A Review of Aeronautical Fatigue and Integrity Investigations in China（June 2008—May 2015）

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ABSTRACT: This review summarizes fatigue, structural-integrity and fracture-mechanics/Damage Tolerance investigations that were performed in china during the June 2008 to May 2015. The review includes basic research on fatigue and structural integrity, Research and Application on fatigue and structural integrity, Application examples and the main research direction in the future.

1. INTRODUCTION

China's rapid economic development will bring great demand for civil aircraft. According to the report of China Market Outlook 2013-2032 for Civil Aircraft released by Aviation Industry Corporation of China, the fleet demand will reach to 5288 by 2032, including 4396 large jet liners and 892 regional jet liners[1]. Besides the safety and efficiency of civil aviation, China pays much more attention to the management of fatigue life and structural integrity for the existing fleet and the developing civil aircrafts.

In accordance with user's requirements, China's aviation industry continuously studies aircraft structural fatigue/damage tolerance and structural integrity, and improves aircraft's service life. On the one hand, emphasizing top-level design, we carried out extensive research in new materials, new processes and new structures. A thorough discussion was also done in terms of structural fatigue and integrity. Thereby, we have achieved a new long-life fatigue design of aircraft structure; On the other hand, development of conventional regional aircraft has been transformed into that of large aircraft and mainline civil aircraft, satisfying the requirements of long life and high reliability. To date, the design goals life of trainer aircraft and civil aircraft developed by China are respectively 8000-10000 hours and 60000-90000 hours. The calendar life goal of aircraft is 30 years.

State high-tech 863 Program, National Natural Foundation, aviation technology research projects as well as business investment provide a strong support for the studies of fatigue and structural integrity. Thus a basic research team led by CAE (Chinese Aeronautics Establishment) is formed. The colleges/universities and the basic research institutes (Aircraft Strength Research Institute, Beijing Institute of Aeronautical materials, Beijing Aerial Manufacturing Research Institute and AVIC Composite engineering technology centre, etc.) mainly focus on the theoretical research. The aircraft design and research institutes and the aircraft manufacturing institutes mainly focus on the applications in airplane types. This team has done a lot of research work and developed some criteria, guides and handbooks in terms of aircraft types through a lot of application research. These results have been widely applied on their independently developed aircraft and service life extension.

The detailed research[2-4] are listed as follows.

- Studying the fatigue and damage tolerance of new materials, new processing and new structures;
- Performing pre-research of aircraft FSI(fatigue and structural integrity) related techniques, and supplying key technologies and software for FSI design and analysis during new aircraft development;
- Building-block verification of aircraft structures;
- Developing and amending standards and regulations for aircraft FSI experiments, and being responsible for the generalized application.
- Measurement and compiling of load spectrum considering the effect of comprehensive environments;
- Performing durability/damage tolerance analysis and life reliability evaluations of aircraft structures, and providing experimental data and conclusions;
- Conducting full-scale aircraft ground FSI experiments, and drawing conclusions to new developed/modified aircraft. Eleven full-scale fatigue experiments have been done on domestic developed/modified aircraft types and foreign entranced ones;

- Studying the health monitoring, damage inspection and maintenance of aircraft structures base on the fatigue/damage tolerance theory and tests.
- Life extending of aging aircrafts.

The research idea of fatigue and structural integrity is presented. The semi-empirical theory, the engineering based application, especially the new materials are studied and extended to the real engineering application. Then, the corresponding handbooks, specifications and outlines are formed and released to guide the new aircraft type research and the life extension of aging aircrafts. The specific research and results are described in the nest sections.

2. BASIC RESEARCH IN FATIGUE AND STRUCTURAL INTEGRITY

2.1 standards, handbooks, methodologies, specification and outlines

China’s aviation industry has studied a lot in aeronautical material performance during the past sixty years. So far more than 2000 types of aviation metals, polymer materials, inorganic non-metallic materials and composite materials have been produced. In addition, we have set some aviation materials research and production based on a certain scale, which have production equipments and detection equipments for producing all kinds of material grades, varieties and specifications. Consequently, more than 1000 kinds of aeronautical materials, thermal processes, physical testing standards as well as various performance testing standards (national standard, national military standard and aviation standard) have been gradually developed. The material performance standards and handbooks are listed as follows:

- 《China aeronautical materials handbook》;
- 《Engine materials selection directory》;
- 《Aeronautical materials selection directory》;
- 《Handbook of mechanical properties of aircraft structural metals》;
- 《Handbook of fatigue properties of aeronautical metals》;
- 《Handbook of welding properties of aeronautical materials》;
- 《Handbook of shot penning of aeronautical materials》 and 《Composite materials properties handbook》;
- Handbook of mechanical properties of aircraft structural metals (Vol.1, Static fatigue strength/durability; Vol.2, Damage tolerance; Vol.3，Corrosion fatigue） (Edited by WU Xueren，Aviation Industry Press, 1996);
- Handbook of fatigue properties of aeronautical metals (Beijing Institute of Aeronautical materials, 1981);
- Handbook of welding properties of aeronautical materials (National Defense Industry Press);
- Handbook of shot penning of aeronautical materials;
- Handbook of material properties of mechanical engineering;
- Composite materials properties handbook et al.

China modern aircrafts are designed following the requirements of structure integrity and durability/Damage tolerance, and performed according to integrity programs and corresponding rules. Current top-level design specifications mainly consist with the following publications:

- 《Military aircraft structural integrity program》;
- 《Military aircraft structural strength standards》;
- 《China Civil Aviation Regulations[CCAR]PART 25 AIRWORTHINESS STANDARDS: TRANSPORT CATEGORY AIRPLANES》;
- 《Durability design handbook》;
- 《Damage tolerant design handbook》 et al.
- Based on the conclusions of aircraft design and usage over the years, the enterprises compiled some design handbooks concerned with fatigue and damage tolerance and structural integrity.
- Handbook of fatigue analysis of Aeronautical structural connectors ;
- Bolts and lugs strength analysis handbook;
- Crack-detection probability curves handbook;
- Aircraft structural reliability design and analysis guideline;
- Handbook of durability and damage tolerance design for civil aircraft;
- Structural durability and damage tolerance design guideline for ARJ21 aircraft;
- Structural durability and damage tolerance design guideline for Y12F aircraft;

- Aircraft structure repair manual (Compilation & translation);
- Handbook of corrosion fatigue design for aircraft structure;
- Aircraft structural landing gear design handbook;
- Structural strength design and verification guideline for civil aircraft;
- Static strength analysis handbook for C919 aircraft structure (fuselage, wing and composite materials)
- Design guideline of durability/Damage tolerance for large fire-fighting/water rescue amphibious aircraft.

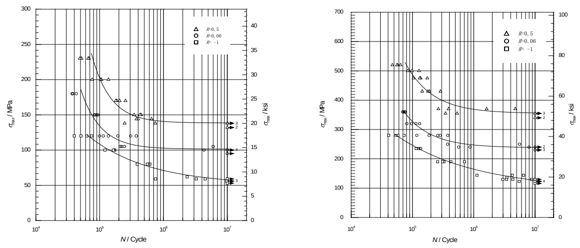
The earlier released military airplane structural strength specification and requirements such as GJB67-85 series, GJB775.1-89, GJB776-89, GJB67.13-90, GJB2750~2760-96 and GJB2876-97 are not appropriate for the research process of new generation of military aircraft, due to its unclear hierarchy and dated technical content.

Consequently, we wrote and released the military airplane structural strength specification(GJB67A-2008) in 2008 and the military airplane structural integrity outline (GJB775A-2012) in 2012. Summing up research experience of internal military aircrafts, these two standards were edited by dozens of aviation experts and academicians, referring to the external advanced standards. Their advantages are concluded as follows.

- Their system integrity makes the hierarchy of military airplane structural strength standards perfect
- The contents cover from the start to develop into various aspects of aircraft structure strength of the whole service process.
- They embodies the aircraft structural integrity design idea
- They are widely used and can meet the demand of land-based aircraft and carrier-based aircraft.
- They can be operated easily with the help of instructions for the standard application.

2.2 New materials
2.2.1 Al-Li alloy
1） Basic fatigue properties

Fatigue tests have been done for 2060-T8(sheet), 2099-T83(extrusion), 2198-T8(sheet), 2196-T8511(extrusion) and the S-N curves with Kt=1.0 and Kt=3.0 are obtained and shown in figure 1.

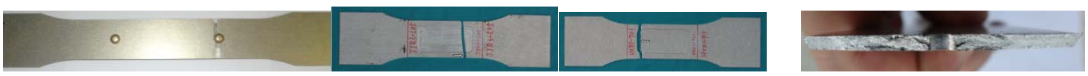


Kt=1.0 Kt=3.0

Figure 1. S-N curves of Al-Li alloys.

2） The influence of manufacture process and treatments

The fatigue tests have been done for 2060-T8(sheet), 2099-T83(extrusion) with chromic acid anodizing, machining and chemical milling, as shown in figure 2.



Chromic acid anodizing Machining Chemical milling Fatigue fracture

Figure 2. fatigue tests of Al-li alloys at different conditions.

2.2.2 superalloy
1） Influence of temperature and heat treatment processes on ultra-high cycle fatigue behavior of superalloy [5]

The influence of temperature, frequency and heat treatment on high/ultra-high cycle fatigue properties of DZ125 superalloy is studied and the results are shown in figure3.

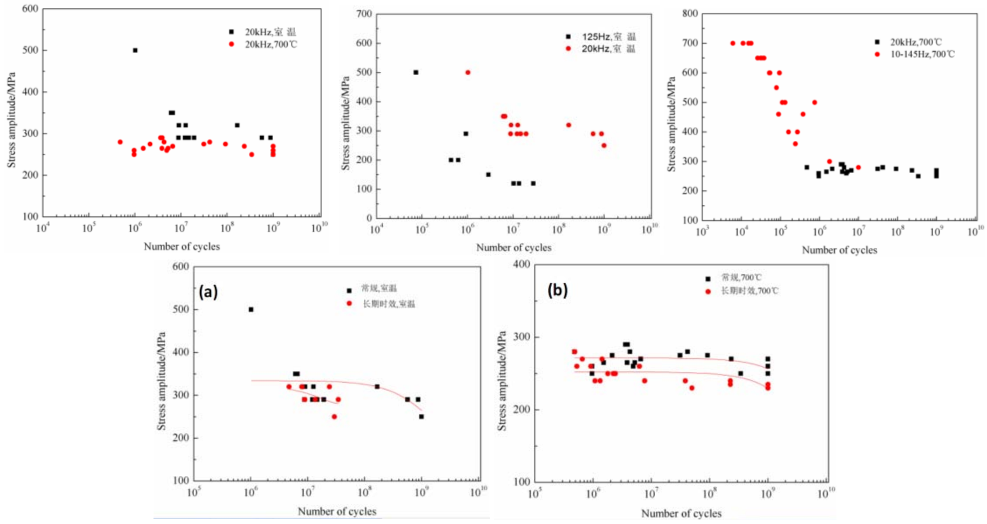


Figure 3. ultra-high cycle fatigue properties of DZ125 superalloy.

The fatigue fracture characteristics of DZ125 superalloy after two kinds of heat treatment, i.e., conventional and aging treatment, are analyzed at room temperature and 700℃ respectively and the results are shown in figure 4.

