analysis research

Compared with metallic materials, the fatigue damage mechanism of composite materials is much more complex, and its research methods can be divided into macroscopic image-only methods and microscopic mechanistic studies, but the complexity and diversity of its damage modes make it difficult to propose a unified theory to accurately describe the properties of composite materials under fatigue loading. In the past three decades, scholars from various countries have conducted a lot of research and proposed numerous models for fatigue problem analysis, including fatigue life model, residual stiffness or residual strength based image-only model, dissipative energy model, etc.

Kangjun Wei et al [26] conducted tensile and compressive fatigue tests on carbon fiber composites at different stress levels, and established a fatigue life model based on S-N curve and made life prediction for pore-containing laminates. Wu Fuqiang [27] constructed a macroscopic damage accumulation model by analyzing the decay law of composite stiffness under fatigue loading, which accurately reflected the nonlinear law of fatigue damage extension of composites. Pan Yingxiong [28] conducted fatigue tests on carbon fiber composite laminates with different lay-up methods from the perspective of energy dissipation to analyze and study the fatigue accumulation damage behavior of the laminates.

Different fatigue damage accumulation models have their characteristics and applicability, and Xi Wang et al [29] reviewed the fatigue damage analysis methods proposed by previous authors for composite laminates and summarized the characteristics of different models and the challenges faced in the current study. Most of the previous studies were based on fatigue test studies on a defined laminate structure to establish a damage model or a life prediction model describing the laminate, but since the fatigue damage phenomenon varies greatly among different laminates and composites under different loading conditions, the scope of application is limited and the test cost and difficulty are high, and the problem of generality and universality of the model needs to be solved. The only image model can describe the degradation law of mechanical quantities such as stiffness and strength from a macroscopic point of view, which is the main method to study the fatigue behavior of composite materials at present. The use of macroscopic quantities to describe the damage accumulation law can not only highlight the research purpose, but also reduce the research cost and facilitate the engineering application, but its dependence on the parameters obtained through experiments is strong.

Conclusion for part 1

This chapter first expounds the research background and significance of this topic. Then, by introducing the application of carbon fiber composites in various aviation fields, the importance of composites for national defense forces is explained. Finally, the research methods of composites at home and abroad are explored, and it is concluded that the progressive damage model can be used to analyze the strength and fatigue life of carbon fiber composites.

PART 2. EXPERIMENTAL DESIGN OF CFRP

2.1 Basic theory of CFRP

2.1.1 Carbon Fiber

Carbon Fiber (CF) is a new material with high carbon content (more than 95%), high specific strength, high specific modulus, high temperature resistance, chemical corrosion resistance, low resistance, high thermal conductivity, low thermal expansion and other special physical and chemical properties, and does not dissolve in organic solvents, acids, alkalis, corrosion resistance is outstanding. In addition, carbon fiber also has the advantages of fiber flexibility and weaveability, the density is less than 1/4 of steel, but the tensile strength is 7-9 times that of steel, Young's modulus is more than 2-3 times that of glass fiber (GF) or Kevlar fiber (K-49), respectively, and is also the most commonly used fiber in high-performance composites [30]. Carbon fibers can be cross-woven into carbon fiber cloth, which greatly increases their strength. fig. 2.1 shows the woven texture of carbon fibers.

Fig. 2.1. Carbon fiber weave texture map.

Carbon fibers are mainly classified as: viscose based carbon fibers, polyacrylonitrile (PAN) based carbon fibers, asphalt based carbon fibers according to the composition of raw materials. According to the manufacturing process and processing temperature is divided into: oxidation fiber (pre-oxidation temperature 200-300 °C), carbon fiber (800-1600 °C), graphite fiber (2000-3000 °C), active carbon fiber, carbon fiber made of vapor phase growth method (VGCF). According to the use of different specifications are divided into two categories of aerospace grade and industrial grade, according to the size of the filament bundle is divided into small and large filament bundle. Generally speaking, those with filament bundles larger than 48K are called large filament carbon fibers, including 120K, 360K and 480K, etc. Carbon fiber is divided into general purpose (GP) and high performance (HP) according to mechanical properties, and high performance is divided into medium strength (MT), high strength (HT), ultra-high strength (UHT), medium model (TM), high model (HM) and ultra-high model (UHM). General purpose grade carbon fibers have tensile strength below 1 GPa and tensile modulus less than 100 GPa, while high performance grade carbon fibers have higher tensile strength than 2.5 GPa and tensile modulus higher than 220 GPa [31].

Toray, Toho, Mitsubishi Rayon, SGL, Hexcel, Cytec, and Zoltek are the seven largest carbon fiber industry developers and manufacturers in the world, and fig. 2.2 shows the production capacity of different carbon fiber manufacturers worldwide [32]. Three Japanese companies, Toray, Toho, and Mitsubishi Rayon, account for about 70% to 80% of the global carbon fiber production, with Toray having the largest production capacity, the most complete variety of specifications, and the best product performance, making it the largest carbon fiber supplier in the world.

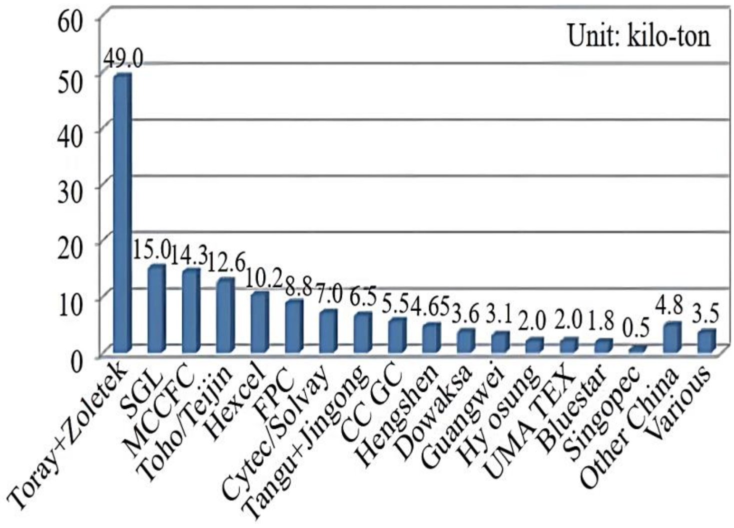


Fig. 2.2. Production capacities of different global carbon fiber manufacturers.

2.1.2 Epoxy resin

Polymeric matrices used in advanced composites can be classified as thermosetting and thermoplastic resins. Thermosetting resins are low viscosity (~2000cp) and low molecular weight monomers that transform into a three-dimensional cross-linked structure with nonmelting properties during the curing process [33]. The cross-linking phenomenon is the result of chemical reactions driven by internal chemical reactions or by heat generated by external heating. As the curing process proceeds, the reaction rate accelerates and the effective volume of the molecular arrangement decreases, leading to a decrease in molecular mobility and an increase in viscosity. As the resin gel forms a rubbery solid, it can no longer melt. Further heating leads to additional cross-linking until the resin is completely cured [34]. A comparison of thermoplastic and thermosetting polymer structures is shown in fig. 2.3. Since curing is a thermally driven event requiring a chemical reaction, thermosets require a rather long reaction time. In contrast, thermoplastics do not require a long curing time. They can be melted, cured, and then cooled. Since thermoplastics are not cross-linked, they may subsequently be reheated to form or join operations [35]. However, due to their inherent high melting point and high viscosity, processing usually requires high temperatures and pressures.

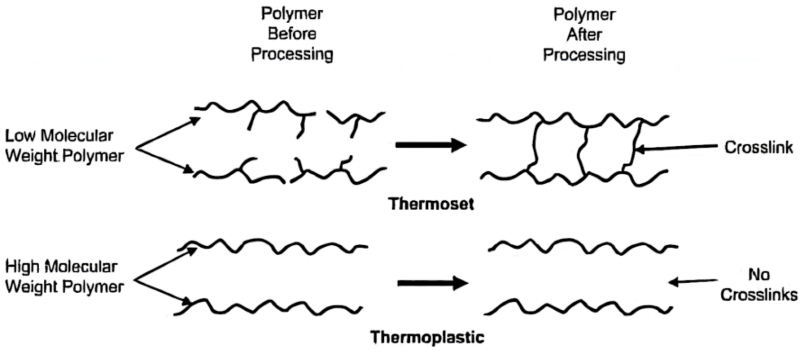


Fig. 2.3. Comparison of thermoset and thermoplastic polymer structures.

Epoxy Resin is the main polymer of thermosetting resin, which is a polymer prepolymer with aliphatic, alicyclic or aromatic chain segments as the main chain and contains two or more epoxy groups. The epoxy group can be cross-linked with the curing agent to form a three-dimensional network of thermosetting cured products, which have excellent physical and chemical properties because of the epoxy group in its structure and a variety of polar functional groups, such as excellent acid and alkali resistance, heat and humidity resistance, bonding. The disadvantages are poor weatherability and toughness (except for some special varieties) and its excellent physical and chemical properties are mainly in the following aspects [36-38]:

(1) High bonding strength and wide bonding surface

The polar functional groups in the epoxy resin molecule are easily adsorbed or chemically bonded with the bonded substrate at the two-phase interface, so the adhesive made of epoxy resin, which has a high bond strength is one of the main components of structural adhesives.

(2) Low shrinkage rate

The curing shrinkage of epoxy resin is about 1-2%, which is one of the lowest shrinkage species of thermosetting resin. To further reduce its curing shrinkage can choose to add appropriate fillers, which can reduce the shrinkage to about 0.2%. Commonly used resins curing shrinkage rate is shown in table 2.1.

Table 2.1

Curing shrinkage of commonly used thermosetting resins

Resin name	Curing shrinkage rate (%)
Phenolic resin	8-10
Polyester resin	4-6
Silicone resin	4-8
Epoxy Resin	1-2

(3) Good stability

Epoxy resin that does not contain impurities such as acids, bases and salts is not prone to deterioration and can be applied for about 1 year. The molecular structure of epoxy resin curing material is based on ether bond and benzene ring as the main chain, forming a dense and closed net structure, and such molecular structure determines that it has the stability of acid and alkali resistance and other media.

(4) Excellent electrical insulation

Epoxy resin cured products are particularly resistant to water absorption and no longer have reactive groups and free ions in their structure, characteristics that give them excellent electrical insulation properties.

(5) Good processability

The epoxy resin is thermoplastic before curing, and presents solid or liquid state depending on the molecular weight, and increasing the temperature can make the viscosity of the resin decrease. When the temperature range is suitable, epoxy resin has good fluidity, and it has good mixing ability after adding curing agent, accelerator, filler and related additives. Curing can be carried out under normal pressure, which is convenient to operate and has good processability. Epoxy resin is commonly used in many fields of national economic construction because of its many excellent properties. Such as the coating industry, glue industry, composite materials and electronics industry, etc.

2.1.3 Carbon Fiber Reinforced Plastic

Carbon Fiber Reinforced Polymer/Plastic (CFRP) is divided into Carbon Fiber Reinforced Plastic (CFRP) and Carbon Fiber Reinforced Thermoplastic Plastic (CFRTP) according to the resin matrix. Thermoset resin starts as a low viscosity resin that reacts and cures during the process to form a higher viscosity solid. Thermoplastics are a high-viscosity resin to be heated and processed. Thermoset resins cure during heat processing and cannot be reheated for reprocessing. Thermoplastics, on the other hand, can be reheated for additional processing. According to the use of materials can be further divided into: structural carbon fiber reinforced resin matrix composites and functional carbon fiber reinforced resin matrix composites. CFRP is widely used in aerospace, transportation, energy and other practical engineering fields.

The performance of carbon fiber composites is influenced by the carbon fiber content, matrix and carbon fiber interface bonding properties. For the carbon fiber content, the higher the content, the better the composite performance.

The effect of different molding processes on the properties of carbon fiber reinforced resin matrix composites also varies significantly. The molding process mainly includes the molding method, molding conditions, molding process, and the applicable range of the molding process. The traditional molding processes of polymer composites mainly include hand-paste molding, hot press tank molding, pultrusion molding, fiber winding molding and Resin Transfer Molding (RTM). These traditional molding processes, from molding process control to finished product quality, have matured after decades of development and are applicable to a wide range of applications, and are also applicable to the preparation of carbon fiber reinforced resin matrix composites. In addition, fiber damage during the molding process, molding conditions, and porosity in the composites all have an impact on the mechanical properties of the composites [40].

2.1.4 Laminate ply design principles

Lamina is a single-layer composite material composed of matrix and fibers, which is the basic unit piece of the composite laminate, whose fibers are usually arranged neatly in one direction. The x-direction is the fiber direction called longitudinal, the y-direction is perpendicular to the fiber direction called transverse, and the z-direction is along the thickness direction of the monolayer material, and the x, y, and z axes are called the main axis of the material, as shown in fig. 2.4. Although both the fibers and the matrix may be isotropic materials, respectively, monolayers are generally anisotropic because of the directional fiber arrangement or the different content of interwoven fibers in the two directions [41].

