RIGID LOADING ACCELERATES FULL-SCALE AIRCRAFT FATIGUE TEST

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Abstract: The fatigue test of full-scale aircraft structures is a time-consuming and laborious long-term work, the purpose of which is mainly to verify whether the aircraft structure meets the requirements of WFD, to verify the fatigue characteristics of the airframe structure, and to provide a test basis for the development of structural damage detection methods and repair plans. It is the eternal goal of the test team to improve the fatigue test efficiency under the premise of ensuring test safety and loading accuracy. In this paper, we summarize the technical advances of using tension pad-lever system in full-scale aircraft structural fatigue test, and integrate these technologies into C919 full-scale aircraft structural fatigue test and C919 aircraft vertical tail/rear fuselage full-scale static, fatigue and damage tolerance test. The application verification shows that the rigid loading system runs normally, is stable and reliable in long-term use, has good control accuracy, and the test efficiency is significantly improved compared with previous. The successful application of these technologies provides an important reference and support for subsequent fatigue tests of other aircrafts.

Keywords: Full-scale Aircraft, Fatigue Test, Rigid Loading, Tension Pad-Lever System, Test acceleration

INTRODUCTION

The full-scale aircraft fatigue test is a top-level compliance verification test using typical fatigue load spectra to verify whether the design, manufacturing and maintenance of the aircraft can meet the requirements of the airworthiness regulations, covering all aspects of materials, design, manufacturing and assembly processes and the use environment. The test results are the fundamental basis for verifying the design conformity and manufacturing conformity of the overall structural fatigue design of the aircraft, as well as the basis for modifying the type design, formulating maintenance plans, determining the service life of the aircraft, ensuring the operational safety of the in-service fleet and carrying out life extension work.

The guiding ideology of structural fatigue has gone through the design stage based on safe life, design stage based on fatigue damage tolerance, and developed to the latest design stage based on widespread fatigue damage, and the design ideas adopted for different structural parts are different. For example, the landing gear of the aircraft still adopts the safety life design idea due to its single force transmission characteristics and the material characteristics of high strength steel, while the fuselage skin, frame, buttress sheet and other parts have adopted the widespread fatigue design idea due to their multiple force transmission characteristics.

The C919 aircraft is a large civil airliner designed and verified by COMAC in strict accordance with the China Transport Airworthiness Standards (CCAR25-R3)[1], of which Article` 25.571 sets clear requirements for damage tolerance and fatigue assessment of the structure. Adequate full-scale fatigue test basis must be used to demonstrate that no widespread fatigue damage will occur during the design life of the aircraft. A type certificate may be issued prior to completion of the full-scale fatigue test provided that the airworthiness authority has approved a plan to complete the required test. And in the airworthiness limitations section of the continuing airworthiness document required by section 25.1529 of this Part, it is stated that the number of cycles in use of any aircraft prior to the completion of that test shall not exceed half of the number of cycles accumulated on the fatigue test piece. For a newly designed aircraft, the most direct way to demonstrate compliance is to perform a full-scale structural fatigue test.

The No. 2 test aircraft of C919 was delivered to the Shanghai Test Base of the Aircraft Strength Research Institute of China (ASRI) in March 2019 to carry out 3 times life time fatigue tests for a total of 144,000 cycles, mainly to verify whether the aircraft structure meets the requirements of WFD, to verify the fatigue characteristics of the airframe structure, and to provide a test basis for the development of structural damage detection methods and repair plans. Modern aircraft development usually adopts the idea of building block design verification [2], as the top of this verification system, the fatigue test of the full-scale aircraft structure is of great significance to the type of development compliance and operation and maintenance.

Conducting a full-scale structural fatigue test requires a comprehensive large-scale project integrating multiple disciplines such as digital design [3-6], loading[7], control[8], measurement[9], analysis [10], hydraulics, non-destructive, health monitoring[11-13], quality management, virtual testing[14], and decision assistance[15]. After years of accumulation and development, ASRI has made technical and management innovations in various aspects, which make the current full aircraft static test more accurate, safer, and more reliable.

This paper briefly analyzes the need for fatigue acceleration of full-scale aircraft structures, and summarizes the technological advances of the Tension Pad-Lever system applicable to the loading of wing/nose/tail sections. The advances and reliability of the described new technology is demonstrated by two full-scale structural fatigue tests on the C919 aircraft.

FULL-SCALE AIRCRAFT STRUCTURE FATIGUE ACCELERARTION NEEDS

Efficient development of aircraft implies the need for fatigue acceleration

To provide a test basis for setting the effectiveness limits (LOV) of aircraft structures and structural change points of certain WFD-sensitive structures; to verify the fatigue characteristics of the main force members of the airframe structure and provide a test basis for determining the inspection threshold value of the airframe structure; to verify the detection method of structural cracks and the applicable repair plan in the structural repair manual and provide a test basis for setting the maintenance outline of the aircraft structure; to verify the fatigue analysis method. For the composite structure indicating the measures of conformity, 2 times life fatigue test needs to be completed before TC, thus putting forward higher requirements on test efficiency.