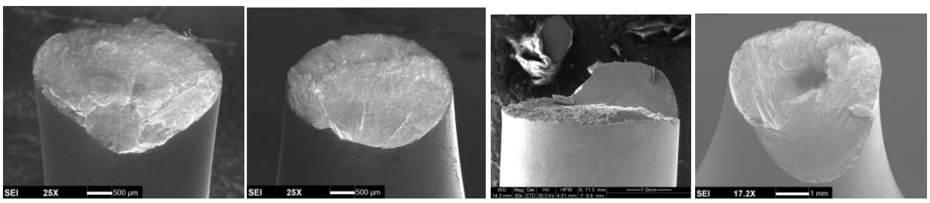


Figure 4. Fracture surfaces of DZ125 superalloy after conventional and aging heat treatment.

2）Ultra-high cycle fatigue crack initiation and propagation characteristics of superalloy[6]

Comprehensive analysis and preliminary study are conducted to reveal the effect of temperature on ultra-high cycle fatigue crack initiation and propagation. The fracture morphologies are shown in figure 5.

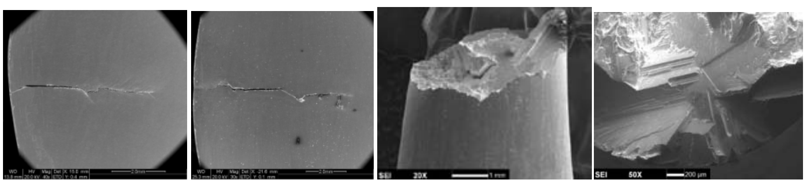


Figure 5. Cracks propagation and fracture characteristics of DZ125 superalloy at room temperature and 700℃.

Comprehensive analysis and preliminary study are conducted to reveal the effect of surface states on ultra-high cycle fatigue crack initiation and propagation. The AFM ((atomic force microscope) stereogram, fracture characteristics, crystal orientation differences near fracture origin zones and morphologies of ••of DZ125 alloy after LSP (laser shock processing) are shown in figure 6.

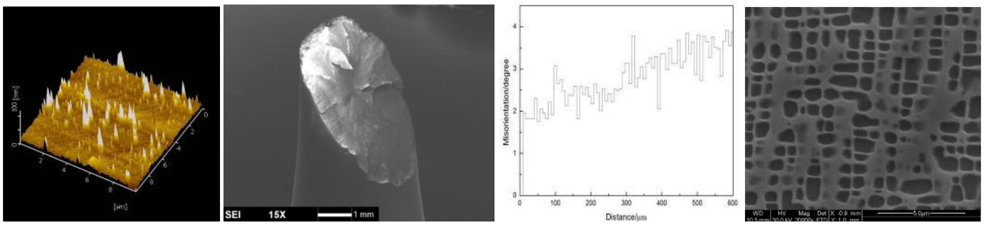


Figure 6. AFM stereogram, fracture characteristics, crystal orientation differences near fracture origin zones and morphologies of ••of DZ125 alloy after LSP (2J).

The ultra-high cycle fatigue deformation mechanism of superalloy is obtained through the study on the crystal orientation evolution before and after fatigue under different conditions. The crystal orientations before fatigue, after fatigue, after LSP and at 700℃ are shown in figure 7.

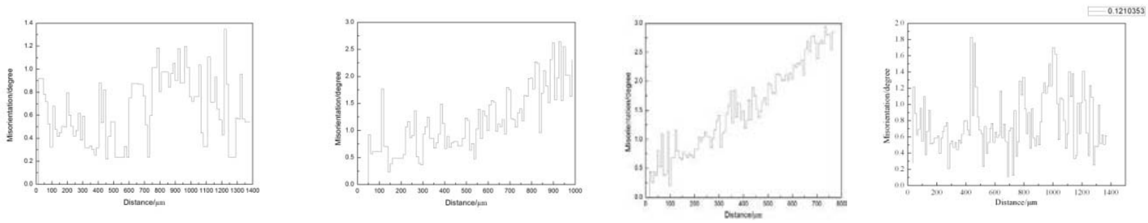


Figure 7. Misorientation of DZ125 superalloy under various conditions.

2.2.3 Composites strength

1）Damage tolerance and fatigue test of composite panels[7-10]

The composite panel strength is studied under tension, compression, shear, biaxial tension and fatigue load. The effects of impact damage and machined notch are taken into account.

Figure 8. Damage tolerance and fatigue test of composite panels.

Damage tolerance and fatigue tests are conducted under interior pressure, and the BVID (barely visible impact damage) and VID (visible impact damage) are studied.

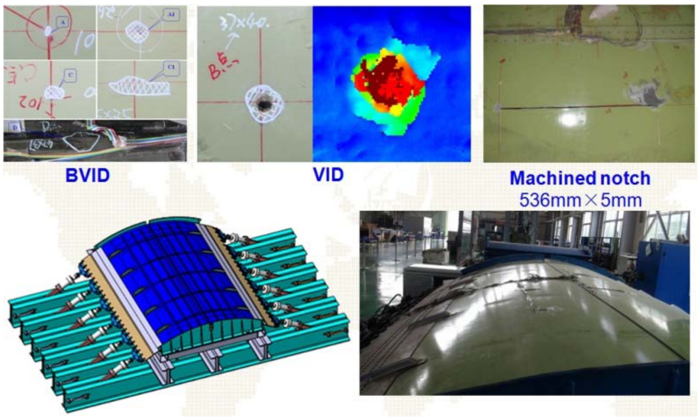


Figure 9. Damage tolerance and fatigue test of composite panel under interior pressure.

2）Damage tolerance and fatigue test of composite structure (subcomponent /box-level)

Damage tolerance and fatigue test of composite structures are conducted under block spectrum loading including the load enhancement factor, as shown in figure 10.

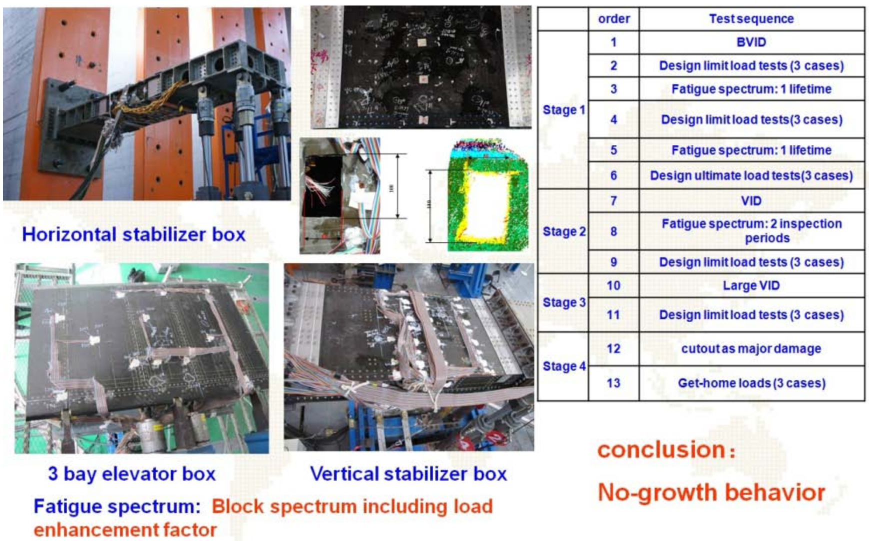


Figure 10. Damage tolerance and fatigue test of composite structure.

3）Building block approach of a stabilizer development[11]

Following the structural integrity programs and building-block concept, the strength of a stabilizer made of T700-BA9916 is studied and verified, as shown in figure 11.

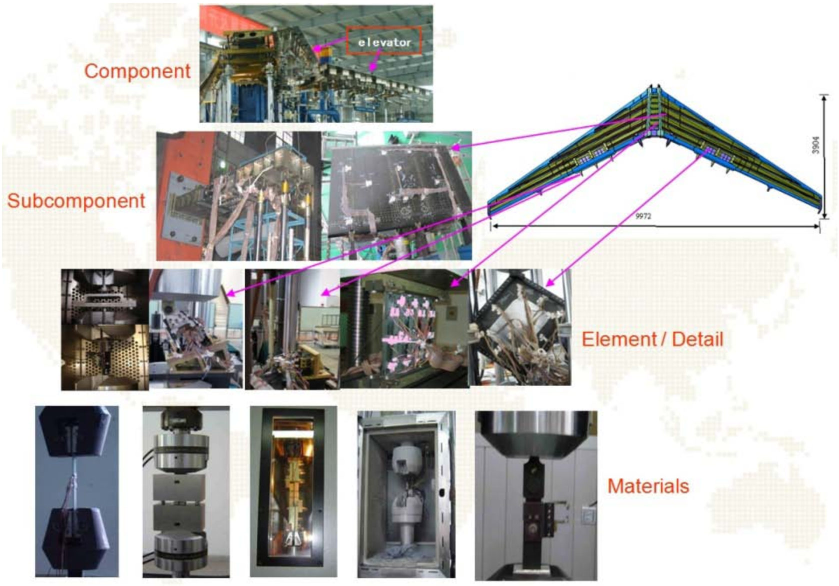


Figure 11. Building-block design, analysis and verification of a stabilizer.

2.3 New process
2.3.1 Friction welding
1）Microstructure measurement[12]

The microstructure of three welding types, i.e., linear friction welding(LFW), friction stir welding(FSW) and inertia friction welding(IFW), are observed and analyzed. Sensitive analysis is conducted between the microstructures and mechanical properties of the welding joints.

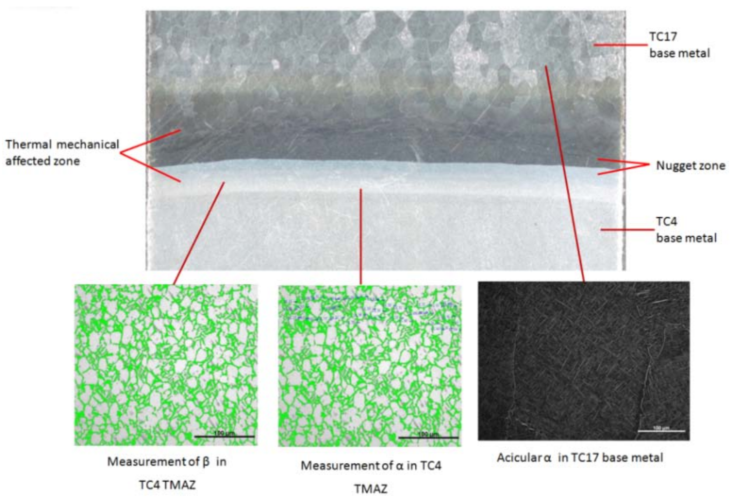


Figure 12. Microstructure of TC4/TC17 titanium alloy linear friction welding joint .

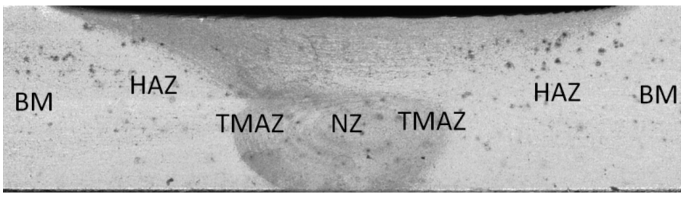


Figure 13. Macro-morphology of 2024-T3 aluminium alloy Friction stir welding joint .