Monolayers with unidirectional fibers have better mechanical properties along the fiber direction and poorer properties in the direction perpendicular to the fibers. Composites in engineering practice are generally made into laminated structure, i.e., single-ply plates of different directions are laminated together, and the fiber direction of each layer is the same, and there is a certain angle between the fibers of different layers, as shown in fig. 2.5. The laminated structure can improve the overall macro-mechanical properties of the composite material, which is conducive to the best performance of the material and meet the requirements of the engineering for the mechanical properties of the material.

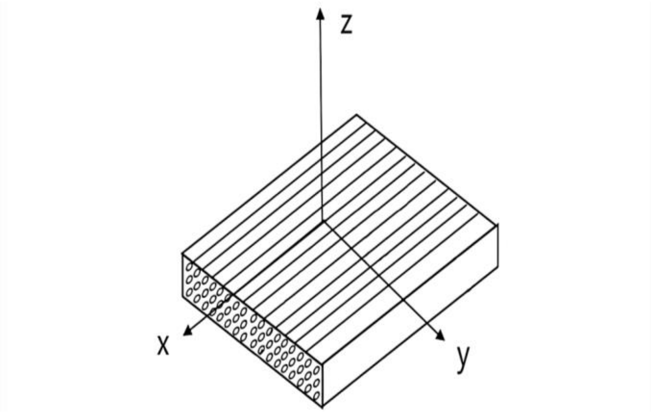


Fig. 2.4. Orthotropic lamina with principal coordinate and non-principal coordinate: x direction is fiber direction; y directions are the matrix direction; z direction is thickness direction.

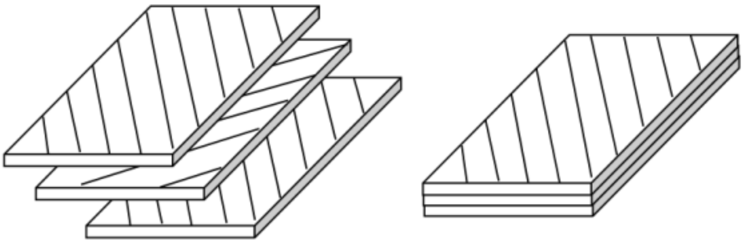


Fig. 2.5. Unidirectional fiber laminate.

Layup design is one of the key elements of carbon fiber composite design, and the design mainly includes three aspects: layup sequence, layup angle, and determination of the ratio occupied by various layup angles. Among them, the lay-up sequence refers to the way of combining various lay-up angles, and the lay-up angle refers to the angle between the axial direction and the main direction of the material. General design principles include.

1 Pavement orientation principle

In order to reduce the workload of construction and design, the type of pavement angle should be as little as possible in the case of meeting the force of the product. And, should be as much as possible to choose 90°, 0°, 45°, -45° these four pavement direction. If the design of quasi-isotropic laminate is required, in addition to the lay-up design with [-45/0/45/90]s, the laminate design with [-60/0/60]s and the same volume content of each oriented layer can also be used. For fiber-wound products, the winding angle is not constrained by Π/4, but ±α winding angle design is still used in most cases.

2 The principle of choosing ply orientation by load

In order to maximize the use of fiber axial high performance, the lay-up direction of the fiber axial and the internal force of the tensile compression direction consistent. If the winding products bear axial tensile and compressive load, the fiber pavement direction and load direction; if the fiber products bear biaxial tensile and compressive load, the fiber pavement should be laid orthogonal to the load direction 0°, 90°; if the fiber products bear shear load, the fiber pavement should be laid in pairs according to

-45°, 45° direction; if the fiber products bear tensile, compressive, shear and other A variety of loads, the fiber pavement should be 90°, 0°, -45°, 45° multi-directional pavement. Among them, 90° direction laid fiber is mainly used to improve the transverse strength of the product, adjust the Poisson's ratio of laminate.

3 Balanced symmetrical laying principle

In general, in order to avoid deformation caused by shear-tension coupling or tensile-bending coupling after curing, the laminate structure is designed as a balanced symmetrical laminate form. When the design needs to use non-equilibrium or non-symmetric lay-up form, should consider the non-equilibrium layer or non-symmetric layer near the surface to reduce the deformation of the laminate after curing.

4 The principle of minimum ratio of lay-up plies

In order to avoid the matrix of the composite material to carry along all directions, reduce the wet thermal stress of the composite material, and at the same time make the Poisson's ratio of the composite material and the connected metal more coordinated and reduce the connection-induced stress, for the direction of 90°, 0°, -45°, 45°of the pavement, the proportion of the pavement in any direction of which should be greater than 6%-10%.

5 Variable thickness design principle

In order to avoid sudden changes in thickness caused by stress concentration, variable thickness pavement design when the number of pavement layers should be gradually changed by the number of steps. The width of each layer step design and pavement step difference should be equal, and step width greater than 2.5 mm. surface should be continuous pavement, which can prevent the step at the peeling damage.

6 The design principle of impact load

The part of the laminate that bears the impact load should have enough fiber laying. And there should be a certain amount of cab 45°pavement to spread the load, and a certain amount of 0°pavement to bear the local impact load. Besides, the local load carrying capacity should be strengthened. For composite structures that are often subjected to out-of-plane impact, the fiber layups on its surface should be uniformly distributed in all directions, with a small angle between two adjacent layers.

2.2 Experimental design of CFRP material laminate

Compared with traditional metallic materials, carbon fiber reinforced composite unidirectional plates have anisotropic characteristics, their mechanical properties are more complex, and they need to face many different action environments in the actual process, the laminate mechanical property parameters and damage forms are the focus of studying the failure of composite parts. In order to evaluate the goodness and applicability of composite materials, this subsection is designed for tensile and fatigue tests on carbon fiber composite laminates through experiments as an important means to study the mechanical properties of composites.

2.2.1 Raw materials and specimen preparation

The 16-ply carbon fiber epoxy resin laminate was prepared by using T700SC-120K large filament carbon fiber prepreg from Toray, Japan, with the lay-up method [0°, 90°, +45°, -45°, -45°, +45°, 90°, 0°] $_S$. The symmetrical lay-up was specified with the long end of the specimen oriented in the 0°direction.The performance parameters of T700SC-120K carbon fiber are shown in table 2.6. Performance parameters are shown in table 2.2.

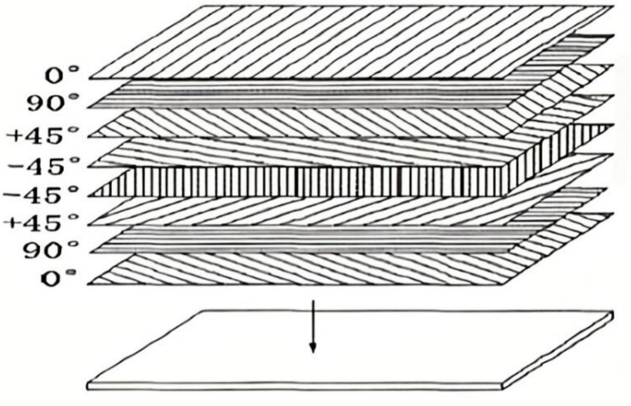


Fig. 2.6. Lay-up method.

Table 2.2

Performance parameters of T700SC-120K

Product number	Tow size	Poisson's ratio	Elastic Modulus /GPa	Tensile strength /GPa	Fiber density /G·cm^{-3}	Elongation /%	carbon content /%
T700SC	120K	0.31	230	4.9	1.8	2.1	≧95%

The specimens were designed as rectangular specimens of 150 mm in length, 20 mm in width, and approximately 2.2 mm in thickness, with the length, width, and thickness directions denoted by X, Y, and Z, in that order, according to the ASTMD 3039 standard (tensile) [42]. Four reinforcing sheets were bonded at the end of the specimen, and the reinforcing sheets were made of 7075 aerospace aluminum alloy, designed to be 35 mm long, 20 mm wide and 2 mm thick in thin sheets. DP460 epoxy resin AB adhesive provided by 3M was used to glue the reinforcement pieces to the end of the specimen to make the tensile and fatigue test specimens, DP460 epoxy resin adhesive (shown in fig. 2.7) has excellent effect on the bonding of aluminum alloy and carbon fiber, the peel strength can reach 6N/mm. To prevent the stress concentration in the bonding of the reinforcement pieces during the test, resulting in the specimen. In order to prevent the stress concentration in the bonding area during the test, the specimen will fail at the end of the reinforcement. It is necessary to grind one end of the reinforcing sheet into a 30° slope and then paste it, and the overall design is shown in fig. 2.8.

Fig 2.7. DP460 epoxy resin AB adhesive.

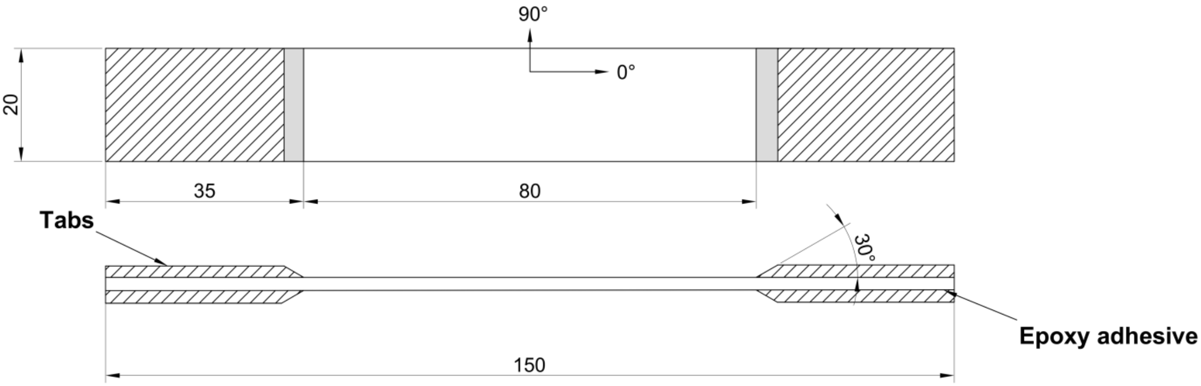


Fig. 2.8. Specimen parameters.

2.2.2 Basic performance test design

CFRP Tensile test

The specimens were tested for quasi-static tensile mechanical properties using a Meitesi CMT5105 universal mechanical testing machine (fig. 2.9) with a loading rate of 1%/min, and the experimental procedure is shown in Fig. Three groups of specimens were tested and the average value was taken as the tensile strength of the specimen, and the average tensile strength was measured to be 900 MPa by the test.

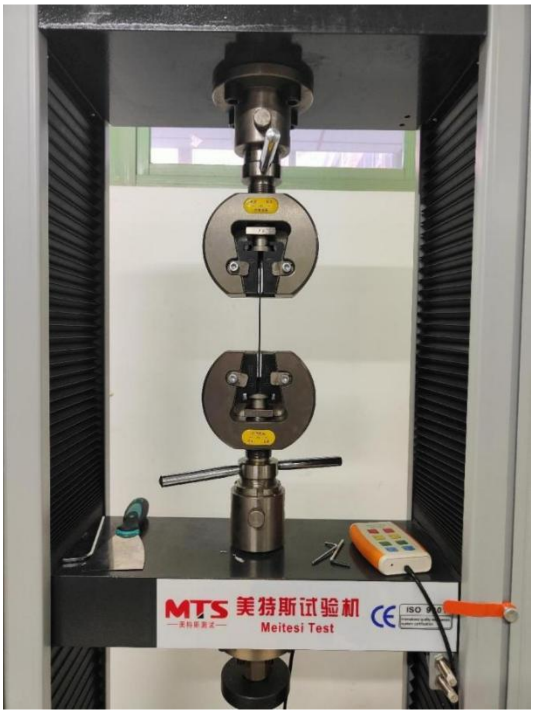


Fig. 2.9. Meitesi CMT5105.

CFRP fatigue test

Fatigue tests were performed at room temperature of 25° using an Instron 8801 electro-hydraulic servo fatigue machine (fig. 2.10) with stress control. Three sets of loads with different stress ratios were set up based on a simplified sinusoidal loading spectrum with interval stops to simulate the aircraft lower airfoil aero-load spectrum [43]. The maximum stress was selected to be greater than 80% of the tensile strength of the specimen (about 720 MPa), and the loading frequency was 10 Hz with the parameters shown in table 2.3 The fatigue load was loaded in the direction parallel to the length direction of the specimen. For different groups of specimens, three specimens were tested to obtain the distribution of fatigue life.