Economy is the long-term pursuit of R&D

Full-scale aircraft structural fatigue tests require a large amount of space, equipment and human resources, and these resources consume project costs all the time. Early completion of the tests can save a lot of R&D expenses, which brings great benefits to the economy of aircraft development.

Technology comparison shows great potential for fatigue acceleration

A comparison of publicly available information shows that most of the airplanes developed by Airbus adopt sectional test scheme, and the fatigue test time is generally shorter. The A400M full-scale aircraft fatigue test takes 36 months to complete 2.5 times fatigue life. Boeing's airplanes generally use full-aircraft structural fatigue testing, with a slightly longer total test period. Most of the aircraft developed by China also adopt the full-aircraft test program, and the total test period is the longest, with the ARJ21-700 aircraft taking 96 months to complete 2 times the fatigue life. Data comparison shows that there is still a long way to go to speed up the full aircraft fatigue test.

OPTIMIZED DESIGN OF TENSION PAD-LEVER LOADING SYSTEM

Research Background

Conducting a ground strength test of a full-scale aircraft structure requires accurate simulation of aircraft loads by external loading. For the parts subjected to distributed aerodynamic loads, such as wing surfaces, the aerodynamic loads need to be discretized into finite element loads first, and then continue to be discretized to the parts where they can be applied, such as the intersection of beams and ribs, under the condition that the total load in the key sections is consistent. The commonly used load transfer methods include adhesive tape-lever system, tension pad - lever system, cardboard loading system, etc. Among them, the tension pad-lever system has become the preferred loading method for fatigue testing of full-scale structures because of its advantages of applying tension and compression loads in both directions, high reliability, high load transfer efficiency, and long-term use in one installation.

In the previous research, systematic studies have been carried out on the selection of the tension pad material, the tension pad adhesion/removal process, and the selection of the lever system, and the application has been carried out in an aircraft, but the problems of insufficient durability of the tension pad material, insufficient tension pad adhesion, and suboptimal lever system design have been exposed in use, so a series of technical studies have been carried out to solve the above problems.

Optimized design and analysis of tension pads

As a load transfer node, the tension pad is composed of a tension block, an aluminum plate and a joint in order from the surface of the test piece. Strong glue is used to bond the tension block to the test piece and the aluminum plate, and bolts are used to connect the aluminum plate to the joint. The tensile pad is made of polyurethane (Shore hardness 80A), and the surface of the test piece is attached to the test piece according to the shape of the test piece, and the other side is flat and attached to the aluminum plate.

In order to simplify the calculation, the design analysis converts the paste area into 80mm×120mm standard parts, the allowable load of the standard parts in the pull direction does not exceed 1700N, the pressure direction does not exceed 3000N, and the safety factor is greater than 4. The form of positive tensile load and 45° shear load are selected for the overall modeling analysis, and the results show that the stress of the aluminum plate is small, and the maximum stress of the tensile loaded tensile block is 0.34MPa. The maximum stress of the shear loaded tensile block is 0.18MPa, which is much smaller than the theoretical damage stress of 35MPa of polyurethane material and meets the safety margin requirement. The analysis results are shown in Figure 1.