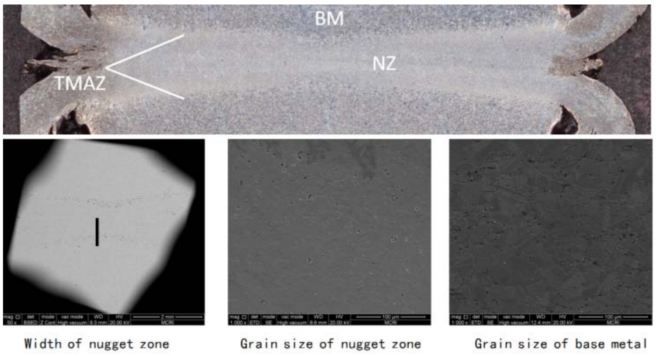


Figure 14. Microstructure of superalloy FGH96 inertia friction welding joint.

2）Mechanical property control method for welding joints[13]

The convention mechanical property of friction welding can exceed 90% base metal and the effectiveness is above 95%.

The effect of heat treatment and welding parameters on the fatigue and fracture properties of friction welding joints are studied, the results are shown in figure 15 and figure 16.

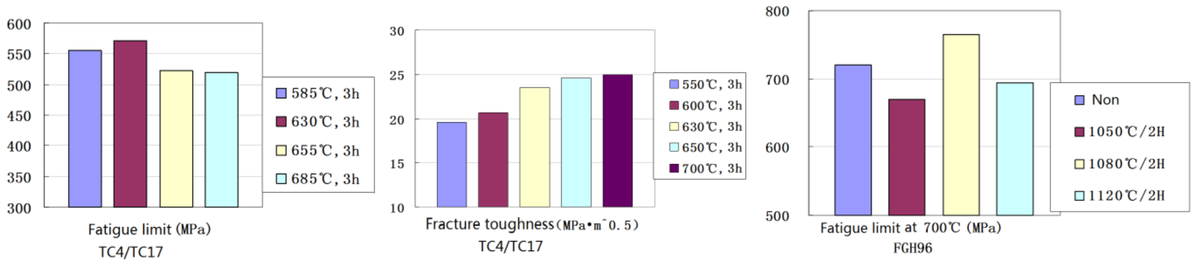


Figure 15. The effect of heat treatment on the mechanical properties of TC4/TC17 LFW joints and FGH96 IFW joints.

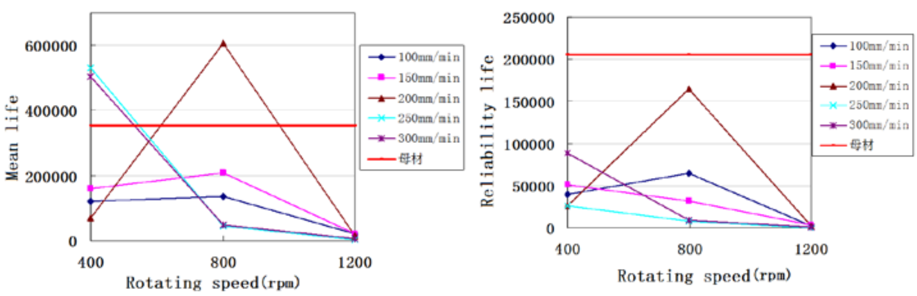


Figure 16. The effect of welding parameters on the fatigue properties of 7050-T7451 FSW joints.

The residual stresses introduced by LFW and IFW are measured using the contour method and the residual stress due to FSW is measured using the hole-drilling method. The residual stress is controlled by selecting proper welding parameters and heat treatment. The residual stress of friction welding is shown in figure 17.

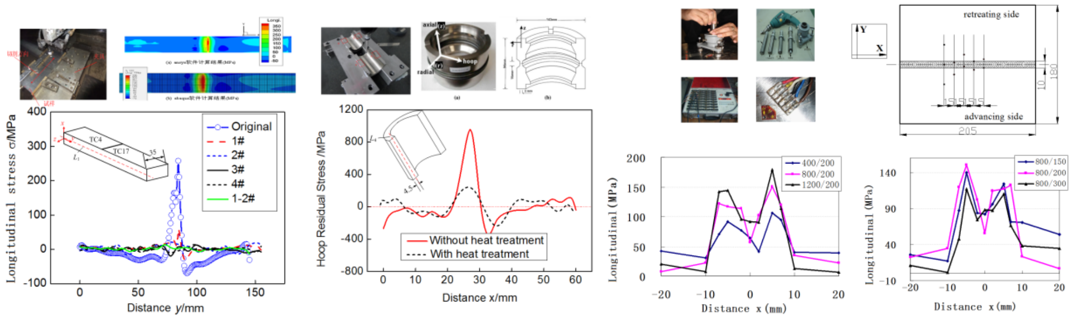


Figure 17. The residual stress distribution of TC4/TC17 LFW joints, FGH96 IFW joints and 2024-T3 FSW joints.

3）Property reliability estimation system for friction welding[14]

The relationships among the welding process, the microstructures and the mechanical properties of welding joints are obtained. The reliability estimation system is established which contains the functions of reliability estimation, mechanical property prediction and welding parameter optimization, etc, as shown in figure 18.

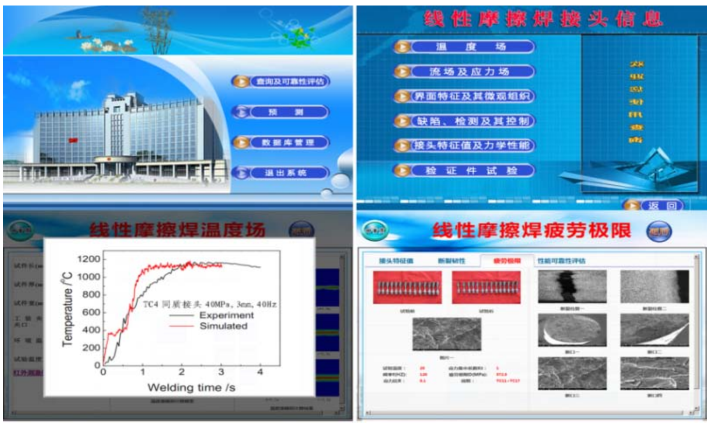


Figure 18. Reliability estimation system for friction welding.

2.3.2 Additive Manufacturing

The fatigue limit of TA15 laser forming exceeds 32-53% of forging titanium alloy and its creep rupture life increases 4 times. After special heat treatment, the bi-model microstructure is formed and crack propagation rate decreases by 1 order of magnitude[15]. The results are shown in figure 19.

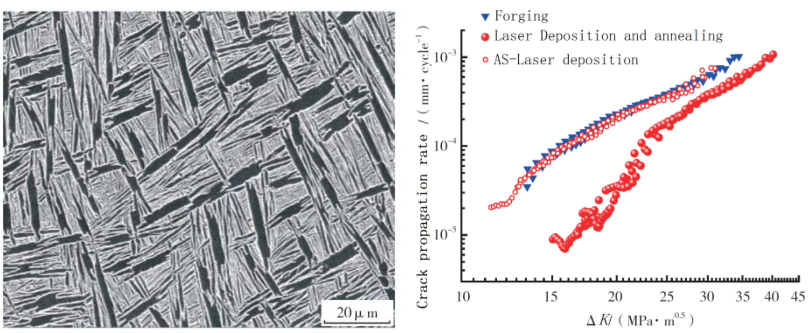


Figure 19. Microstructure and fracture property of TA15 by laser forming.

The fatigue limit of TA15 laser forming exceeds 32-53% of forging titanium alloy and its creep rupture life increases 4 times. After special heat treatment, the microstructure of TC4 titanium alloy manufactured by laser forming and electronic melting is typical lamellar microstructure which can increase the fracture properties, as shown in figure 20[16].

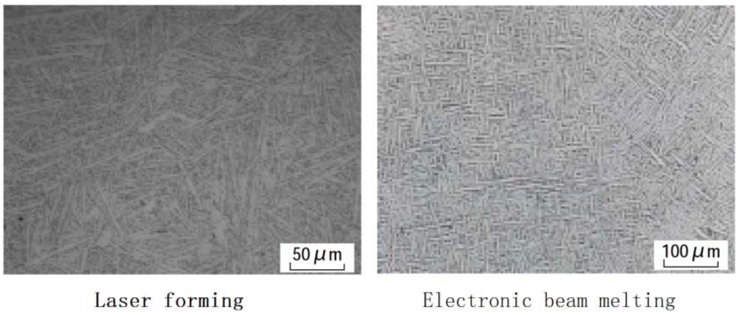


Figure 20. Microstructure of TC4 by laser forming and electronic melting.

The additive manufacturing technology has been used in the complex structure production and repair, as shown in figure 21, figure 22 and figure 23[15,17].

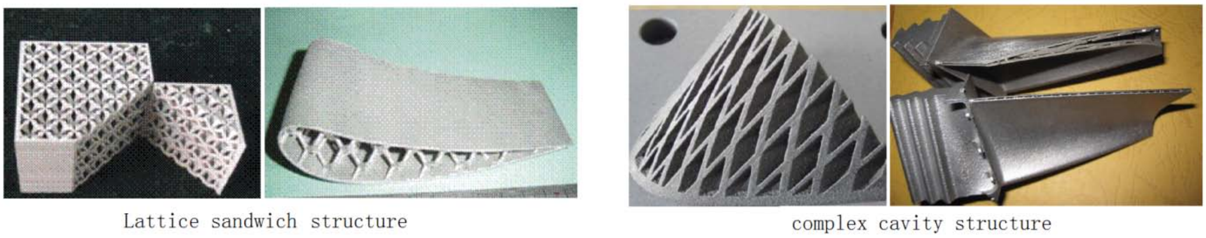


Figure 21. Complex structures by selective laser melting forming .

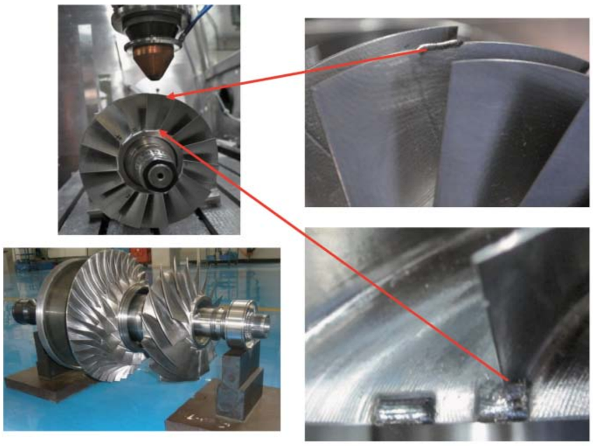


Figure 22. Damage repair of integral impeller by laser engineered net shaping.

Figure 23. Central Wing flange of C919 aircraft by laser forming.

2.4 Load spectrum compiling

In preliminary design phase, the aircraft loads are determined through theory calculation methods, which are corrected based on the measured force and pressure of wind tunnel tests in closed design phase and in detailed design phase. In design acceptance phase, the structural loads are obtained through the flight tests under real flying conditions. The relationship between the measured data and flight parameter is established by the method of parameter recognition[18].