Fig. 2.10. Instron 8801 electro-hydraulic servo fatigue machine.

Table 2.3

Setting parameters of fatigue test

Stress ratio	Minimum stress/MPa	Maximum stress/MPa
0	0	720
0.3	216	720
0.6	432	720

2.3 Analysis of experimental results

2.3.1 Load-displacement characteristics analysis

The maximum tensile stress to which the carbon fiber composite material is subjected before reaching damage under tensile test load is called ultimate tensile strength.

Tensile strength calculation formula:

$$\sigma_t = \frac{P_{max}}{bh}$$

Tensile modulus calculation formula:

$$E_t = \frac{\Delta Pl}{bh\Delta l}$$

In the formula: σ_t is the ultimate tensile strength; P_{max} is the maximum load; b is the specimen width ; h is the specimen thickness is ; E_t is the tensile modulus.

The test T700 laminate tensile test displacement-load is shown in fig. 2.11. The average tensile strength of 900 MPa and the average tensile modulus of elasticity of 135.135 GPa were calculated for each group of test pieces, as shown in table 2.4. The tensile strength, tensile elastic modulus and Poisson's ratio data obtained for the specimens were similar, thus indicating that the non-homogeneity of the carbon fiber composite specimens was within the experimental error range for the laminate tensile test and the test results obtained were good.

Table 2.4

Laminate tensile test results data

Test piece	Ultimate load (KN)	Tensile elastic modulus (GPa)	Tensile Strength (MPa)
A1	39.281	51.014	892
A2	39.556	51.371	910
A3	40.143	52.134	899
Average	39.660	51.506	900

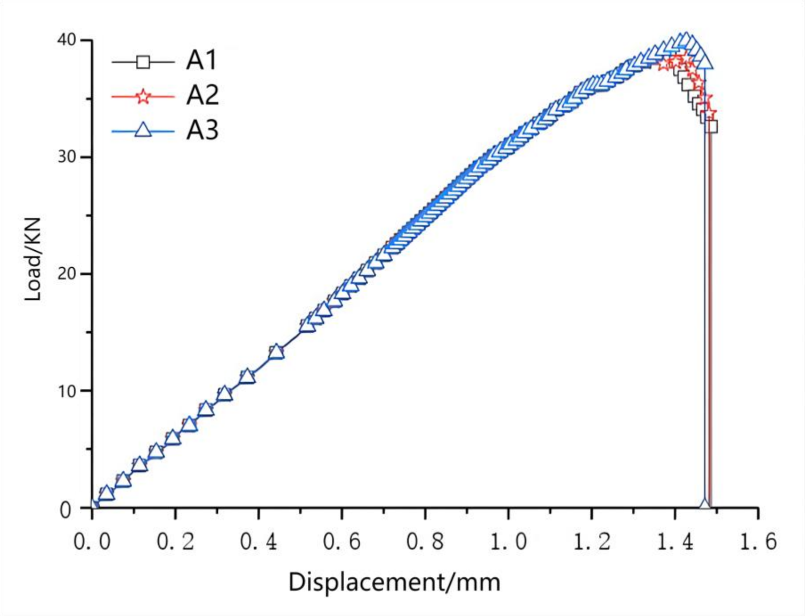


Fig. 2.11. Displacement-load diagram of laminate tensile test.

2.3.2 Fatigue life characterization

Compared to metallic materials, the mechanical property parameters of composites are more scattered [44], and multiple sets of tests were performed at different stress ratios R to ensure three sets of stable data, with an average fatigue life of 875 weeks for the specimen with R = 0; 19,865 weeks for the specimen with R = 0.3; and 15,23518 weeks for the specimen with R = 0.6. The obtained fatigue life results were fitted with the stress ratio to obtain the curves shown in fig. 2.12. The fatigue life of the composites varied widely from 103 to 106, and the nonlinear fitting curve revealed that the relationship between stress ratio and fatigue life was roughly a power function, and the fitted relationship equation was N(R)=3.32R6 (R>0), with R being the stress ratio and N being the fatigue life in 100 million weeks. The fatigue life of carbon fiber composites is greatly influenced by the stress ratio, and at low stress ratios, the fatigue life of carbon fiber composites is only about 0.1% of that of the high stress ratio specimens.

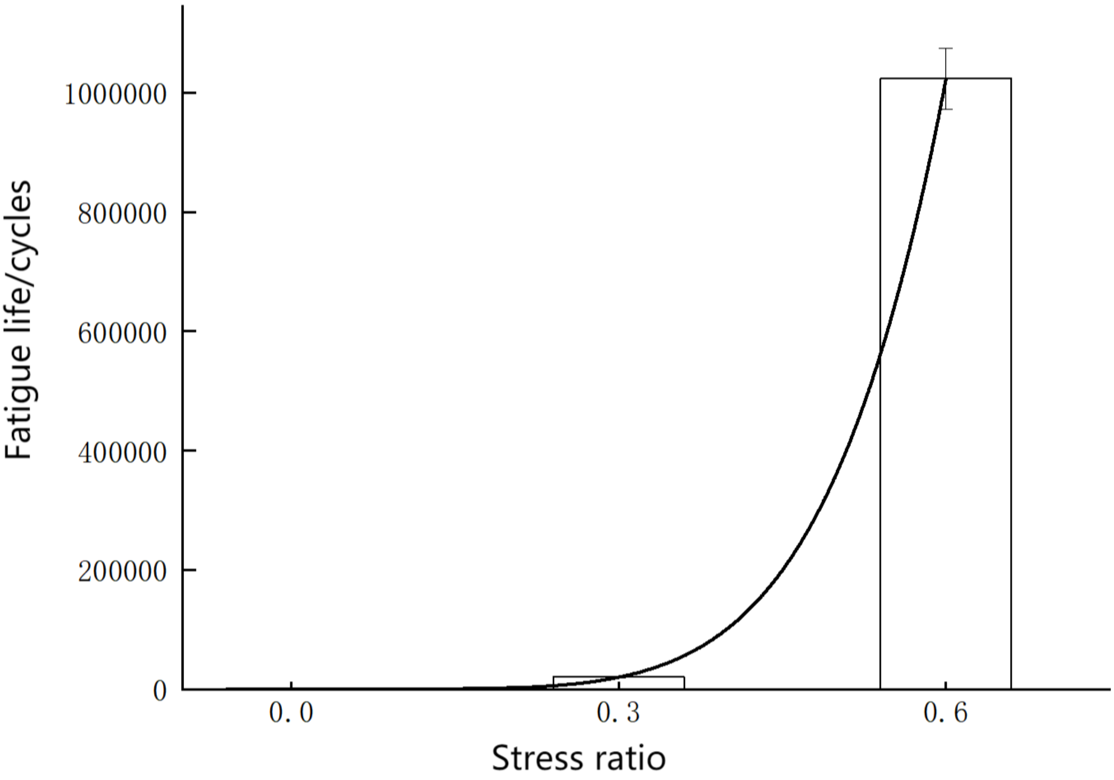
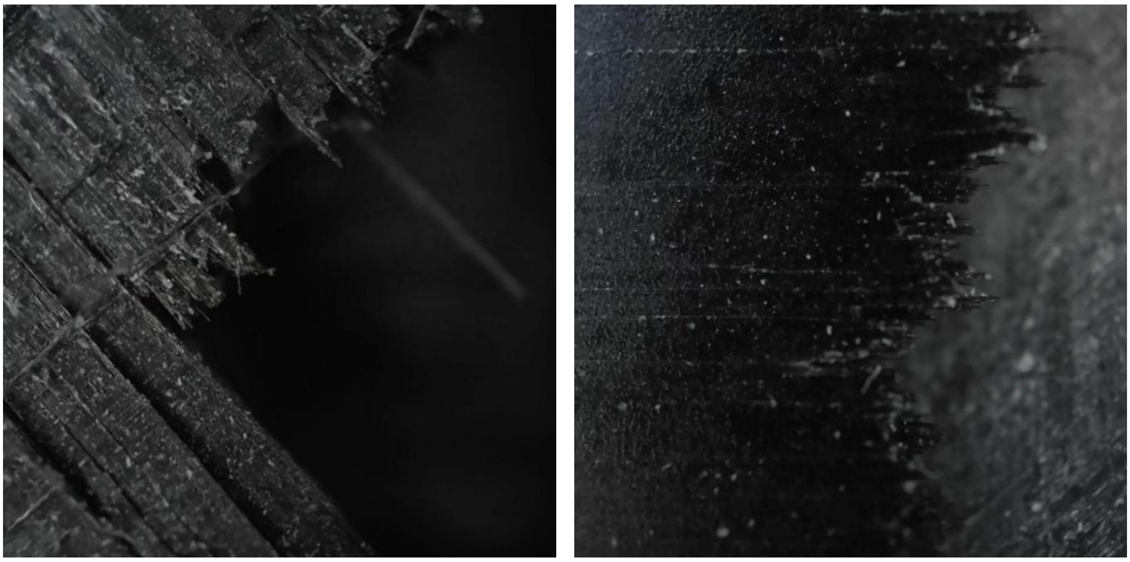


Fig. 2.12. Relation between stress ratio and fatigue life.

2.3.3 Fracture analysis

Compared with the tensile fracture, the delamination damage between the fiber layers of the fatigue specimen is obvious, as shown in fig. 2.13.



(a) Tensile fracture (b) Fatigue fracture

Fig. 2.13. Microscopic fracture.

The fiber bundles were observed and found to be detached from the epoxy resin matrix in the fatigue specimen compared to the fracture of the tensile specimen where the fiber bundles were tightly bonded to the matrix, indicating that the resin matrix gradually failed and detached from the fiber surface during exposure to fatigue loading, as shown in fig. 2.14. The fiber bundle is subjected to fatigue damage produced by cyclic loading, and the damage gradually accumulates and expands until failure.

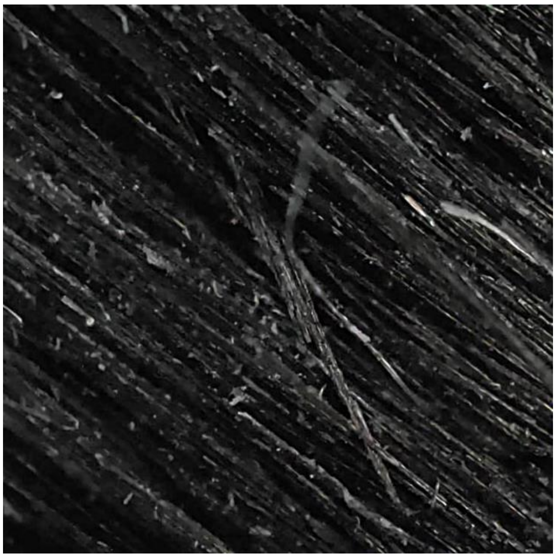


Fig. 2.14. Fiber bundle separation.

The tensile fatigue damage mechanism of composites is usually interpreted as a coupling of four failure types, namely matrix cracking, interlaminar delamination, fiber fracture, and interfacial debonding. All four of these failure types were observed at the fracture site of fatigue failure specimens, indicating that the fatigue damage modes of composites are diverse and composite and cannot be evaluated using only one [45]. In the initial stage of cyclic load fatigue damage, the resin matrix develops fatigue cracks at the defects. In carbon fiber laminates under fatigue loading, the resin base cracks gradually increase and accumulate, which then extend to the matrix-carbon fiber contact interface and cause stress concentrations at the interface layer. When the matrix fatigue fails, interface damage occurs and the fibers are debonded from the surrounding matrix. When matrix damage extends between different fiber layers, interlaminar delamination occurs within the laminate. When the matrix partially fails, the load-bearing situation of different fiber layers changes, which may lead to partial fiber fracture or composite interface debonding until the specimen fails as a whole.

Conclusion for part 2

In this chapter, the basic theory of carbon fiber epoxy resin matrix composites is introduced at first. The composition, basic performance and lay-up mode of the composite were analyzed. Finally, the stress-strain relationship and fatigue life characteristics are analyzed, and the fracture factors are discussed.

PART 3. CFRP TENSILE FATIGUE STRENGTH ANALYSIS

3.1 Laminate finite element simulation

ABAQUS software was used to create a 3D model of composite laminate with the same fiber performance parameters as T700 type carbon fiber. Model length: width: thickness = 150:20:2.2 in mm, fiber mechanical properties, layup direction, thickness and other information are the same as the actual specimen, set the calculation cell side length to 1, the model grid and direction as shown in fig. 3.1. In the thickness direction, the schematic diagram and coordinate system XYZ are drawn for each layer of fiber layup direction, as shown in fig. 3.2, where the black line represents the direction of carbon fiber extension within the layer, and the single layer thickness t is 0.1375.