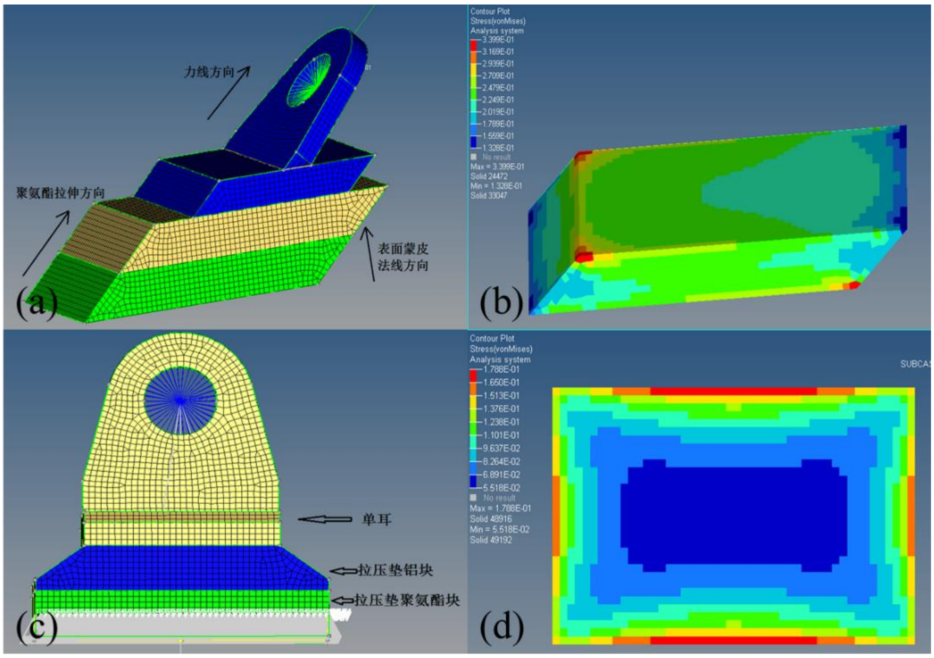

Fig. 1: Stress analysis of tension block ((a): shear type overall modeling. (b): shear block stress analysis. (c): push-pull type overall modeling. (d): pull block stress analysis.).

The standard 80mm×120mm polyurethane plate pulling pad was made, pasted on the metal surface and 2mm thickness composite surface respectively, and tensile damage test was carried out to record the ultimate load when pulling off the damage as shown in Table 1 (where serial number 1-7 is the test result of metal surface, serial number 11-14 is the test result of composite surface), and the damage result of the specimen is shown in Figure 2. The damage load was 22kN, and the damage was caused by the debonding of the aluminum plate from the surface of the pulling pad. In the 2mm thickness of composite material surface paste pressure pad to carry out damage test measured the minimum load of 8.8kN, damage are polyurethane tearing, analysis of the reason for the tensile process of the composite material plate bending deformation is serious, resulting in uneven pressure pad, pressure block in the local load is serious tear failure. The actual use load of the two applications does not exceed 1.7kN, meeting the safety margin of more than 4 use requirements.

Table 1: Tensile damage test load statistics of tension pad.

No.	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*11*	*12*	*13*	*14*
Failure load (kN)	40.5	28	24	22	41	39	44	8.8	9.8	12	13

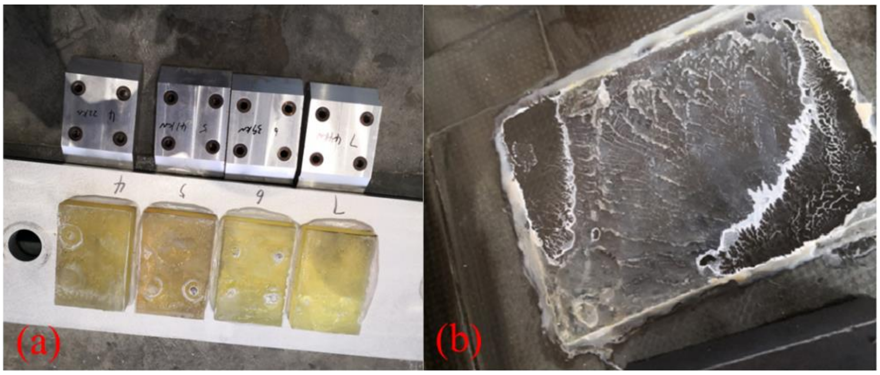

Fig. 2 Results of tensile pad verification test ((a): Metal surface adhesion failure diagram. (b): Composite surface adhesion failure diagram.).

Optimized design of lever systems

According to the structural characteristics of the test piece and the layout of the nodes of the tension pad, the tension pad lever system is designed in three forms. class A is a planar connection, where all the lever connection points of the lever system are in a plane; class B is a linear connection, where all the lever connection points of the lever system are in a straight line; class C, a mixture of class A and class B.

The primary lever is of variable section design and is bolted to the tension pad. The single lug is designed in two sizes, one is a single lug with a circular hole and a joint bearing, which serves to fix the lever position and release the rotational degrees of freedom, and the other is a long lug with a long hole, which serves to release the translational degrees of freedom caused by the deformation of the system and restrain the rotational degrees of freedom of the system in both directions, thus forming a static connection between the primary lever and the tension pad. The design result is shown in Figure 3.

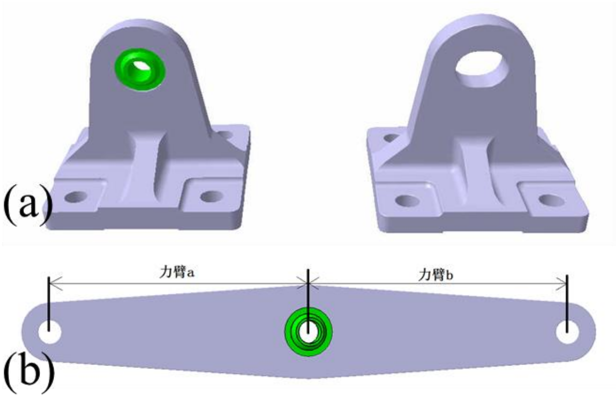

Fig. 3 Primary lever design diagram ((a): Single lug design form. (b) Lever structure form.).