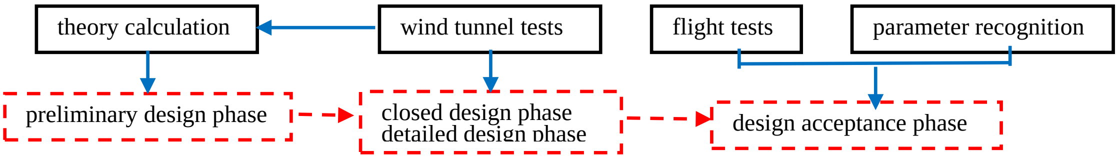


Figure 19. The loads acquiring approach for different phases of aircraft design.

1）Data processing of actual load

The measured data of test flight are processed and analyzed for the consistence, correlativity and repeatability. Then the effective data are obtained for load spectrum compiling. The effectiveness of test data is analyzed and the results are shown in figure 20.

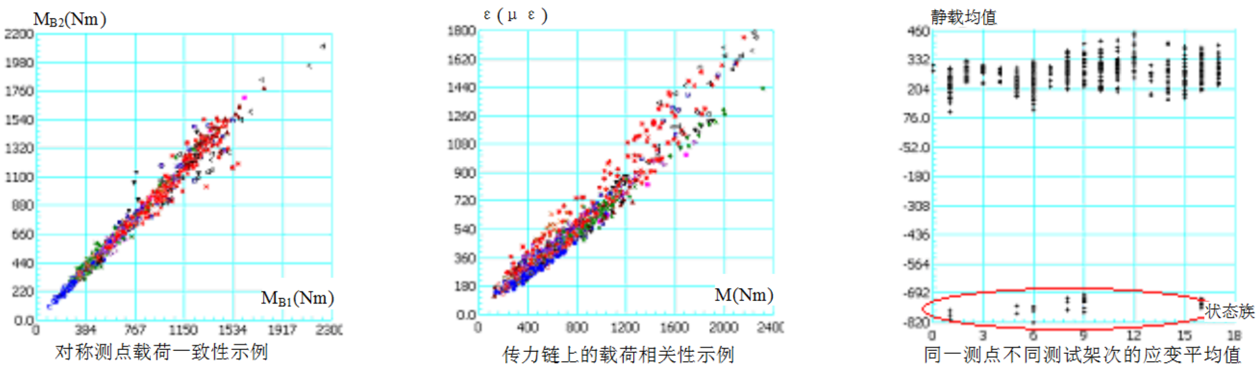


Figure 20. Effectiveness analysis of test data of flight load of rotor components.

2）Load spectrum compiling

According to the different types of aircraft, such as the transport aircraft and fighter, the corresponding spectrum compiling methods are studied. In recent years, the spectrum compiling method based on the flight simulation is obtained. Moreover, the dynamic response characteristics of flexible wing under external loads are fully considered in the process of spectrum compiling[19]. The technical flow chart of spectrum is shown in figure 21. Magnitude of load, frequency and sequence are the basic elements of load spectrum.

A typical aircraft load spectrum[20] is shown in figure 22.

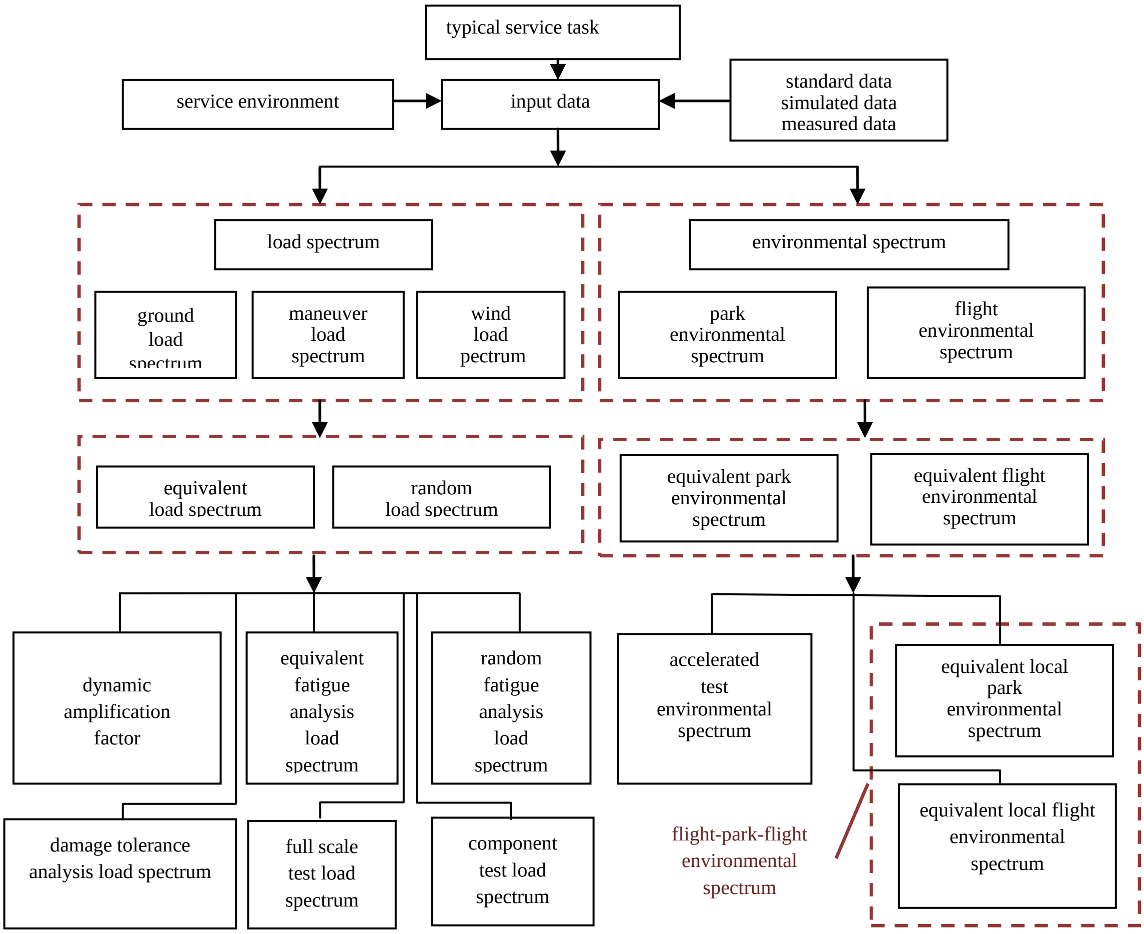


Figure 21. Technical flow chart of spectrum compiling.

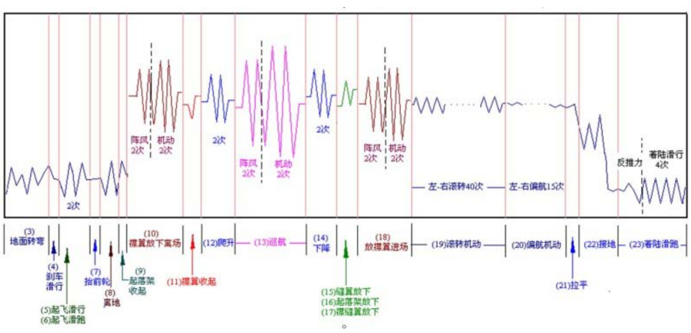


Figure 22. Typical aircraft load spectrum.

2.5 Durability and damage tolerance design, analysis and tests
2.5.1 fatigue analysis method

The analysis method system has been defined as COMAC Fatigue Quality (CFQ) which has been developed based on the experiences gathered from aviation industry and the large amount of coupon-level tests. This method is based on the well-established and general fatigue theory and supported by the large amounts of pyramids tests on coupons, components, sub-assembly parts, section-scale and full-scale aircraft with the statistical analysis of the test results.

The expression of CFQ SN curve can be written as:

$$N = \begin{cases} 10^5 \left(\frac{CFQ}{\sigma_{max}}\right)^{\beta} & \ldots \sigma_{max} > \sigma_{lim} \\ \emptyset & \ldots \sigma_{max} \le \sigma_{lim} \end{cases} \quad (1)$$

where N is the fatigue life; CFQ is the stress maximum the structure can endure under 10^5 load cycles; σ_{max} is the stress maximum of load spectrum; β is material constant; σ_{lim} is the fatigue limit.

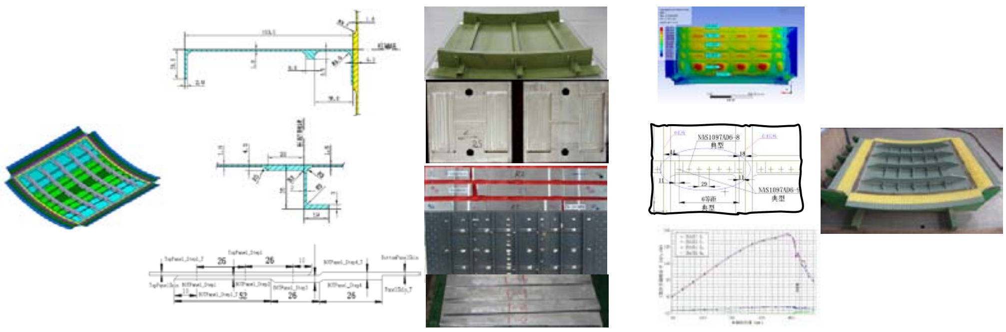
The frame work and core theory of CFQ have been done and the tests have carried out on 5 types of coupons[21]: low load transfer (LLT), middle load transfer(MLT), high load transfer (HLT), open hole (OH) and lug, as shown in figure 23.

Figure 23. Five kinds of fatigue specimens .

2.5.2 Design and analysis of integral structures

1）Design and detailed optimization of integral panel structures

We studied the new conceptual design method for full fuselage structure. Some key technologies, including new structure layout and configuration technologies and structural parameters integrated optimization technology, are formed via the building-block detailed design, analysis and verification optimization[22] (Figure 24).



Structure layout and configuration design

Detailed optimization, design and verification

Structural parameters integrated optimization

Figure 24. Design and detailed optimization of integral panel structure.

2）Optimization of integral fuselage panel based on detailed analysis technologies

We investigated the influence of material parameters and structural detailed design parameters on overall fatigue properties[23], and built the technology of fatigue sensitivity analysis for integral panel structure. This work benefits on realizing the optimization control, structural weight loss and rapid design analysis of overall aircraft performance.

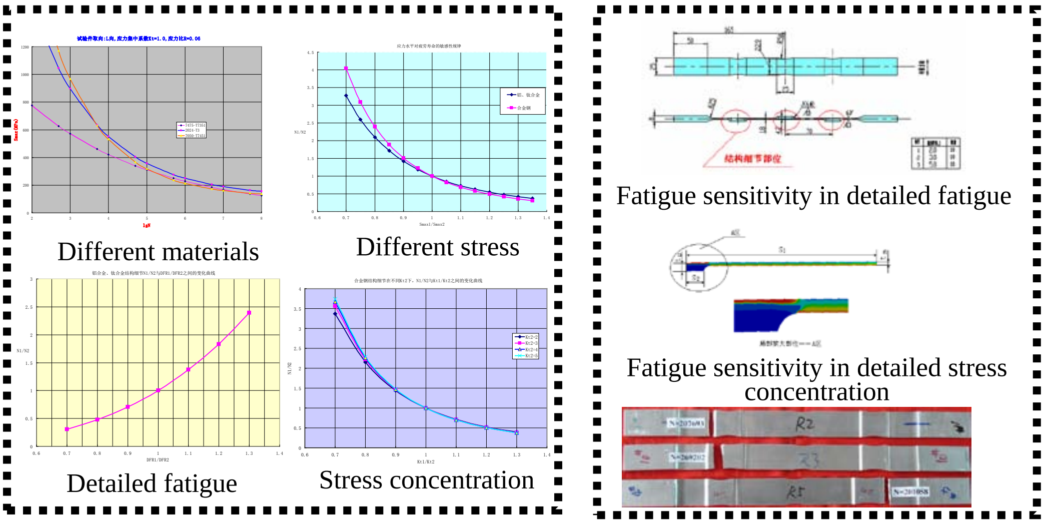


Figure 25. Fatigue sensitivity analysis of mechanical parameters.