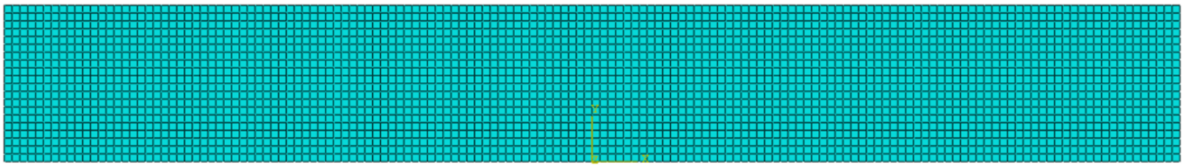


Fig. 3.1. ABAQUS finite element model grid.

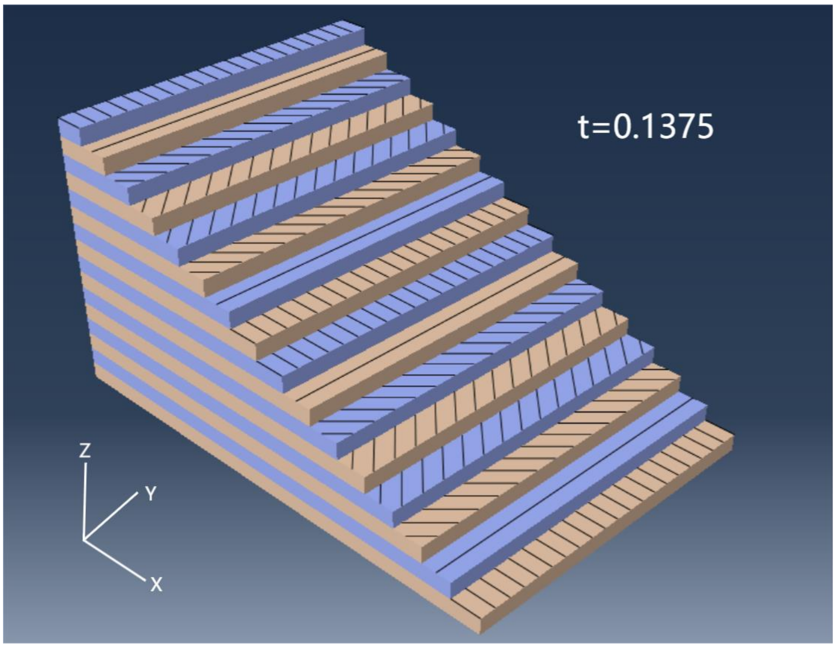


Fig. 3.2. Finite element model of carbon fiber composite laminate.

The flow of progressive damage analysis is shown in fig. 3.3. It can be seen that the analysis process divides the load into several incremental steps, solves for the stress-strain state at each incremental step and determines the damage according to the failure criterion. The load ΔP is increased and the solution process is repeated until the structure fails or the final load is reached.

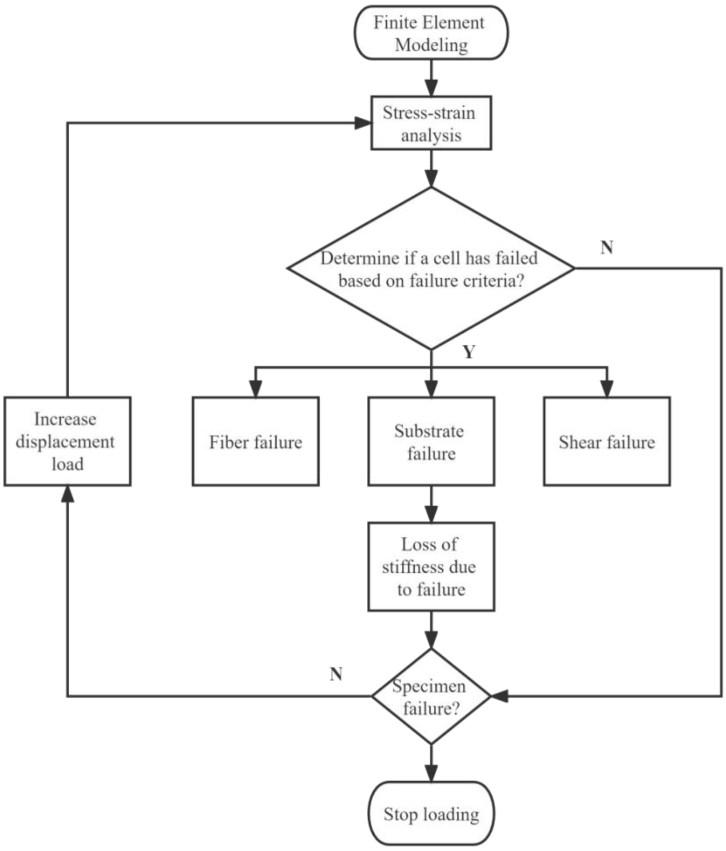


Fig. 3.3. The Flow Chart of Progressive Damage.

3.2 Development and validation of progressive damage analysis model

3.2.1 UMAT Material Subroutine

The user material subroutine UMAT of ABAQUS is a code written by the user according to the FORTRAN language, according to the corresponding interface provided by ABAQUS. UMAT can define material intrinsic relationships that are not available in the ABAQUS material library, and can be used for any analysis process of mechanical behavior analysis, or can be used in conjunction with other user subroutines such as USDFLD. Since there is data transfer between the main program and UMAT, and even some variables are shared, it is necessary to follow a fixed framework for writing UMAT. The variables commonly used in UMAT are defined at the beginning of the file, such as the Jacobi matrix DDSDDE, the stress tensor matrix STRESS, the array STATEV used to store state variables, the array PROPS of material constants, the time increment DTIME, etc.

The transverse shear stiffness and the hourglass control stiffness of the unit need to be taken into account when using UMAT. These stiffnesses are based on the initial shear modulus values of the material, and when using UMAT ABAQUS cannot obtain the shear modulus values by defining the elastic properties of the material, so the user must define the hourglass control stiffness of the reduced integral unit and the transverse shear stiffness of the plate and shell in the "HOURGLASS STIFFNESS" and "TRANSVERSE SHEAR STIFFNESS" options unit.

3.2.2 Static load progressive damage analysis program design

In this paper, the Hashin two-dimensional failure criterion [46] is selected, which considers five failure modes of fiber pulling, matrix pulling, and base fiber shearing, as shown in equations (3-1) to (3-5).

Longitudinal tensile failure:

$$(\frac{\sigma_{11}}{X_t})^2 + (\frac{\tau_{12}}{S_{12}})^2 \geq 1(\sigma_{11} > 0)$$

Longitudinal compression failure:

$$(\frac{\sigma_{11}}{X_c})^2 \geq 1(\sigma_{11} < 0)$$

Lateral stretch failure:

$$(\frac{\sigma_{22}}{Y_t})^2 + (\frac{\tau_{12}}{S_{12}})^2 \geq 1(\sigma_{22} > 0)$$

Lateral compression failure:

$$(\frac{\sigma_{22}}{Y_c})^2 \geq 1(\sigma_{22} < 0)$$

Base fiber shear failure:

$$(\frac{\sigma_{11}}{X_c})^2 + (\frac{\tau_{12}}{S_{12}})^2 \geq 1(\sigma_{11} < 0)$$

In order to improve the readability of the program and to make it easier to write, the program can be modularized, i.e., the UMAT program is written by dividing it into several subroutine segments, calling different subroutine segments to achieve different functions, and finally connecting the segments into a whole according to the analysis process [47], and the whole program is divided into the following parts.

(1) Read the material parameters, update the strain, and call the subroutine segment to calculate the undamaged stress-strain relationship stiffness matrix.

(2) Determine the damage to the material, call the subroutine segment to update the damage variables as well as the material parameters.

(3) Call the subroutine segment to calculate the post-damage stiffness matrix.

(4) Update the stress and state variables and end the subroutine.

The subroutine is written according to the above structure and the material properties are defined in the user material option i.e. the parameters to be read by the subroutine. Fifteen state variables are set in the non-independent variable option. Among them, SDV1-SDV5 are the flags of whether the unit enters the five failure states, the value of 1 in the failure state and 0 in the non-failure state, which correspond to fiber stretching, fiber compression, matrix stretching, matrix compression, and base fiber shear failure, respectively, indicating the damage initiation values corresponding to the five failure modes calculated by Hashin's criterion, and SDV11-SDV15 are used to calculate the viscous damage variables.

3.2.3 Model validation and analysis

The laminate was subjected to damage simulation analysis under tensile load, and the Abaqus load displacement curve is shown in fig. 3.4. From the figure can be seen, with the increase in displacement, the damage began to appear, but at this time the laminate can still carry, after reaching the maximum displacement load suddenly drop, the laminate basic damage. The tensile damage load of the laminate is 37.54 kN, and the test result is 39.66 kN. From the results, it can be seen that the results of the simulation in this paper are close to the test results, so the results obtained from the calculation are on the safe side.

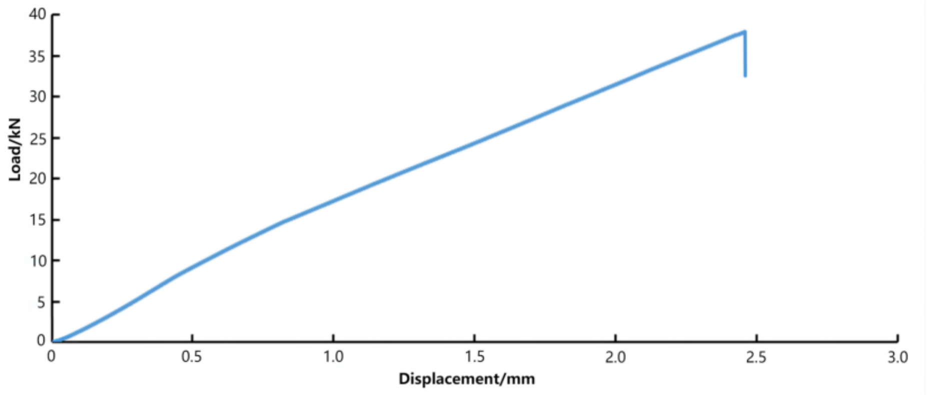


Fig. 3.4. Abaqus load displacement diagram.

3.2.4 Wing static strength analysis

Single wing is used for analysis, one end is fixed, and the other end is subjected to vertical upward load. As can be seen from fig. 3.5, with the increase of the displacement of the wing, the slope of the image also gradually increases. At this time, multiple fibers play a role in hindering the wing's buckling, but the damage accumulates continuously until the wing is damaged and the load drops suddenly. From this, the maximum yield displacement and maximum load of the wing can be judged.

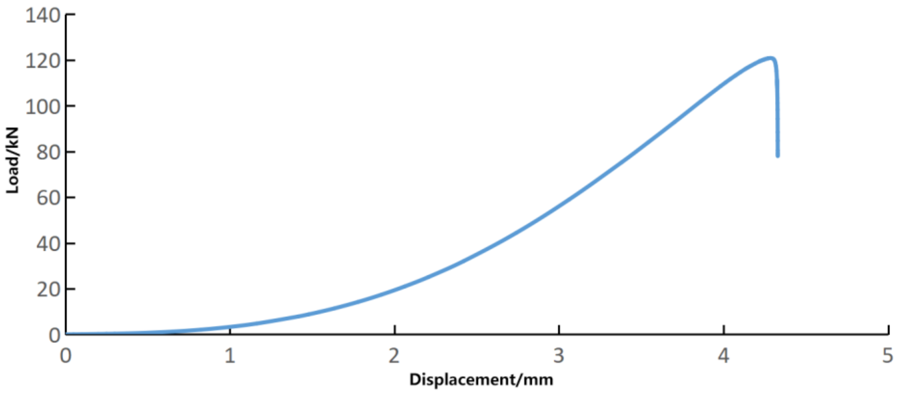


Fig. 3.5. load displacement diagram of wing.

It can be seen from the cloud picture that the initial stress is mainly concentrated on the two front end faces of the wing, and with the gradual increase of displacement, the stress concentration position gradually shifts to the fixed end face of the tail, until finally the ring breaks and the wing breaks.