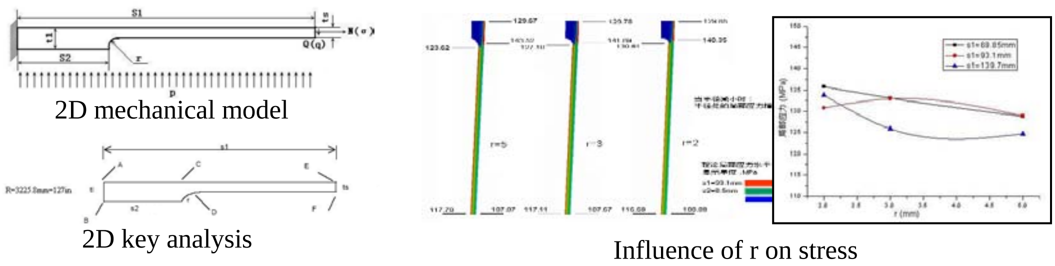


Figure 26. Fatigue sensitivity analyses of geometry parameters.

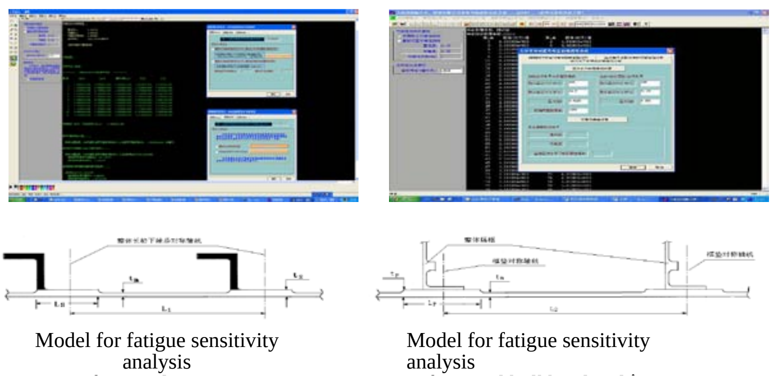
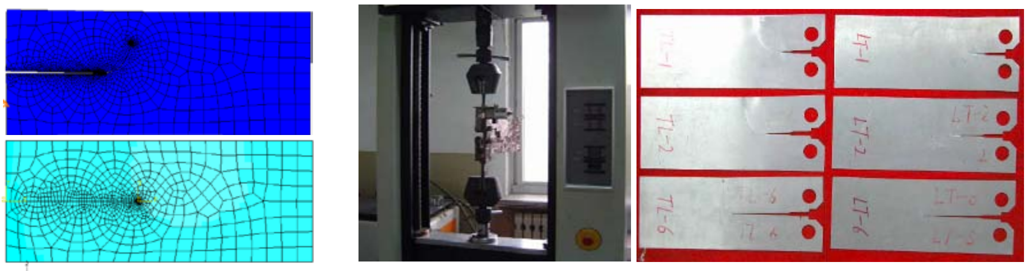


Figure 27. Sensibility analysis of fatigue life.

3）Crack turning and crack arrest technologies for integral fuselage panel structure

Conventional crack arrest methods and theories cannot work for integral panel due to its bad crack arrest property. Thus some new theories are needed in the analysis. Based on the 2-order crack turning theory, we adopted the analytical-experimental coupling technology to build a new crack arrest method, aiming at improving residual strength of integral panel[24]. The results are shown in figure 28, figure 29 and figure 30.



Crack turning simulation　　Verification of crack turning process

Figure 28. Crack turning analysis.

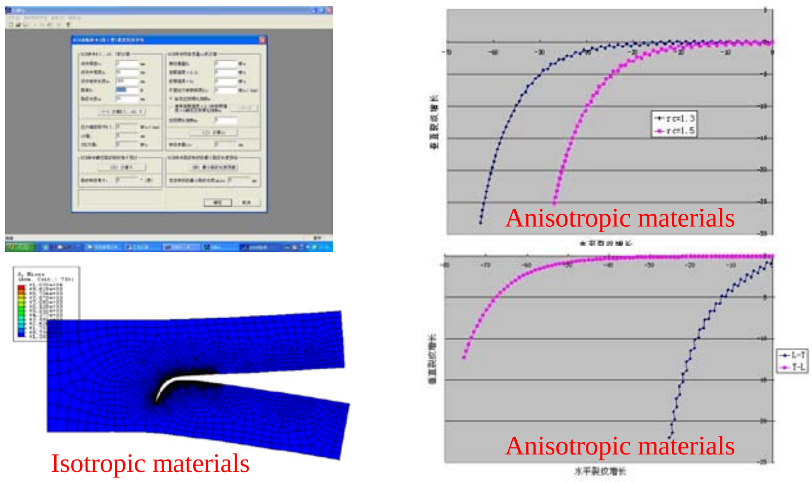
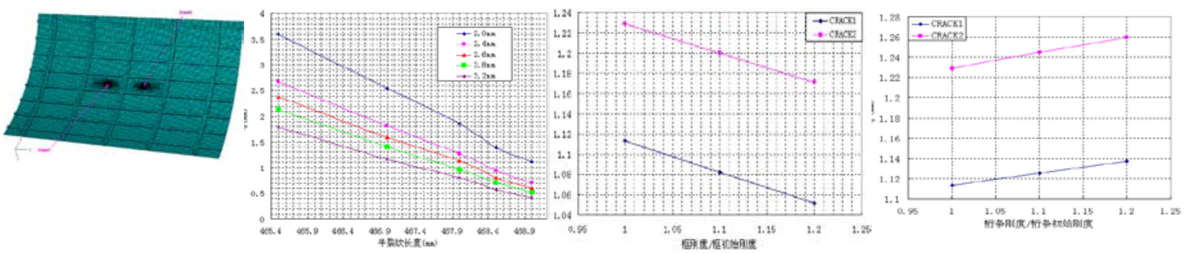


Figure 29. Prediction of crack turning path.



Influence of frame pad thickness On crack turning process　　Influence of frame stiffness On crack turning process　　Influence of stringer stiffness On crack turning process

Figure 30. Influences of structure parameters on crack turning process.

4）Structural integrity analysis, test and verification

The structural integrity is analyzed and verified following the static safety and fatigue/damage tolerance idea[22], as shown in figure 31. The tests are carried out according to the building-block verification idea, as shown in figure 32.

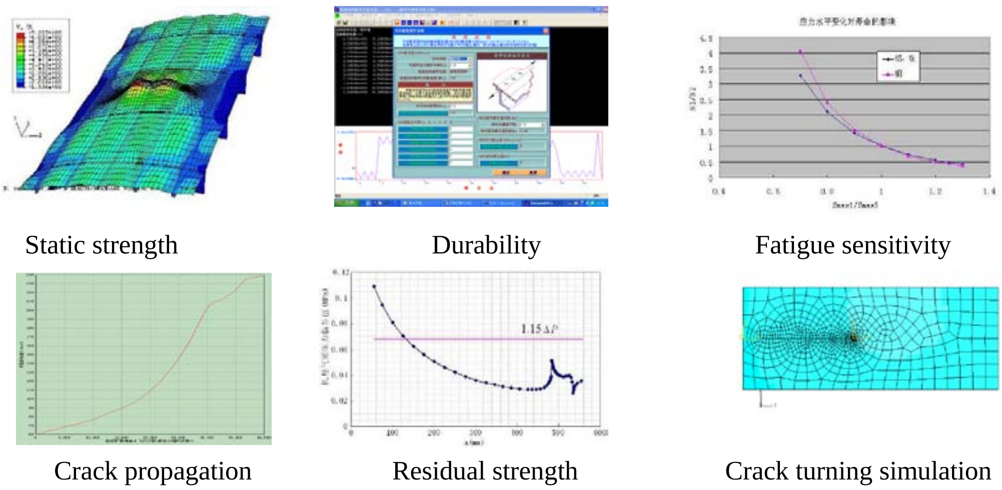


Figure 31. Structural integrity analysis of integral panel.

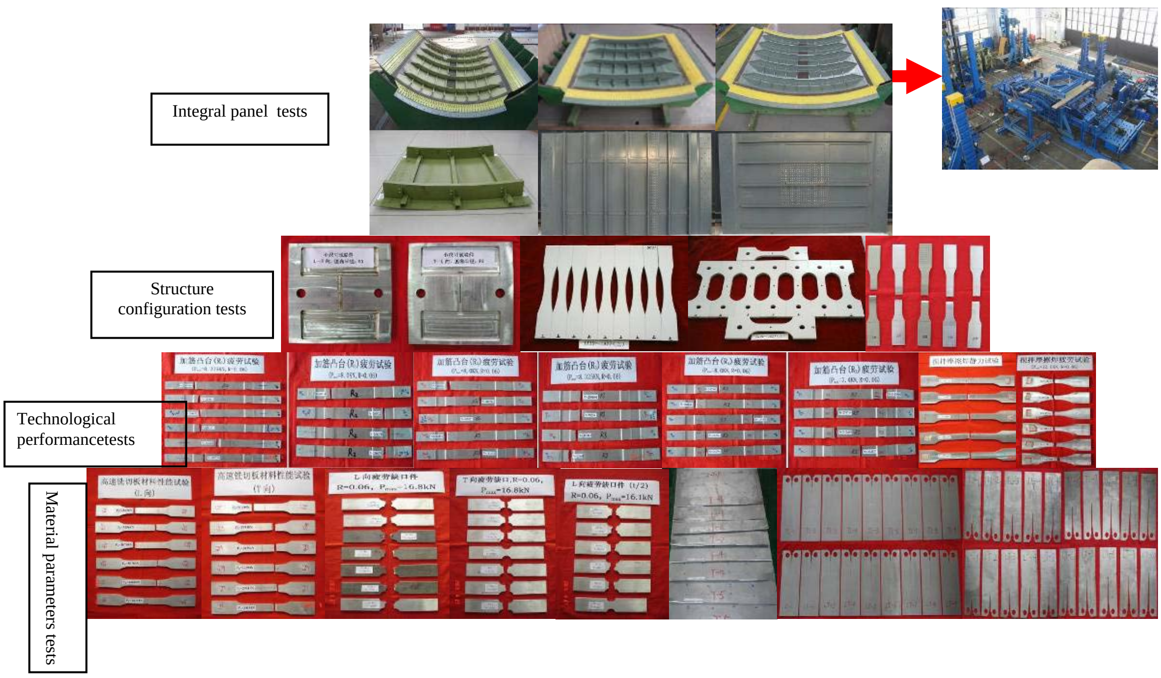


Figure 32. Structural integrity design and building-block verification of integral panels.

2.5.3 Technical research of accelerated fatigue life testing

1）Precise fatigue damage model based on damage mechanics

Based on the fatigue damage evolution equation by Lemaitre2005, we studied the effects of material hardening and mean strain on fatigue damage, and built a precise model suitable for arbitrary cyclic loading[24-27], written as

$$\frac{dD}{dN}=(\frac{R_v}{2ES})^s\frac{1}{(2s+1)H}\{[(\sigma_{s1}+H\Delta p_1)^{2s+1}-(\sigma_{s1})^{2s+1}]+[(\sigma_{s2}+H\Delta p_2)^{2s+1}-(\sigma_{s2})^{2s+1}]\}$$

$$\frac{dD}{dN_{\text{half1}}}=\begin{cases}0 & \text{if } \varepsilon_{p\max}\le 0\\ (\frac{R_v}{2ES})^s\frac{1}{(2s+1)H}((\sigma_{s1}+H\Delta p_1)^{2s+1}-(\sigma_{s1})^{2s+1}) & \text{if } \varepsilon_{p\min}\ge 0\\ \frac{\varepsilon_{p\max}}{\varepsilon_{p\max}-\varepsilon_{p\min}}(\frac{R_v}{2ES})^s\frac{1}{(2s+1)H}((\sigma_{s1}+H\Delta p_1)^{2s+1}-(\sigma_{s1})^{2s+1}) & \text{if } \varepsilon_{p\min}<0<\varepsilon_{p\max}\end{cases} \tag{2}$$

$$\frac{dD}{dN}=\frac{dD}{dN_{\text{half1}}}+\frac{dD}{dN_{\text{half2}}}$$

where D is the fatigue damage; N is the fatigue life; R_v is the triaxial stress function; E is the modulus of elasticity; S and s are the damage evolution parameters; H is the tangent modulus in the microcosmic scale; $\bullet_{s1}$ is the yield limit of the first branch of load cycle; $\bullet_{s2}$ is the yield limit of the second branch of load cycle; $\bullet\, p_1$ is the equivalent plastic strain increment of the first branch of load cycle; $\bullet\, p_2$ is the equivalent plastic strain increment of the second branch of load cycle; $\bullet_{pmax}$ is the maximum plastic strain; $\bullet_{pmin}$ is the minimum plastic strain.

2）Load spectra simplification of equivalent damage

We established a method for load spectra simplification based on the equivalent damage principle[28]. The test results of 45°lugs structure illustrate that: when the load spectra are simplified as constant spectra, the number of loading cycles is merely 26.1% of that on program block spectra. This conclusion implies that the fatigue test time can be shorten by 73.9% for accomplishing the same life (or producing same damage).

Figure 33. 45°lugs structure test.

The rapid damage method on load spectra enhancement is based on the standard S-N curve equation [29]. When the stress S_{ai} is changed to S_{aj} (in elasticity) using the enhancing load spectra, the rapid damage method based on the standard *S-N* equation is described by:

$$\frac{N_j}{N_i}=\left(\frac{S_{aj}}{S_{ai}}\right)^B \qquad B=\frac{\lg N_1-\lg N_2}{\lg S_{a1}-\lg S_{a2}} \tag{3}$$

where N is the fatigue life; S_a is the stress amplitude.

The rapid damage method is:

$$\frac{N_j}{N_i}=K^{B_m} \qquad K=\left[\frac{S_{aj}(S_{m0}-S_{mi})}{S_{ai}(S_{m0}-S_{mj})}\right] \tag{4}$$

where N is the fatigue life; S_a is the stress amplitude, S_m is the mean stress, S_{m0} is a stress constant.

3）Effects of load spectra simplification on crack growth life

(1) Effects of spectra truncation of low loads on crack growth life

Different to the conventional spectra truncation method (load is omitted when damage is smaller than 10-7), we deleted the spectra once their stress amplitudes are10% lower than the maximum stress. The effects of overload and low loads on crack growth are obtained [30].

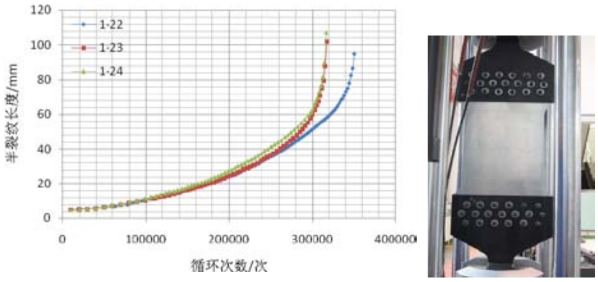


Figure 34. Test results on load spectra with truncation of lower loads and verification.

(2)   Effects of load spectra simplification (RMS algorithm) on crack growth life

We adopted the RMS algorithm to substitute constant spectra loading for random spectral amplitude loading, and calculated the crack growth life on random spectra loading. Crack growth rate formula based on constant spectra loading is used in the calculation. The results show a good agreement [31]. Although load cycles have not been reduced, the simplification by RMS algorithm improves the experimental loading frequency and accuracy.

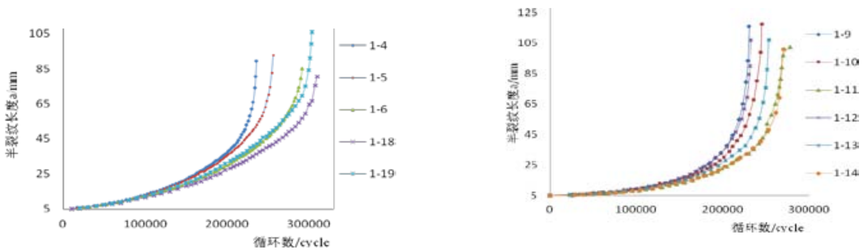
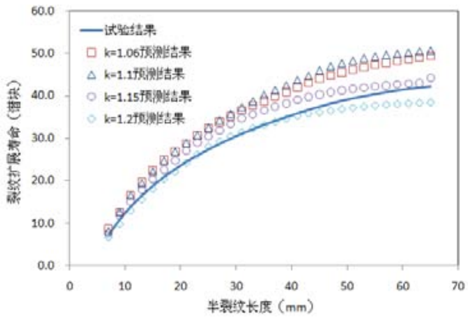


Figure 35. Test results for test piece MT W400.

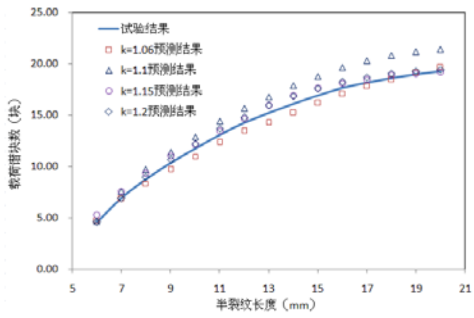
(3)   Influence of load spectra enhancement on crack growth life and experimental verification
Considering retardation effect, we use the crack growth model on random load spectra, and obtain the relation between the numbers of load cycles before & after enhancement .[31-33]:

$$\frac{a}{b} = k^{-n} \tag{5}$$

where a is the fatigue life after load enhancement; b is the fatigue life before load enhancement; k is the load-enhancement factor; n is a material constant.



(a)



(b)

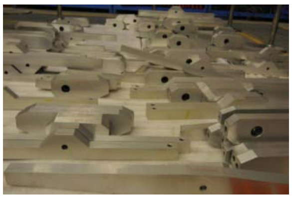
Figure 36. Comparison of the results of numerical simulation and experiment for test pieces (a)MT W400 (b)and MT W70.

Figure 36 shows that error approximations for test pieces MT W400 and MT W70 are respectively smaller than 23% and 17%. In general, the predictions on load spectra enhancement on k=1.15 and k=1.2 are closer to experimental results.

2.5.4 Efficient test and damage-detection technologies

1）Test design and implementation

The lightweight lever system is designed to exert the proportional load. The pull-compress pad and vacuum chuck[34] are used to improve the test efficiency, as shown in figure 37.


lightweight lever system


pull-compress pad

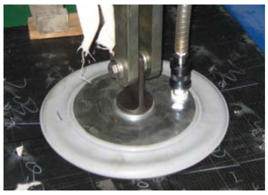
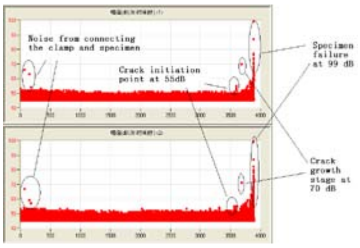

vacuum chuck

Figure 37. The efficient test equipments.

2）NDT(Non-destructive testing)

We designed and produced the test pieces to study the monitoring technology by acoustic emission for fatigue crack initiation. We can well predict the crack initiation through the real-time history of amplitude, as shown in figure 38.



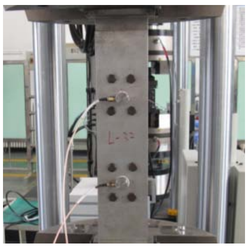


Figure 38. Typical structure tests by acoustic emission.

we can directly obtain the crack states of the monitored points by measuring their resistances using the ICMS (Intelligent Coating crack Monitoring System), as shown in figure 39.

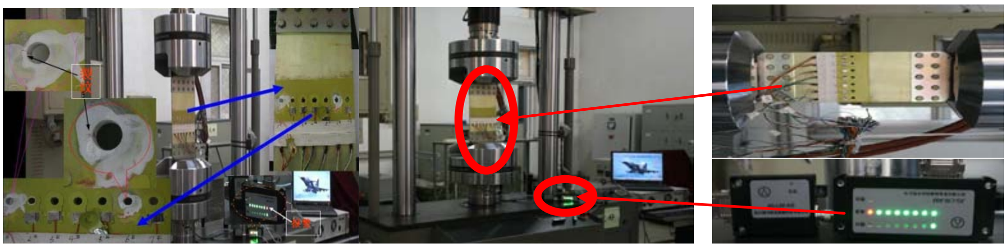


Figure 39. Components tests and second-generation airborne monitoring system .

The ultrasonic C-scan, infrared thermal imaging and ultrasonic phased array techniques are also used in the damage detection of aircraft structures, as shown in figure 40, figure 41 and figure 42.

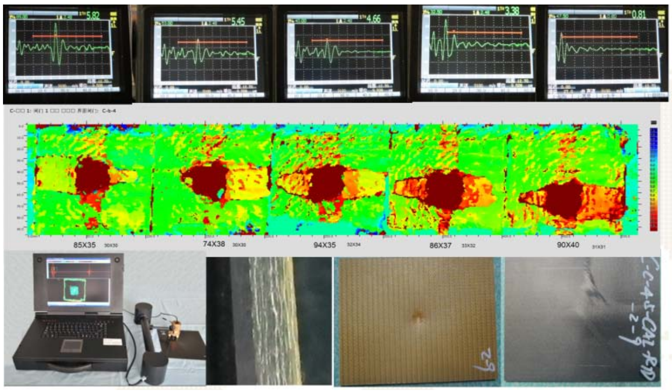


Figure 40. Non-destructive testing of absorbing structure using ultrasonic C-scan technique.

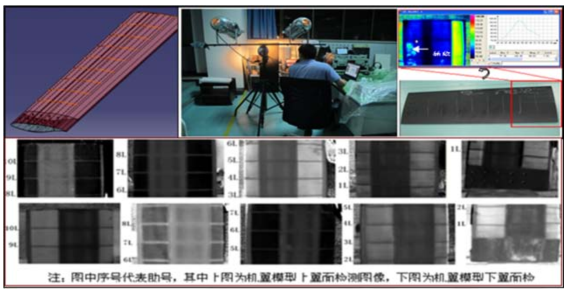


Figure 41. Infrared thermal imaging for complex structures(C919 wing).