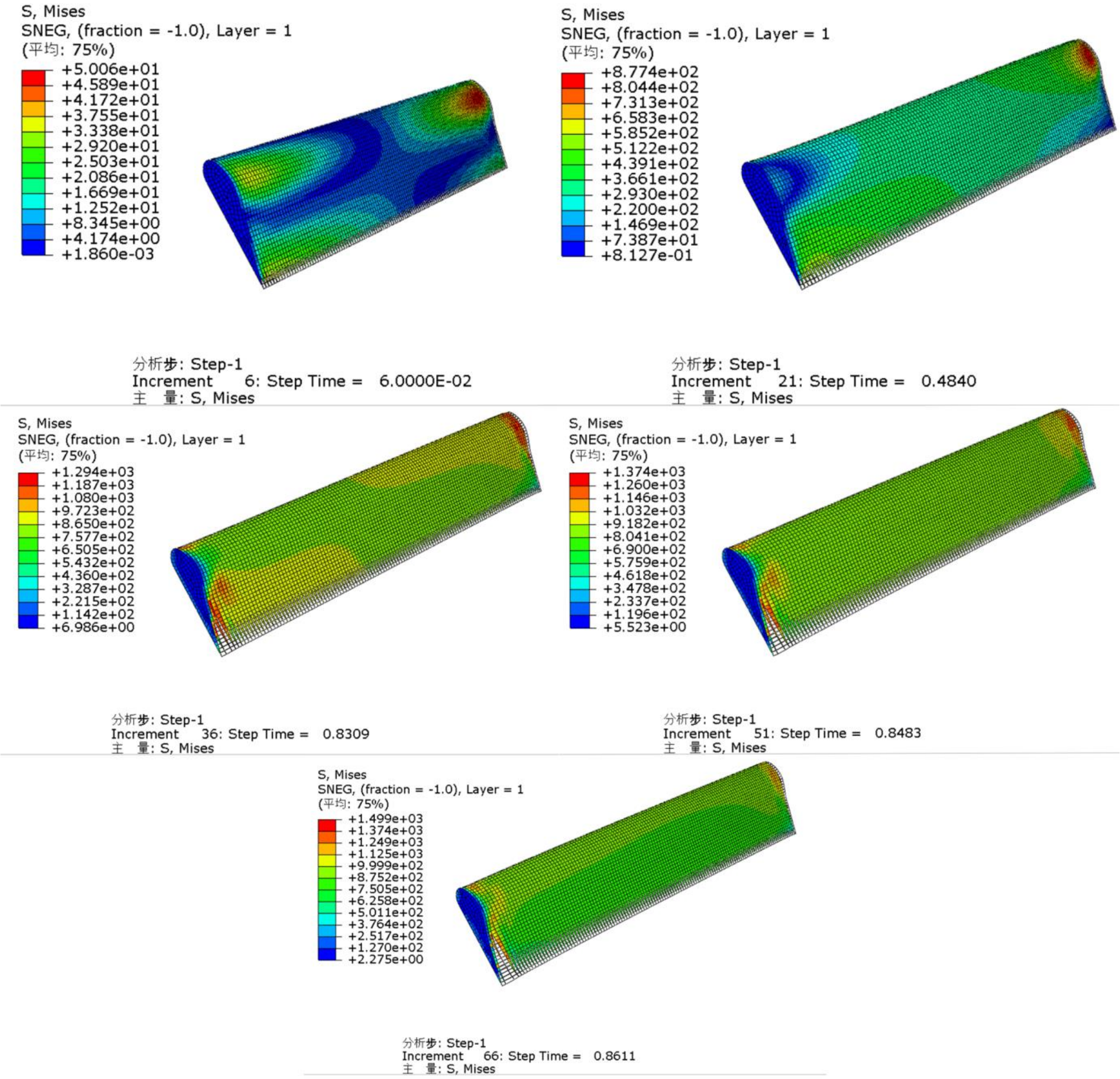


Fig. 3.6. cloud picture analysis.

3.3 Fatigue analysis method for composite laminates

3.3.1 Cumulative damage model

The static codes introduced in the previous section have basically been extended to fatigue failure codes, and Hashin and Rotein [48] replaced the corresponding ultimate strength in the Hashin code with the residual strength to obtain the failure code under fatigue loading and successfully predicted the fatigue failure behavior of glass fiber laminates. The two-dimensional Hashin has the following form in the fatigue analysis process.

Fiber stretch failure:

$$(\frac{\sigma_{11}}{X_T(n,\sigma,r)})^2 + (\frac{\sigma_{12}}{S_{12}(n,\sigma,r)})^2 \geq 1$$

Fiber compression failure:

$$(\frac{\sigma_{11}}{X_C(n,\sigma,r)})^2 \geq 1$$

Substrate tensile failure:

$$(\frac{\sigma_{22}}{Y_T(n,\sigma,r)})^2 + (\frac{\sigma_{12}}{S_{12}(n,\sigma,r)})^2 \geq 1$$

Substrate compression failure:

$$(\frac{\sigma_{22}}{Y_C(n,\sigma,r)})^2 + (\frac{\sigma_{12}}{S_{12}(n,\sigma,r)})^2 \geq 1$$

Matrix fiber shear failure:

$$(\frac{\sigma_{11}}{X_C(n,\sigma,r)})^2 + (\frac{\sigma_{12}}{S_{12}(n,\sigma,r)})^2 \geq 1$$

σ_{ij} is the principal stress and shear stress of each cell; $X_i(n,\sigma,r)$ 、 $Y_i(n,\sigma,r)$ 、 $S_{12}(n,\sigma,r)$longitudinal strength, transverse strength and shear strength of the material, respectively, indicating tensile when i=T and compression when i=C. n is the number of cycles; σ is the stress level; r is the stress ratio.

From the equation, it can be seen that the tensile, compressive and shear strengths are no longer constants, but vary with the number of cycles, stress level and stress ratio. If any unit of the material satisfies one of the above equations, then the unit is considered to undergo fatigue failure of the corresponding mode.

3.3.2 Fatigue life model

The fatigue life model is a fatigue failure criterion based on the S-N curve or Goodman's formula, which does not consider the accumulation of damage and is able to predict the fatigue life under a fixed load. In order to be able to obtain the S-N curve, many scholars have conducted numerous studies from the theoretical, experimental and both combination points of view.

Bond et al [49] proposed a semi-empirical fatigue life prediction model combining theory and experiment by studying the fatigue behavior of glass fibers at different stress levels.

$$\sigma_{max} = b \cdot lg(N) + c$$

where b, c are fourth-order polynomials in the stress ratio r, which can be measured by tests under cyclic loading.

In order to adapt the prediction of fatigue life to the case of arbitrary stress ratios, Harris et al [50] proposed a regularized fatigue loss

$$\mathrm{a} = f(1-\mathrm{q})^{\mu}(\mathrm{c}+\mathrm{q})^{\gamma}$$

where a, q and c are the normalized stress amplitude, average stress and strength limit, respectively. $\mathrm{a} = \sigma_{\mathrm{a}}/\sigma_{\mathrm{t}}$， $\mathrm{q} = \sigma_{\mathrm{m}}/\sigma_{\mathrm{t}}$， $\mathrm{c} = \sigma_{\mathrm{c}}/\sigma_{\mathrm{t}}$; σ_{t}、 σ_{m} are the stress amplitude and average stress of the cyclic stress, $\sigma_{\mathrm{a}} = (\sigma_{\mathrm{max}} - \sigma_{\mathrm{min}})/2$,$\sigma_{\mathrm{m}} = (\sigma_{\mathrm{max}} + \sigma_{\mathrm{min}})/2$; σ_{c}、 σ_{t} are Compressive strength and tensile strength values； f、 μ、 γ are the fitting coefficient, measured by fatigue test.

Later Gathercole et al [51] assumed during their study that $\mu = \gamma$ and is linearly related to the log value of fatigue life lgN. As shown in equation (4-12) and substituting it into equation (4-13), the final model of life prediction is obtained as shown in equation (3-14).

$$\mu = \gamma = A + B\lg N$$

$$\mu = \frac{\ln(\mathrm{a}/f)}{\ln[(1-\mathrm{q})(\mathrm{c}+\mathrm{q})]} = A + B\lg N$$

However, Shokrich [52] questioned the above model, arguing that it can only describe the life characteristics of transverse and longitudinal fatigue loading, and the tensile and compressive strengths defined in the equation are meaningless when subjected to shear fatigue loading, so that c = 1. And it was found experimentally that the results obtained by taking the logarithm of lg on each side of the above equation are more consistent with the actual situation. So the life prediction model under shear fatigue loading is modified as:

$$\mu = \log_{10}(\frac{\ln(\mathrm{a}/f)}{\ln[(1-\mathrm{q})(\mathrm{c}+\mathrm{q})]}) = A + B\lg N$$

Where A and B can be obtained from fatigue tests of laminates; the recommended value of 1.06, derived from tests by Gathercolel [51], is taken.

3.4 Fatigue analysis model building and validation

3.4.1 Fatigue progressive damage analysis program design and implementation

Similar to the static load progressive damage analysis, the fatigue progressive damage model is also divided into three main parts: stress analysis, failure determination, and material property degradation. Unlike the static load, fatigue not only requires the reduction of stiffness for the units that meet the failure determination, but also the degradation of residual stiffness and residual strength for the units that do not fail according to the cumulative damage model above, and the number of cycles and stress levels need to be defined.

3.4.2 Model Validation and Analysis

The average tensile strength of the laminate was measured from the previous static tensile test, and the maximum stress was selected to be greater than 80% of the tensile strength of the specimen (i.e.720 MPa), and then the stress ratios were selected to be 0, 0.3, and 0.6, respectively, for the fatigue tests under three different stress levels of pull-pull. The fatigue test life data at each stress level were obtained as shown in table 3-1.

Table 3.1

Tensile-tensile fatigue test data with different stress ratios

Stress ratio	Minimum stress/MPa	Maximum stress/MPa	Fatigue Life
0	0	720	909
0.3	216	720	20410
0.6	432	720	1555000

The finite element model is established according to the material parameters and the geometry of each specimen, and the loading at each stress level is simulated by creating the analysis step and the load amplitude. STATEV (22) in the subroutine is the state variable to store the life value calculated by the fatigue life model, and the longitudinal fatigue life state variable SDV22 at each stress level is output respectively after loading, as shown in fig. 3.7. The minimum value of the life in the cloud is selected to take its logarithmic value to compare with the test results, and the curve is plotted as shown in fig. 3.8. It can be seen from the figure that the simulation results of this paper agree well with the test results, and the errors are 3.74%, 2.67% and 2.02% respectively.

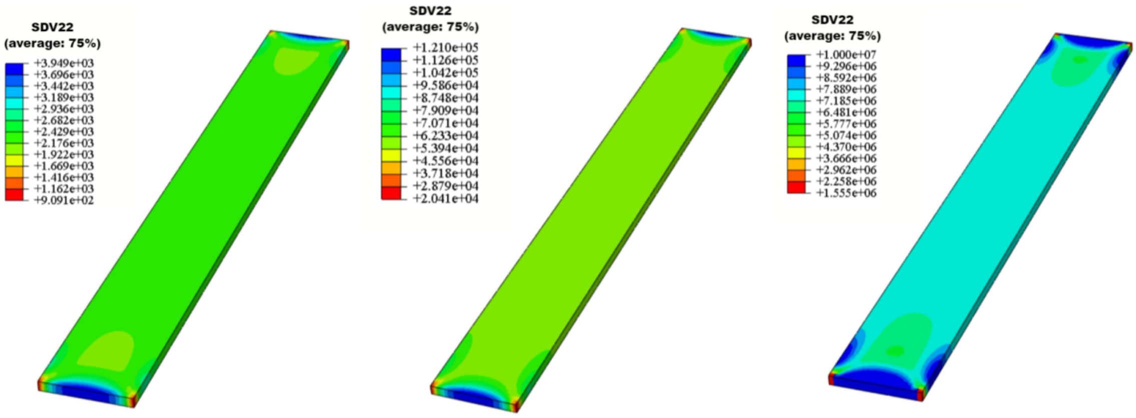


Fig. 3.7. Predicted values of fatigue life under various stress levels.

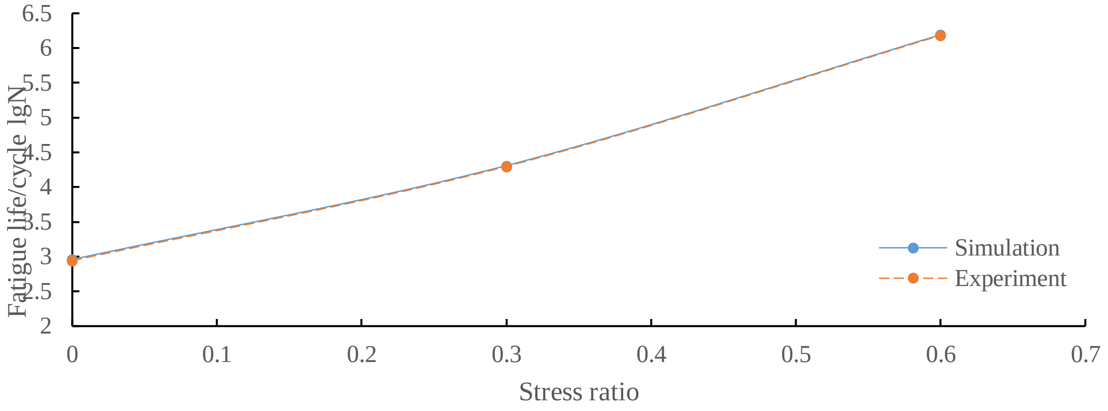


Fig. 3.8. Comparison of tensile-tensile fatigue results.

3.4.3 Wing fatigue analysis

The progressive damage analysis was used to establish the fatigue model of the wing. Under the vertical displacement of the end face of 0.06m each time, the damage occurred when the fatigue cycle number of the wing was 44130.

As can be seen from the figure 3-9, the earliest damage occurred at the far end of the front of the wing, which is consistent with the stress concentration in the static strength test, proving that the results of the fatigue analysis test are correct to a certain extent.

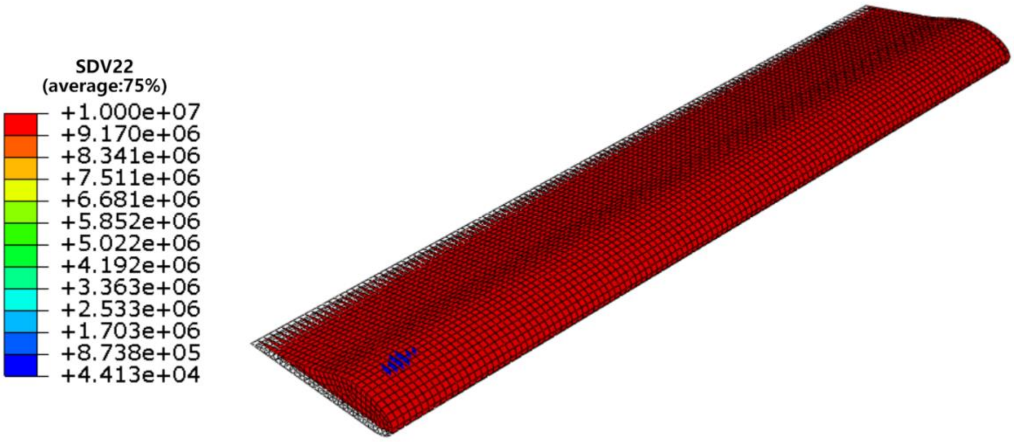


Fig.3.9 Fatigue cloud analysis

Conclusion for part 3

In this chapter, firstly, the laminated plate and simple wing model are established by abaqus simulation software. Then, the UMAT material subroutine is introduced, and the static progressive damage analysis program is compiled based on the two-dimensional Hashin failure criterion. The experimental results are selected to verify the program, and the simulation results are close to the experimental results, so the calculated results are safe.

Secondly, the fatigue problem of composite materials is summarized, and the analysis methods of fatigue behavior of composite materials are introduced from the aspects of cumulative damage model and fatigue life model. Secondly, the progressive damage analysis program under fatigue loading is compiled based on the selected model and references. The results show that the errors between the simulation results and the experimental results are 3.74%, 2.67% and 2.02% respectively under different stress levels. Finally, the program is applied to a wing, It is shown that finite element simulation can be used to verify the structural design of aircraft in a limited way.

PART 4. LABOUR PROTECTION

There are harmful substances, fiber dust and harmful gases in the production and processing of carbon fiber composite materials, which seriously affect the health of operators. Only by earnestly implementing the labor health policy of "prevention first," fully understanding and mastering the types and harmfulness of harmful substances in the production and processing of carbon fiber composite materials, and taking effective modern scientific and technological management measures to make the production and processing of carbon fiber composite materials, Harmful substances and dust on site meet the national health standards.

Carbon fiber production process will produce acrylonitrile, hydrogen cyanide, CO, ammonia, nitrogen oxides (NOx) and other harmful substances. In order to strengthen the occupational health management and protect the health of workers, this chapter studies the possible occupational hazard factors and hazard degree in the production process of carbon fiber and composite materials [53-55].

4.1 Harmful and dangerous work factors

The proces of manufacturing composite requires that use of a number of machines (electric machinery, pneumatic tools) to process, such as drilling, sandblasting, polishing, decoration and hand and mechanical contact work, from a variety of processes can be seen, these processes depend on the size of the material and the required degree of precision, in addition, the material manufacturing process often needs to be repaired, will use shear planting, cutting, these jobs will cause harm to workers, the prevention of mechanical hazards, please refer to rotating machinery (motor, grinding machine), rolling machinery and other general machinery and its treatment.

In addition to mechanical hazards, attention shall be paid to the hazards of electrical equipment. Some manufacturing equipment or processing equipment used in the manufacturing process of composite materials may leak electricity, so it is necessary to install leakage circuit breaker and grounding. In addition, there will be organic solvents on site. If the electrical equipment of lighting or local exhaust device is not explosion-proof, there is the possibility of fire and explosion, so attention shall be paid to the prevention of fire and explosion.

The hazard factors generated during the preparation and processing of composite materials include:

1. Reinforced fiber: Many reinforced fibers can cause irritation to eyes, skin and upper respiratory tract, some can cause allergy, and the mechanism of harm to organs is not clear at present.

2. Dust: The dust is mainly generated in the process of sand blasting, polishing, decoration and repair. As for the hazard of dust, the current research shows that the dust often contains some fibers, and the latent temperature of dust heat can reach as high as 250℃.

3. Solvent: Many solvents are evaporable and flammable. Many of them will irritate the skin and eyes. Some of them will be absorbed by the skin, causing harm to some organs. In addition, they will cause multiplication effect with resin. Preventive measures must be taken. Careful selection of gloves and protective gear management is important for prevention.

The main dangerous place of carbon fiber preparation is the cleaning workshop of carbon fiber workshop, including four posts of pre-oxidation, carbonization, surface treatment and fiber collection. The main occupational hazard factors include chemical hazard factors, physical hazard factors and dust:

1. Chemical harmful factors include hydrocyanic acid, NO, NO2, CO, CO2, CH4, etc., among which one kind of highly toxic chemical substance;

2. Physical harmful factors are high temperature and noise;

3. The dust is carbon fiber dust.

In the production process of carbonization unit, especially in the processes after passing through high-temperature furnace, a small amount of carbon fiber dust with diameter of only several microns and variable length will be generated, which will disperse and float in the air, or adhere to the ground, equipment or operators. Carbon fiber board dust is very harmful to electrical equipment, so it must be paid more attention to. Therefore, manufacturers need to meet the requirements of national health and safety regulations to ensure the health and safety of the working environment and labor.

4.2 Hazard factor detection

4.2.1 Test Method

Sampling objects and detection points are determined according to the evaluation requirements [56]. Sampling objects, detection points and sampling time are determined to detect the concentration/intensity of occupational hazard factors in the workplace. See fig. 4.1 for the detection objects and detection points of each factor.

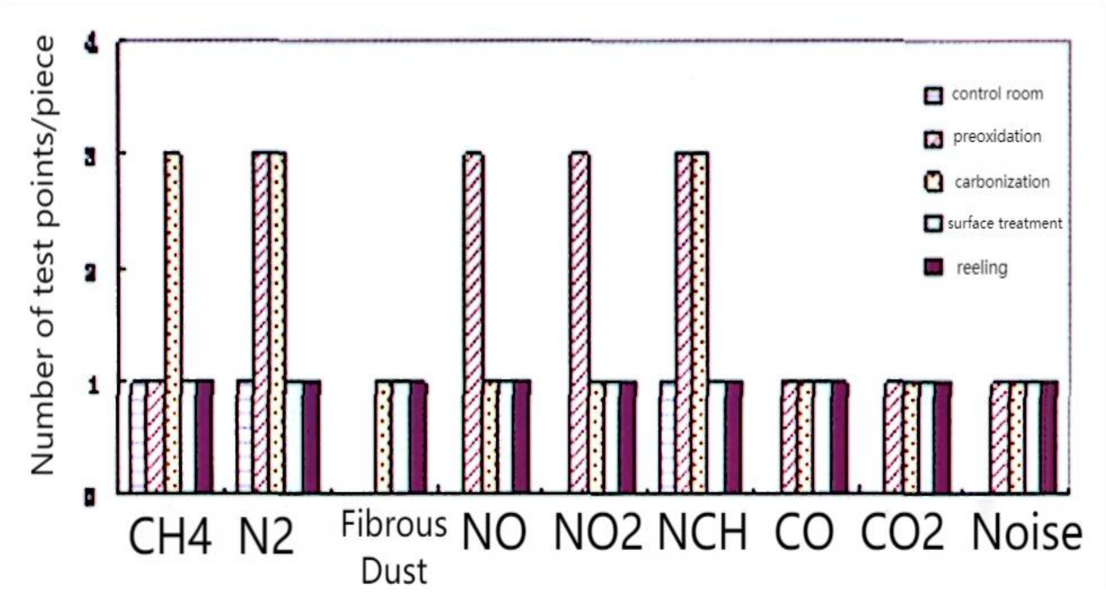


Fig. 4.1. Detection object and detection point setting.

See table 4.1 for sampling, detection methods and analytical instruments for occupational hazard factors such as dust, harmful gas and noise, and see table 4.2 for sampling and detection methods for hazard factors.

Table 4.1

Sampling, testing and analytical instruments

Serial No.	Instrument Name	Relevant parameters
1	Dust sampler	Flow rate: 0~30L/min
2	individual dust samplers	Flow: 0.1min~3L/min
3	Infrared spectrophotometer	Wavelength: 4000cm-1~400cm-1
4	CO detector	Range: 0~200ppm Temperature: -10℃~+45℃;
5	Wet and dry bulb thermometer	Humidity: 10%RH~100%RH
6	Sound level meter	20Hz~12.5kHz; 30dB~130dB（A）
7	Atmospheric sampler	Flow: 0.1~2.0L/min
8	Atmospheric sampler	Flow: 0.01~0.5L/min
9	Spectrophotometer	Wavelength:340m-100mi Absorbance:-0.301~1.999
10	CO2 detector	Range:0~10000ppm Temperature:Room temperature ~+400℃
11	Gas chromatograph	Rate: 0~+30℃/min
12	Atomic absorption spectrometer	Si 251.6nm Band 0.2nm

Table 4.2

Hazard sampling and testing methods [57-59]

Test items	Sampling method	Test items	sampling method
Fiber dust concentration (spot/individual)	perchloroethylene membrane enrichment method	CO	direct reading method
NH3	Large bubbles (liquid absorption method)	CO2	direct reading method
NO/NO2	Perforated glass plate (liquid methane absorption method)	CH4	Aluminum foil bag gas collection method
HCN	Small bubbles (liquid absorption method)	Noise (spot/individual)	direct reading method

The detection time and frequency shall be in accordance with the sampling specifications. The dust shall be collected individually for one working shift (8h) and continuously for 3 working days; Sampling shall be carried out for 15min each time at fixed points in short time, and sampling shall be carried out once at different time periods in the morning and afternoon every day, and continuous sampling shall be carried out for 3 working days; During individual sampling of noise intensity, each type of work shall be measured once per shift (8h) for 3 consecutive working days. During fixed-point measurement, workplaces with centralized noise equipment and high equipment noise intensity or long stay time of operators shall be selected to set detection points. The highest concentration detected in the working place during the working day was used as the value for evaluation.

4.2.2 Evaluation method of test results

For the evaluation and use value of the time-weighted average concentration and short-term (15min) exposure concentration of dust and various chemical harmful factors, the highest value of the detection result shall be selected; The average value of measurement data shall be selected as the fixed-point test result of noise intensity, and the equivalent sound level of individual exposure to noise shall be selected as the evaluation value of the test result of equivalent sound level of individual exposure to noise every week (40h).

All types of work in carbon fiber production are exposed to harmful factors, mainly HCN, NH3, CO, etc. The on-site detection data show that the concentration of NH3, HCN and CO exposed by the operators does not exceed the exposure limit [60], which may be related to the closed production equipment during production and the timely discharge of harmful factors from the workplace. According to the regulation [61], the toxic operation level of the four posts of pre-oxidation, carbonization, surface treatment and wire collection in the workshop is 0, i.e. relatively harmless operation, based on the concentration of various poisons exposed to the workers and other factors.

4.3 Analysis of working conditions and formulation of protective measures

4.3.1 Labor protection measures

There are harmful substances in the production and processing of carbon fiber composite materials, which are harmful to human body. So long as has the profound understanding to the harmful substance, takes the correct management and the dustproof anti-poison equipment management measure. Operators shall have corresponding protection awareness, such as:

1. Reform the production process to eliminate or reduce the production of dust and poison. In the reform of production process, non-toxic or low-toxic raw materials can be used to replace toxic and high-toxic raw materials (solvents), so as to reduce the opportunity for operators to contact harmful substances. Adopt new process, new technology, update equipment and improve operation mode to reduce and shorten process flow. The production is large-scale, mechanized and automated, and the harm of dust and poison is solved.