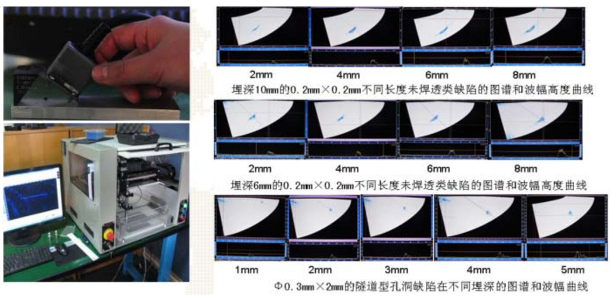


Figure 42. Ultrasonic phased array inspection for friction welding joints.

2.6 The key research techniques

2.6.1 WFD(widespread fatigue damage)

1）SIF(stress intensity factor) calculation[35]

The SIF is calculated by FEM and engineering method considering the interference effect of multi-cracks, such as the combined method and the repeating method. The results are shown in figure 43.

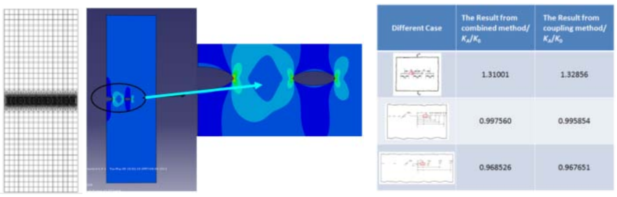


Figure 43. SIF results obtained by FEM and engineering method.

A random model for multi-cracks growth prediction is established, written as

$$\frac{da_i}{dt} = X_{0i}\alpha_i S_{maxi}^{\gamma_i} F_i^{\gamma_i}(a_i, \ldots, a_n) a_i^{b_i} \qquad i = 1, \ldots, n \tag{6}$$

where a_i is the ith crack length; n is the number of cracks; F_i is the interaction factor; • $_i$ is the growth factor of the ith crack; S_{maxi} is the stress level for the ith crack; X_{0i} is the random variable which controls the growth of the ith crack.

2）Fatigue and crack growth of WFD structures[36]

The relationship between fatigue properties and the number of structure details is studied. The reliability life of WFD structures is predicted and the performance of multi-cracks growth is obtained. The results are shown in figure 44.

Figure 44. Fatigue and crack propagation of WFD structures.

3）MSD tests

The research of multi-site damage (MSD) on typical wing panel and typical fuselage panel has been done, as shown in figure 45. The research focuses on the crack initiation and growth of MSD and failure criterion of MSD on both wing panel and fuselage panel.

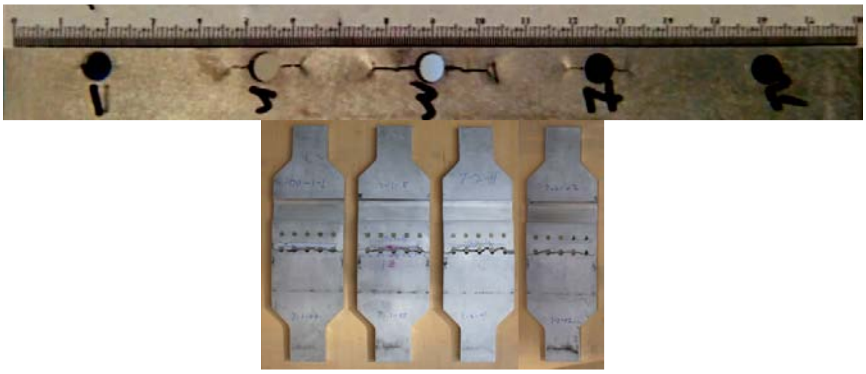


Figure 45. MSD test coupons.

4）WFD research on real aircraft structures[37]

In order to verify the estimation method, various WFD structures are tested, including fuselage plate, oil-draining-hole panel and full scale aircraft structures, as shown in figure 46, figure 47 and figure 48.

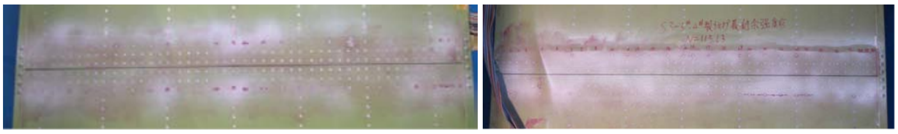


Figure 46. Fuselage plate specimen for WFD test.

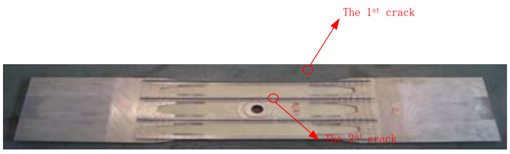


Figure 47. The locations of cracks initiation of oil-draining-hole panel.

Figure 48. WFD of Y8 full scale fatigue tests.

2.6.2 Corrosion fatigue

The corrosion fatigue mechanisms include four forms, i.e., pitting corrosion, local deformation, hydrogen embrittlemen and adsorption, among which the pitting corrosion is the mainly responsible for the aircraft structure corrosion. Moreover, the prediction models for corrosion fatigue life are studied, including probabilistic model, analytical probabilistic model, Neural Network Model and particle swarm optimization model[38].

Under two kinds of action of “corrosion/fatigue” and “fatigue/corrosion/fatigue”, the effect on fatigue characteristic and fracture mechanics discrepancy of specimens are analyzed under the conditions of several temperatures and different durations [39] .

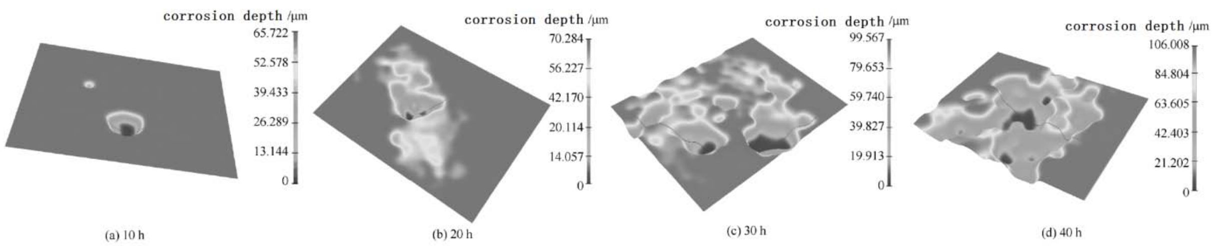


Figure 49. Corrosion damage feature metallograph of LY12-CZ at different corrosion time.

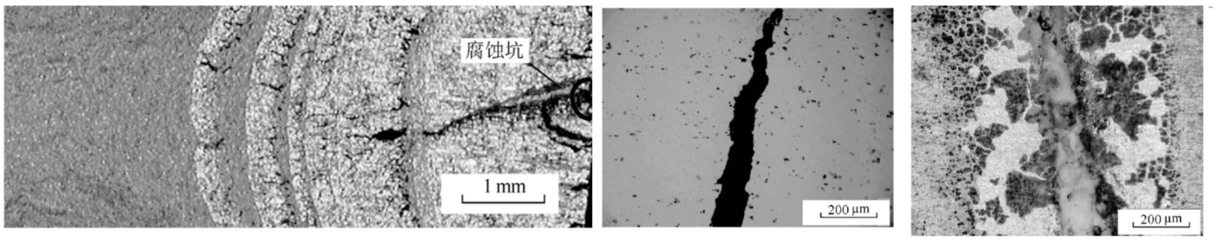


Figure 50. Corrosion crack initiation, propagation and passivating of LY12-CZ.

The relationship function between corrosion grade and fatigue limit was obtained for LD2 aluminum alloy. The relationship between fatigue limit and the service calendar year of LD2 material was established[40].

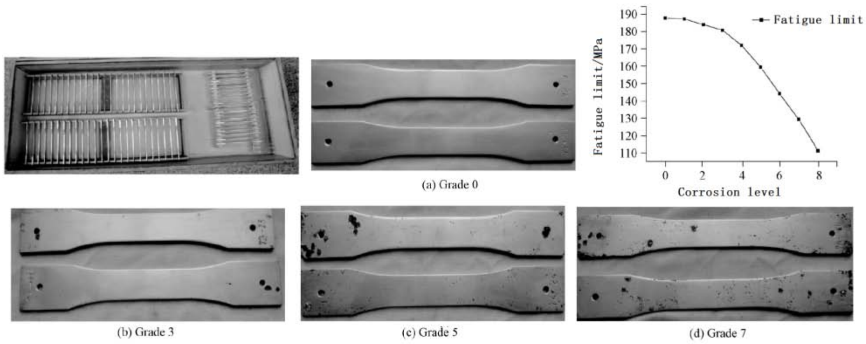


Figure 51. The corrosion surface of LD2 specimen at different corrosion levels.

Corrosion fatigue lifves of aircraft structures are evaluated and the crack growth in corrosion environment is analyzed. Practical components, such as bolts, lugs and connections, are tested in corrosion environment to verify the estimation method, shown in figure 52[41-45].

Figure 52. Corrosion fatigue verification of aircraft structures.

The corrosion-fatigue test techniques of lap jointed structure were studied from the aspects of specimen design, fatigue load spectrum and load mode, typical corrosion environment, and the test data processing principle, as shown in figure 53[43].

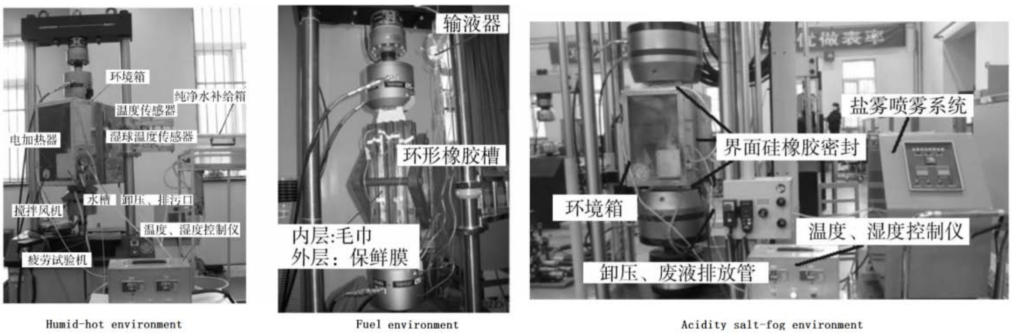


Figure 53. Corrosion fatigue tests of lap jointed structures at humid-hot, fuel and acidity salt-fog environment.

3. RESEARCH AND APPLICATIONS OF FATIGUE AND STRUCTURAL INTEGRITY

3.1 Applications in new aircraft types

In the design stage, new materials, new structures and new process research are conducted considering the fatigue spectrum, structural fatigue, damage tolerance material selection and structural design, etc. The key fatigue parts are tested including coupons, typical structures, demonstrative parts and full size aircrafts. In the production stage, the manufacturing process is strictly controlled to ensure the fatigue and damage tolerance characteristics of aircrafts. Reasonable use and maintenance documents are made. Meanwhile, the service situation of airplanes is monitored and the problems appeared during the service process are solved in time to ensure the plane safety of the whole life.

3.1.1 ARJ21-700 aircraft

In the design phase of ARJ21-700 aircraft, the guidelines are established, realizing the theory load spectrum compiling and the real load spectrum measurement. The fatigue/damage tolerance design requirements are considered following the fatigue/fracture analysis methods. Moreover, the WFD problems are also taken into account. Fatigue/damage tolerance tests are conducted to verify the analysis methods. In flight test phase, the fatigue lives are further analyzed based on the measured real load spectrum. Based on this, the full scale fatigue test is operated.

Strength test on structure components focuses on verifying the forms and analytical approaches. Based on the structural integrity programs and building-block design concept, they use non-standard testing methodologies to work on critical structure[46].

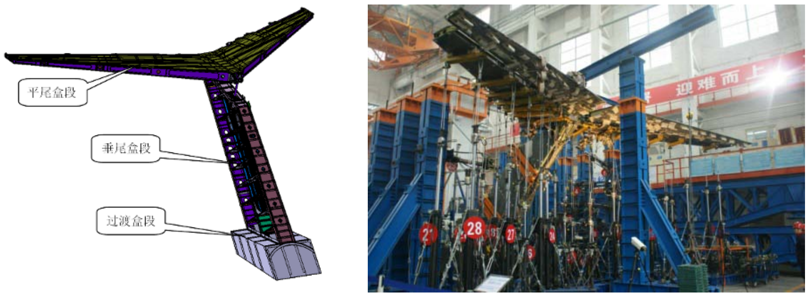


Figure 54. Empennage testing for ARJ21-700 aircraft.

We applied push-compress pad technology in the fatigue reliability test on flap motion mechanism for ARJ21-700 aircraft. This application simplifies the following load spectra in motion mechanism and shortens loading time by 51%[47].

Figure 55. Fatigue reliability test of flap motion mechanism for ARJ21-700 aircraft.

Recently, we applied the entire integration framework to design loading system, as shown in Figure 56, 57. Figure 56 shows the application of vertical plane loading technology in loading design. Combining detail analysis and experiments, it adopts virtual testing method and physical experiment. Figure 57 shows the Full-scale static and fatigue test for ARJ21aircraft.

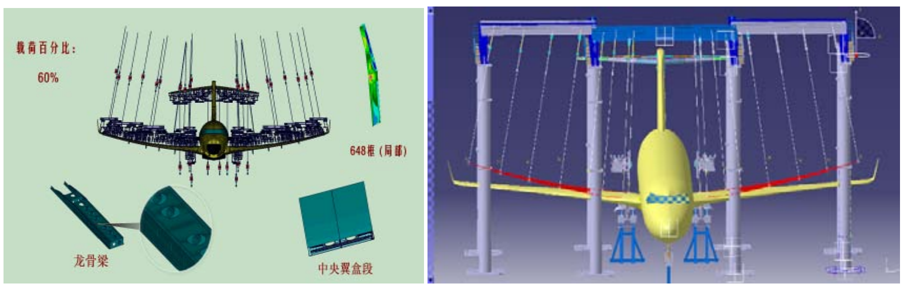


Figure 56. Vertical plane loading technology.

Figure 57. Integration frame loading system of full-scale static and fatigue test for ARJ21-700 aircraft.

3.1.2 C919 Aircraft

The following results are obtained via strength test for Aircraft C919:

1）Structural static strength analysis handbook

2）Fatigue assessment systems for metallic structure

(1) Typical flight mission profiles and load spectra

(2) Fatigue assessment methods for structure details

(3) Detailed fatigue characteristics test system

(4) Structure repair program for C919 large passenger aircraft

(5) Strength tests for new materials and typical structures

Figure 58. Fatigue and damage tolerance test on fuselage panel for civil aircraft.

Figure 59. Static/fatigue test on fuselage segments for civil aircraft(airtight loading on positive and negative pressure).

3.1.3 Helicopters(Z15/EC175)[48]

1）Design concept

In the process of developing Z-15 and AC313, the analysis and verification of static structural strength and fatigue strength are carried out simultaneously. Meanwhile, the design concept of damage tolerance is introduced. The impacts of defects and environment on structural fatigue are studied. The design concept is shifted from “safety life” to “damage tolerance”, and it is applied to model design.

Figure 60. Z-15 and AC313.

2）Design for fatigue for rotor system

The design and verification of fatigue and damage tolerance are one of the key technologies in developing helicopter rotor system. The rotor system design flow chart is shown in figure 61.

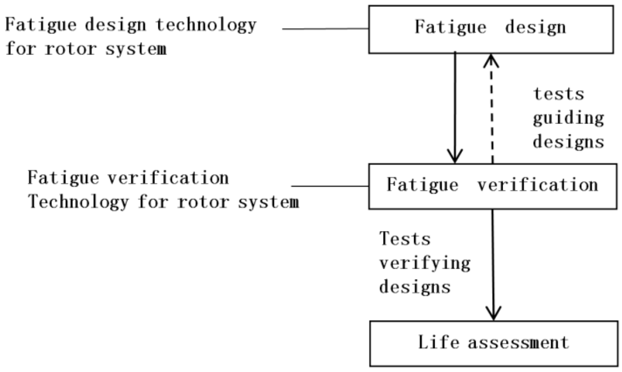


Figure 61. Flow chart for rotor system fatigue design.

3）Verification of structural defect tolerance

The impacts of environment, the internal crack and (or) scattering crack or accidental injuries are considered in structural fatigue design and in verifying the structural defect tolerance. The defect tolerance test of helicopter blade is shown in figure 62.

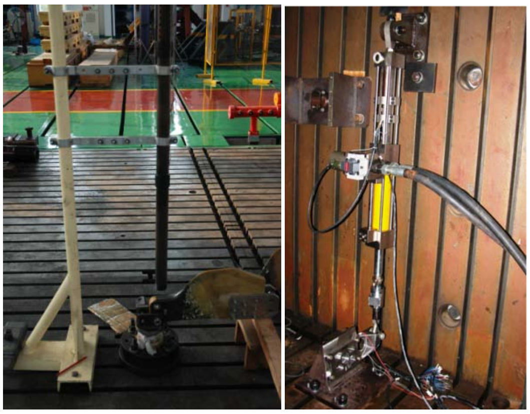


Figure 62. Defect tolerance test of helicopter blade.

4）Lightning damage verification of the rotors

Lightning strokes cause injuries to structures of the composite materials such as the main and tail rotors. Fatigue test of blades with lightning damage verifies that the structures stoked by lightning have the capacity to return safely. The lightning damage of blades is shown in figure 63.

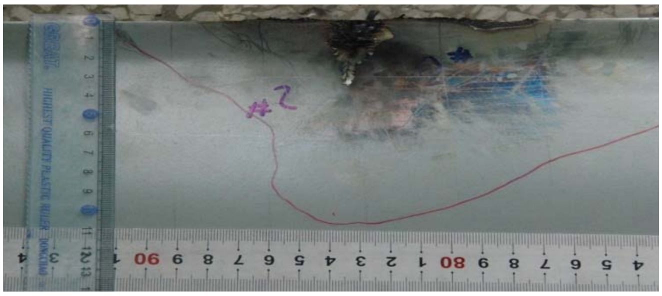


Figure 63. Lightning damage of blades.

5）The fatigue design for airframe structures

The fatigue tests with design target life are conducted successfully for the integrated fuselage structure and structural inspection period test is operated after local repair.

Figure 64. Middle airframe strength test.

6）Fatigue test for empennage and horizontal tail

The effects of initial defects, impact damage and environment factors are considered in the fatigue tests of composite empennage.

Figure 65. Static fatigue tests on empennage and horizontal tail for EC175/Z15 aircraft.

3.2 Applications in the life extension for aging aircrafts [49]

Through innovation of the spectrum compiling, comprehensive applications of crack diagnosis method, durability estimation, repair technology and the development of single plane monitoring technology, the fatigue life determination and extension for a certain type of aircraft is accomplished and the service lives of air fleet are successfully extended. The key technology in fatigue life determination is listed as follows.

The representative take-off and landing is selected through comprehensive consideration of outfield aircraft damage. In the spectrum compiling, the data from thousands of outfield take-off and landing is counted besides the measured take-off and landing for a given flight profile. The compiled random load spectrum reflects the real service situation of aircraft for the representative take-off and landing is determined based on large sample data.

Comprehensive crack diagnosis method is adopted in the tests to continuously trace the process of crack initiation and propagation. The techniques are listed as follows.

1）Acoustic emission
2）Random monitoring visual inspection
3）Endoscope
4）Radiograph
5）Eddy current testing
6）Keeping pressure inspection

The single aircraft damage degree is calculated through the gravity overload statistics of every aircraft and the residual life is determined. According to the damage and the aircraft characteristics, the corresponding single aircraft monitoring program is provided. For the aircraft with serious damage, the flight tasks are limited or the aircraft is overhauled in advance. For the aircraft with lighter damage, the service life is extended according to the specific circumstances.

Using the durability repair idea, the key parts are repaired in time once it has problems and safety is achieved. In order to guide the full scale fatigue test, the typical structures of key parts are tested for durability estimation in advance. The economic lives of key parts are evaluated through relative spectrum tests and typical structure tests. The economic repair plans are created, including repair times, the repair period, the repair items, repair requirements and repair methods.

4. PERSPECTIVES

1）Structural health monitoring

The main research idea for structural health monitoring is that data is obtained through the sensors attached on the structures and the information transmission systems, then, the real-time monitoring of structural health is realized and the damage is detected and determined using the corresponding analysis software.

By means of Structural health monitoring and sensor, structural health monitoring is successfully applied in various strength tests. However, a lot of research should be done before the practical application in flight.
2）FSI research for new materials, new process, and new structures [50-52]

This research emphasizes on composite structures, aero-engine material, friction welding, electron beam welding, laser welding, additive manufacture, integrated structures and smart structures.
3）Advanced fatigue/damage tolerance analysis and assessment technologies

We will perform the research on fatigue and integrity assessment technology based on new material, new manufacturing technique and new structures to provide corresponding analysis method and software.
4）Durability design technology in integrated environment

Based on the fatigue tests and the environmental tests of components and sub-structures, the influence of comprehensive environment on full-scale structures are emphasized in the future research, including low pressure, high/low temperature, temperature shock, acceleration, impact, vibration, hot humid environment, mold, solar radiation, rain, sand and dust, ice and freezing, etc [53]. Thus, a lot of theory research and verification work have been conducted. Moreover, we are establishing the environmental worthiness laboratory to satisfy the requirements of large civil aircrafts.

5. CONCLUSIONS

China's aviation industry faces a huge market requirement and has good prospects of development. The key problem is that the products reach the first level to meet the airworthiness requirements and the quality high enough to satisfy the international customers. Therefore, China aviation pays great attention to the fatigue/damage tolerance integrity research of aircraft structures. They try hard to put the scientific research achievements into the aircraft products being developed, especially for the whole life circle research of civil aircrafts, which provides products with first class quality and ensures the flight safety and reliability. In the premise of safety, we extend the service lives of aging aircrafts. The research on new fatigue/damage tolerance theory and practice for the new materials, new process and new structures create foundation for the development of future aircrafts.

For the first time to participate in the ICAF conference, we introduced China aviation industry status in the FSI. Meanwhile, we expect to study the progress of international structure fatigue integrity technology. China's aviation industry expects to carry out academic exchanges and cooperation with global partners and to promote the progress of aviation development jointly.

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