2. Labor protection articles are necessary for carbon fiber composite production and processing operators. Work clothes are not easy to stick carbon fiber dust (fine). They are made into jumpsuits with elastic bands at the collar and cuffs.

3. Dust and gas mask: convenient stowage, good effect after long-term use, easy to clean and replace.

4. Anti-allergic ointment: It can effectively prevent allergic reaction caused by dust and solvent. It can be rubbed on the skin surface to block poison and dust from entering the pores of human body. For those who have allergic reaction, it can relieve itching and diminish inflammation.

5. Strengthen the management of labor hygiene, and conduct regular physical examination for the operators exposed to the production and processing of carbon fiber composite materials; In addition, dust and poison monitoring shall be carried out regularly in the workplace, so as to control and prevent pollution in time when problems are found, and ensure safe and healthy production. We shall earnestly

implement the labor health policy of "prevention first," adhere to the unity of safe and healthy production and economic benefits, and adhere to the unity of development of production and environmental protection productivity; The purpose is to restrain the phenomenon that endangers the health of workers.

4.3.2 Protective measures for preparation and processing environment

1. Engineering control: main engineering control adopts isolation (separated from storage place and operation process, enclosed and closed system) and local exhaust facilities. Possible locations include resin blending; Heating, shaping, coating and finishing; exhaust gas removal, etc.

2. Administrative management: administrative management is different from engineering control, mainly reducing labor exposure, including labor safety, health and hygiene education and training; Production and operation process, equipment improvement and operation standard; Provide workers with personal protective equipment, properly maintain and clean them, and frequently inspect the site and require the workers to really "wear personal protective equipment"; Keywords Industrial hygiene program; Plant cleanliness; Good automatic inspection, supervisor inspection and work supervision, and labor scheduling for high exposure operation to reduce labor high exposure time.

3. Precautions for personal protective equipment for workers: Gloves, protective clothing and protective glasses are in great demand, especially when they are exposed to chemicals. Pay attention to their anti-penetration force. Sometimes the manufacturer 's information is incomplete, and the personal protective equipment may have to be tried for a period of time to know its effectiveness. Generally speaking, resin molecules are larger than solvents and plasticizers. Special attention shall be paid to the protection of the latter. Sometimes, hands may contact during composite operation, so gloves shall be carefully selected. In general, respirator is not necessary for compound operation because the solvent used has low volatility, but it shall be worn if the concentration is

too high, and it shall be used if the concentration is too high for large-area handling operation by hand.

4. Strengthen the storage management of chemicals. If a large amount of resin, solvent and catalyst is used in the workplace, it shall be properly managed. The key points are as follows: do not store too much chemicals on site, and store the required amount; Regular inventory of chemical stocks; hazard awareness training for workers; Separate storage to avoid mixing of hardeners with flammable liquids and organic vapors; Be careful to avoid splashing during loading and unloading, and add mousse to pollute the workplace; Containers should be properly designed for chemical needs and properly managed and maintained; Emergency response plans and drills are required for possible major fires and explosions. Fire extinguishing facilities such as fire extinguishers and water sprinkling facilities shall be provided according to laws and regulations; and gas detector.(Specific process scope: Lamination curing, winding, hot pressing, pultrusion, spraying, trimming, etc. in the industry of manufacturing fiber reinforced plastics by using glass fiber or carbon fiber as reinforcing fiber and mixing with thermotropic resin molding).

Due to the good heteroelectricity of carbon fiber, carbon fiber dust as conductive dust is very harmful to electrical equipment. Carbon fiber dust may enter into the electrical equipment with low dust-proof level, cause short circuit of electrical elements and damage electrical equipment. At the same time, it will damage the insulation of electrical equipment. and further reduce the insulation resistance thereof. Make the enclosure, base, hood and other metal parts of electrical equipment carry dangerous voltage. In addition, although carbon fiber is a non-toxic material, the dust may cause skin swelling and allergy when it comes into contact with human body. People with allergic constitution are not suitable for this work.

In order to prevent hazards and ensure safety, various protective measures shall be taken for carbon fiber board. Firstly, all personnel entering the site shall change shoes, clothes and caps, wear protective clothing, goggles and masks, and then clean regularly to ensure that the room is quiet and clean without dust and impurities. It is better not to place easily conductive appliances in carbon fiber processing room.

4.4 Fire Safety Rules for Workplaces

According to the "Hygienic Standard for Design of Industrial Enterprises" issued by China, the new and modified. In the expansion project and technical transformation, the regulations of "Three Simultaneities" of main works and labor health facilities shall be implemented to ensure that the factory buildings and mechanical equipment meet the requirements of labor safety and health. First of all, the design of carbon fiber composite production and processing plant must be tall, wide production area, all air-conditioning control, ventilation equipment and dust control facilities are good.

since that carbon fib dust generated dure the machining of the carbon fiber composite material has electrical conductivity, the carbon fiber dust can cause the short circuit of nearby electrical equipment and other adverse effect, and in particular, special protective measures such as air purification and the like should be taken for the electronic computer control system, and the workshop should be far away from the carbon fiber production and processing workshop.

A great deal of carbon fiber dust is produced in the machining of carbon fiber composite materials, and the most harmful to human body is fine dust. Inhalation of carbon fiber dust will lead to pulmonary fibrosis in workers.

Carbon fiber dust is not a simple existence, carbon fiber composite materials also used some aluminum powder and talcum powder, etc., metal matrix with magnesium alloy, titanium alloy, nickel alloy, aluminum, lead, copper and its alloys, etc., in the cutting and drilling process to produce some metal debris particles. So take modern science and technology gas prevention and dust control facilities is very important. In the workplace dust removal had better use semi-enclosed or fully enclosed equipment, can make carbon fiber dust meet the national health standards.

Conclusion for part 4

This chapter discusses the harmful substances existing in the production and processing of carbon fiber composite materials, and analyzes the harmful factors generated in the preparation and processing of composite materials, including: Reinforcing fibers, dust, solvents, etc. Workplace hazards include: Chemical harmful factors include hydrocyanic acid, NO, NO2, CO, CO2, methane, etc. Physical harmful factors include high temperature, noise, carbon fiber dust, etc. Finally, through the development of appropriate protective measures to ensure the safety of workers rights and interests, to create a safe, healthy and efficient working environment.

PART 5. ENVIRONMENTAL PROTECTION

With the deepening understanding of carbon fiber composite materials and the continuous improvement of manufacturing technology, the application research and equipment of carbon fiber composite materials in relevant fields have made continuous progress, and the application in transportation, wind power generation, oil exploitation, power transmission and other fields will be closely related to the effective reduction of greenhouse gas emissions and the solution of global warming and other environmental problems. This has important strategic significance for changing the economic structure, energy conservation and emission reduction.

The strength and elastic modulus of carbon fiber are excellent, and the future growth and production are expected by many enterprises and countries. The use of carbon fiber has made a great contribution to the countermeasures against global warming. The impact of carbon fiber on the environment is evaluated based on the LCA life cycle assessment, which includes the life cycle from raw material mining to the use of carbon fiber products to disposal. As a result, when carbon fiber is used to reduce the body structure by 30%, the carbon fiber is 50 tons per ton, and the airframe structure of an airplane is reduced by 20%, the reduction effect of 1400 tons will be obtained in the life cycle of 10 years.

5.1 Application of Carbon Fiber Composites in Environmental Protection

5.1.1 Application of Carbon Fiber Composites in Environmental Protection

Carbon fiber composite materials are also widely used in aircraft manufacturing, such as helicopter fuselage, blades, etc., and more widely used in large aircraft. The front fuselage section, vertical tail stabilizer, outer wing, drag plate, fairing panel and other components are shown in fig. 5.1. As with cars, carbon fiber composites also reduce the weight of the entire aircraft, reduce fuel efficiency, and achieve energy conservation and emission reduction functions.

Greenhouse gas emissions are closely related to energy consumption. The extensive application of carbon fiber epoxy composites in aircraft can reduce mass, save fuel, reduce emissions, reduce pollution, increase range and improve economy.

Fig. 5.1. Airbus A350.

5.1.2 Application of Carbon Fiber Composites in Automobile Field

As an automobile material, carbon fiber has the greatest advantage of light weight and high strength. Its weight is only 20% -30% of that of steel, but its hardness is more than 10 times that of steel. Therefore, the use of carbon fiber materials in automobile manufacturing can make breakthrough progress in light weight of automobiles and bring energy saving benefits [62].

Carbon fiber composite materials are commonly used in automobile manufacturing, such as automobile bodies, wheel hubs (shape: cylindrical), transmission shaft (transmission shaft composition: Shaft tube, telescopic sleeve and universal joint), tail wing, interior decoration, etc. are shown in fig. 5.2. As a new composite material with light weight and high strength, carbon fiber is only 1/4 of steel, which reduces the weight of the automobile to a great extent, makes the automobile lighter, greatly reduces the fuel efficiency of the automobile, thus reducing the emission of waste gas and plays a great role in environmental protection.

Fig. 5.2. Sports car with carbon fiber composite body.

5.1.3 Application of Carbon Fiber Composites in Wind Power Generation

Wind power has been around since the early 1900s, when wind turbines were small, with very small blades and very little electricity. In order to make the wind power generation device produce more natural power, and maximize the reduction of power generation methods such as coal, oil, gas, etc., and maximize the reduction of exhaust emissions to the atmosphere, carbon fiber composite materials are applied to the blades of wind power generation devices. As shown in fig. 5.3, it is not only light in weight, but also excellent in strength and rigidity, which greatly improves the power generation.

Wind energy is a kind of clean and renewable green energy, inexhaustible. Due to the influence of design and manufacturing technology, the capacity of wind turbine in China is still small, and the blades are made of glass fiber reinforced materials. In order to ensure the power generation under extreme wind load, the blade must have sufficient rigidity. To reduce the mass of the blade and meet the requirements of strength and rigidity, the effective method is to use carbon fiber reinforced composite materials [63]. Today, with the rapid growth of the installed capacity of wind turbines in the world, it will become the main trend to increase the consumption of carbon fiber composite materials for long-blade large-capacity wind turbines.

Fig. 5.3. Wind power generation device.

5.1.4 Application of Carbon Fiber Composites in Wastewater Treatment

With the development of industry and economy in our country, the discharge of wastewater is also increasing. The application of new materials is very important. Therefore, reasonable carbon fiber composite production wastewater treatment and recycling methods are of great significance for saving water resources and responding to national energy conservation and emission reduction policies [64].

In general, carbon fiber composites have excellent properties such as light weight, high strength, high stiffness, fatigue resistance and corrosion resistance. In order to solve energy and environmental problems, the application of carbon fiber composites in large aircraft, wind power blades, automobile parts and other fields will promote the realization of energy conservation and emission reduction. Pay attention to the process of promoting the localization of high-performance carbon fiber, realize the continuous upgrading of domestic carbon fiber technology and serve the benign development of energy-saving and environment-friendly economic construction. This is in line with the spirit of the two sessions and promotes the construction of an environment-friendly society.

5.2 The recycle and utilization of carbon fiber composite

With the increasing application and annual output of composite materials, a large number of composite material wastes are also brought [65], especially the characteristics of high strength, high modulus and good corrosion resistance of carbon fiber composite materials make it difficult to treat and utilize the wastes, and the pollution of carbon fiber composite material wastes to the environment has attracted extensive attention. In view of the difficulty in recycling carbon fiber composite wastes, relevant laws and regulations have been issued at home and abroad to guide the research on recycling of thermosetting carbon fiber composite materials and realize the resource recycling of wastes [66-67]. Therefore, the recycling and utilization technology of carbon fiber composites has become a research hotspot in the world.

5.2.1 Pretreatment of Carbon Fiber Composite Waste

There are two main sources of carbon fiber composite waste:

(1) Production process wastes mainly refer to leftover materials, waste materials or waste products generated in the production process of carbon fiber composite materials;

(2) The wastes scrapped after use mainly refer to the waste products of composite materials that have reached the service life or have not reached the service life but are damaged during use or construction [68].

Generally speaking, carbon fiber reinforced resin matrix composites (thermosetting and thermoplastic) are composed of carbon fiber, resin and filler. In the waste of carbon fiber reinforced resin composite materials, there will be metal fixtures, oil stains, binders and other components. Therefore, before the recycling of carbon fiber reinforced resin composite waste, it should be pretreated first, and then according to the different recycling and utilization methods, the waste should be processed into the required size. The pretreatment methods of carbon fiber reinforced resin composite waste include cutting, disintegration and crushing, etc., as shown in fig. 5.4 [69].

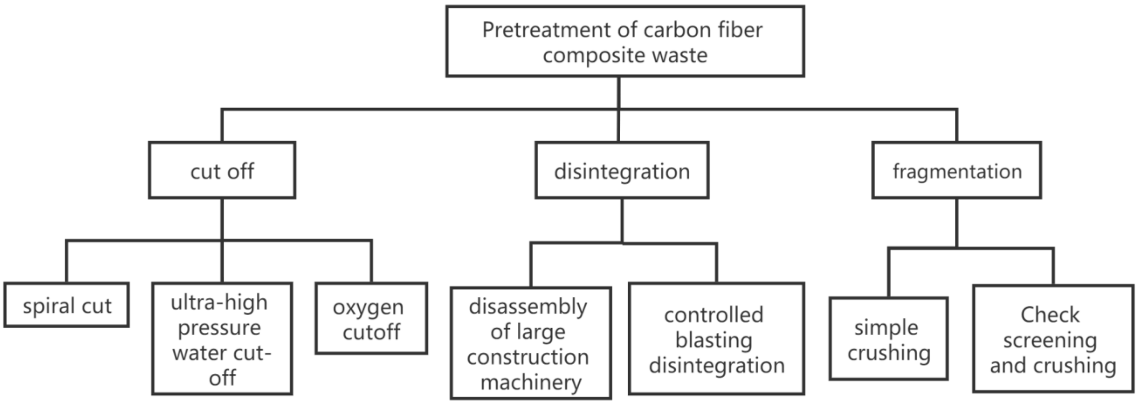


Fig. 5.4. Classification of Carbon Fiber Composite Waste Pretreatment.

5.2.2 Carbon fiber composite material waste recovery method

In recent years, Europe, America, Japan and other countries have carried out research on recycling and utilization of carbon fiber composite waste to develop efficient and economical carbon fiber recycling technology. Generally speaking, according to the material composition and characteristics of carbon fiber composite waste, the methods of carbon fiber composite waste at home and abroad mainly include chemical recycling, energy recycling and physical recycling.

Chemical recovery

Chemical recycling refers to a method in which carbon fiber composite waste is first pulverized and then chemically decomposed into fuel and by-products that can be recycled. Because of the high value of carbon fiber itself, the cost of recycling carbon fiber will be lower than the recycling cost of carbon fiber. Generally speaking, the chemical recycling method mainly recycles the high-value carbon fiber in the waste. The chemical recycling method can be divided into three types according to the recycling technology and equipment: a fluidized bed recovery process, a thermal cracking recovery process and a supercritical fluid recovery process.

(1) fluidized bed recovery process;

Fluidized bed recycling process refers to a method of separating carbon fiber and resin at a certain temperature in a fluidized bed reactor using air as fluidizing gas. This process is developed and promoted by the University of Nottingham, UK.

Jiang[70] studied the surface characteristics of recycled carbon fibers obtained at a temperature of 500°C, a fluidization time of 10min and a fluidization velocity of 1m/s. The analysis showed that after treatment, the hydroxyl (-OH) on the surface of the original carbon fiber was converted into carboxyl (-COOH) and carboxyl (-C=0) with higher oxidation degree, while the oxygen/carbon value on the surface did not change, and the change of chemical composition on the surface of carbon fiber had little effect on the interfacial shear strength of recycled carbon fiber and epoxy resin. Yip et al. [71] studied the mechanical properties of recycled carbon fibers at a fluidization temperature of 450°C and a fluidization velocity of 1m/s. The length of recycled carbon fibers ranged from 5.9 to 9.5 mm. The results showed that the tensile strength of recycled carbon fibers was about 75% of that of original carbon fibers, while the tensile modulus was basically unchanged.

(2) Thermal cracking recovery process;

Thermal cracking recovery process is also called high temperature decomposition method. This process decomposes the resin in carbon fiber composite materials at high temperature (without combustion, at this temperature, carbon fiber, filler, etc. will not cause chemical reaction) under oxygen-free condition, so as to realize the recovery of carbon fiber or other materials. The process comprises the following steps: putting the pretreated composite material into a cracking reactor, cracking the resin at the temperature of 400 - 500 DEG C to form an intermediate product with carbon deposit (generated by resin cracking) remaining on the surface of the carbon fiber, and putting the intermediate product into an oxidation reactor to remove the carbon deposit so as to obtain the carbon fiber tow. Thermal cracking recovery process is shown in fig. 5.5.

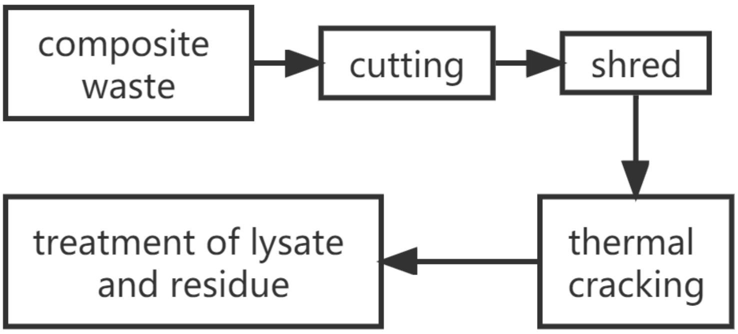


Fig. 5.5. Schematic Diagram of Thermal Cracking Recovery Process.

After the resin of the thermosetting carbon fiber composite material is decomposed, phenol is the main component, and phenolic resin or epoxy resin can be produced. The carbon fiber recovered by the process has good quality, and after thermal cracking, the metal fixture in the composite material can be directly removed from the solid by-product. Therefore, the thermal cracking recovery process is the most promising recovery technology at present. However, this process is technically difficult, with high requirements for recovery equipment and high recovery cost.

American Adherent Technologies Inc (ATI) has successfully developed a low-temperature and low-pressure thermal decomposition method of carbon fiber composite materials. The research results show that the surface damage of carbon fiber recycled by this method is very small, and the tensile strength of carbon fiber is only reduced by about 9% compared with that of original carbon fiber [72].

German Karl Meyer Company [73] invented a new process, which is to introduce protective gas into a special heating furnace to isolate oxygen, so that the carbon fiber will not be affected after the resin of composite material is decomposed. The key of this technology is heating temperature and protective gas, so that the treated carbon fiber is convenient for reuse. The appearance of carbon fiber recovered by this process is not much different from that of original carbon fiber, only the length of carbon fiber becomes shorter, and the tensile strength is slightly reduced. In view of its lower cost, can be used for airplane interior decoration or other composite material products with uncritical performance requirements.

(3) Supercritical fluid recovery proces

Supercritical fluid (the special state in which the temperature and pressure of fluid exceed its inherent critical temperature and pressure) has the viscosity and diffusion coefficient similar to that of gas, and the density and dissolving power similar to that of liquid. Therefore, under certain conditions, supercritical fluid can penetrate porous solid materials and dissolve organic materials. The resin in the composite material waste can be decomposed by the super dissolving capacity of the supercritical fluid, clean carbon fibers can be obtained, and the performance of the carbon fibers can be well reserved.

Pickering research team of Nottingham University [74] studied the dissolution of carbon fiber reinforced resin composites in carbon dioxide, water, acetone, methanol, ethanol and propanol under supercritical state. The research shows that supercritical propanol has the best dissolution effect on the resin, and the tensile strength and tensile modulus of the recycled carbon fiber are 99% of the original carbon fiber. Bai Yongping et al. [75] of Harbin Institute of Technology studied that adding oxygen in supercritical water can greatly improve the decomposition speed, and the tensile strength of the recycled carbon fiber is almost not reduced.

Physical recovery

Physical recycling refers to a method in which carbon fiber composite waste is crushed, metal is removed, and then the waste is crushed into powder with different particle sizes, and the powder is used as raw material. This method is usually used when the waste is relatively pure. The method is the most common method adopted in China at present, and the treatment method is simpler and the production cost is lower.

Japan Zhifu Onoda Company uses the waste of carbon fiber reinforced resin composite material as raw material of cement after physical treatment. The test shows that: The flexural strength and gel time of the prepared cement are basically the same as those of ordinary cement.

Energy recovery

Energy recovery refers to the energy recovery of carbon fiber reinforced resin composite waste through controlled incineration. The recovered energy can be converted into electricity or heat, which can be used as fuel to replace coal or regional heating. This method is one of the simplest methods for recycling composite materials. For size structural members, decomposition, cutting, shredding and other procedures shall be conducted before incineration. In view of the problem that the incineration process is easy to release toxic gas and smoke to pollute the atmosphere, it is necessary to design a high-performance incinerator to solve this problem. The method can be used as a final treatment method of the carbon fiber composite material waste, and is used for treating the waste which is difficult to treat by other methods.

Generally speaking, physical recovery and energy recovery are not efficient for recycling carbon fibers, which are only suitable for uncontaminated composites, and the use value of recycled products is relatively low; Energy recovery will bring environmental pollution, waste of resources and other problems. Chemical recovery is a very potential research and application direction.

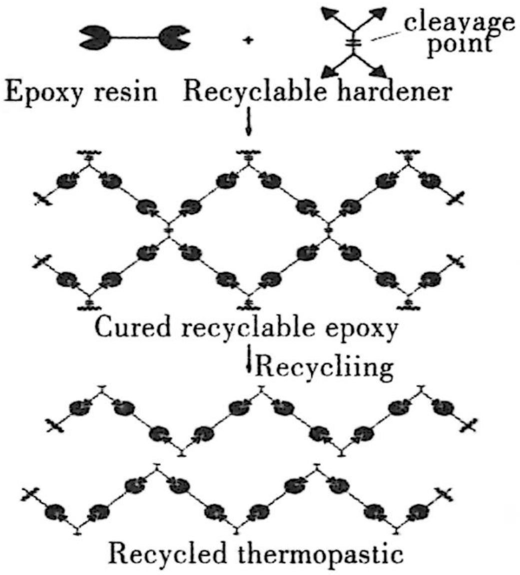


Fig. 5.6. Schematic Diagram of Reaction and Degradation of Acetal Bond Monomer.

5.2.3 New Idea of Carbon Fiber Composite Waste Recycling

When the matrix resin is a thermosetting resin, due to the inherent cross-linking property of the thermosetting resin, the carbon fiber composite material cannot be melted and plasticized again, and the thermosetting determines that the carbon fiber composite material can only be heated and molded once, so the carbon fiber composite material cannot be processed repeatedly. and separating the two is not so easy. Stefan J.Pastine of Connora Technologie solved this problem by changing the synthesis recipe of the epoxy resin. The idea is to replace one of the monomers with a monomer having an acetal bond, the presence of which makes the final polymer three-dimensional network acid-degradable. Therefore, when the carbon fiber composite is put into acetic acid at 100℃, the resin part will be decomposed, and the carbon fiber filtered out can be reused [76].

Researchers at Colorado State University recently developed a polymer synthesis process that allows polymers to be recycled back to their original molecular state by heating, leading to a new class of sustainable biopolymers that are both bio-renewable and recyclable. Recently, researchers at the University of Colorado at Boulder have taken it one step further-recycling carbon fiber composites into new materials with original strength characteristics. These include carbon fibers and adhesives. Both composites can be completely recycled by soaking them in organic solutions at room temperature [77].

Conclusion for part 5

At present, due to its excellent comprehensive properties, carbon fiber reinforced resin composites have become indispensable new structural and functional materials in many fields such as aerospace, automobile, environmental engineering, new energy, transportation, construction, sports equipment, etc. Especially with the rapid development of aviation, major infrastructure, new energy vehicles and wind power in China, the application of carbon fiber composite materials will be more and more extensive, and the recycling and reuse of its wastes will become an important issue that must be faced.

Therefore, the research on efficient recycling technology of carbon fiber composite materials has great economic benefits, not only can realize the reuse of high-value materials, but also the recycling and reuse of carbon fiber composite materials can greatly reduce energy consumption and environmental pollution, which plays an important role in the development of composite materials industry.

GENERAL CONCLUSIONS

The following are the outcomes of my design work:

- Application status of carbon fiber composite materials in the aviation field.

- Exploration of research methods of strength of carbon fiber composite materials.

- Experimental design of basic properties of carbon fiber composite materials.

- Establishment of finite element model and progressive damage model and design of analysis subroutine.

- Compared with tensile fracture, delamination damage between fiber layers of fatigue samples is obvious.

- UMAT material subroutine is written by selecting two-dimensional Hashin failure criterion, and static progressive damage analysis model is established. The finite element model is used for simulation analysis and the feasibility of the program is verified by comparing with the experimental results.

- The fatigue progressive damage analysis model is established by using the UMAT material subroutine based on the composite fatigue damage accumulation model. The simulation results are in good agreement with the experimental results, and the errors are 3.74%, 2.67% and 2.02% respectively under different stress levels.

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