The secondary lever is designed to be connected according to the position of the primary lever. The secondary lever of the large angle class, the angle with the primary lever is within 90°±26°, the same plane lap design form, in the plane with the primary lever through the joint bearing connection, the middle hole to install the joint bearing. The linear connection type secondary lever, in a straight line with the primary lever, is directly connected with the primary lever by bolts, with a long hole at one end and a round hole at the other, and the middle hole is fitted with a joint bearing. The design principle of the final lever is the same as that of the secondary lever. The low stress area of the lever is grooved to reduce the weight of the lever system while avoiding stress concentration. The typical lever form is shown in Figure 4.

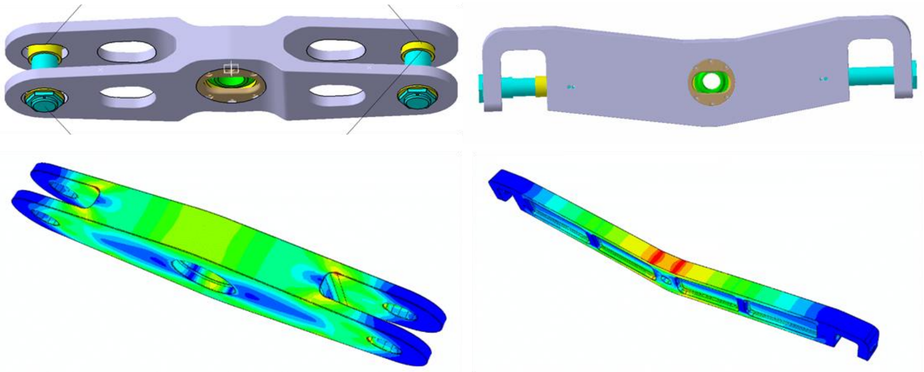

Fig. 4 Schematic diagram of typical lever design and analysis results.

Typical design results for a tension pad - lever system

The wing, vertical tail and lateral fuselage parts of the aircraft are loaded by the tensile type tension pad-lever system, and the nose and rear fuselage vertical loads are applied by the shear type tension pad-lever system, as shown in Figure 5.

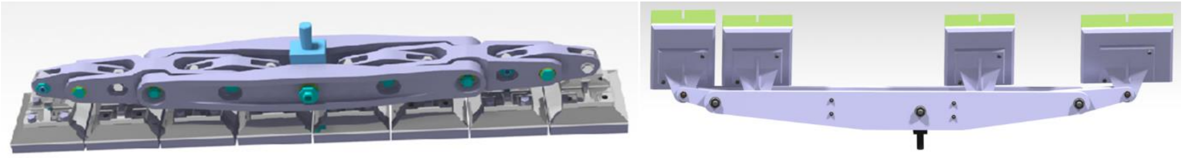

Fig. 5 Typical results of tension pad-lever system design.

Tension pad - lever system verification test

To verify the fatigue characteristics of the tension pad and lever system, two groups of tension pads were attached to the horizontal tail of an aircraft, each group of 16 pieces, one group was applied with positive pull-pressure load on the vertical attachment surface, and the other group was applied with 45° directional pulling/shearing with the attachment surface, the pulling load was 27.2kN, the pressing load was 48kN (4 times safety factor), and the constant amplitude fatigue was carried out with 100,000 cycles of load test. The results show that the tension pad does not show obvious degradation of performance such as open glue, tearing, loss of elasticity, etc. The lever system is stable and reliable, and no failure, transitional wear, bolt loosening and other failures are detected. The photos of the verification test site are shown in Figure 6.

Fig. 6 Photo of the verification test of the tension/shear block-levers system.

FULL-SCALE AIRCRAFT FATIGUE TEST APPLICATION EXAMPLES

The above new technology is applied for the first time in the fatigue test of full-scale structure of C919 aircraft, in which the tension pad-lever system is applied to the wing vertical, nose vertical, rear fuselage vertical and fuselage lateral loading, in which 34 wing vertical loading points, 12 nose/tail vertical loading points and 10 fuselage lateral loading points are arranged symmetrically on both sides and loaded in a synchronized and coordinated manner.

The project completed installation and commissioning on November 28, 2019, and completed the 2000-cycle fatigue test by the end of December 2019, and has since continued to operate at a rate of about 2500 per month under the condition of continuous optimization of the control parameters. The test data showed that the loading accuracy of the full-scale fatigue test met the test requirements, the systems operated well, and no malfunction occurred during the test, and the use of the new test technology achieved the expected purpose. The photos of the test implementation are shown in Figure 7.

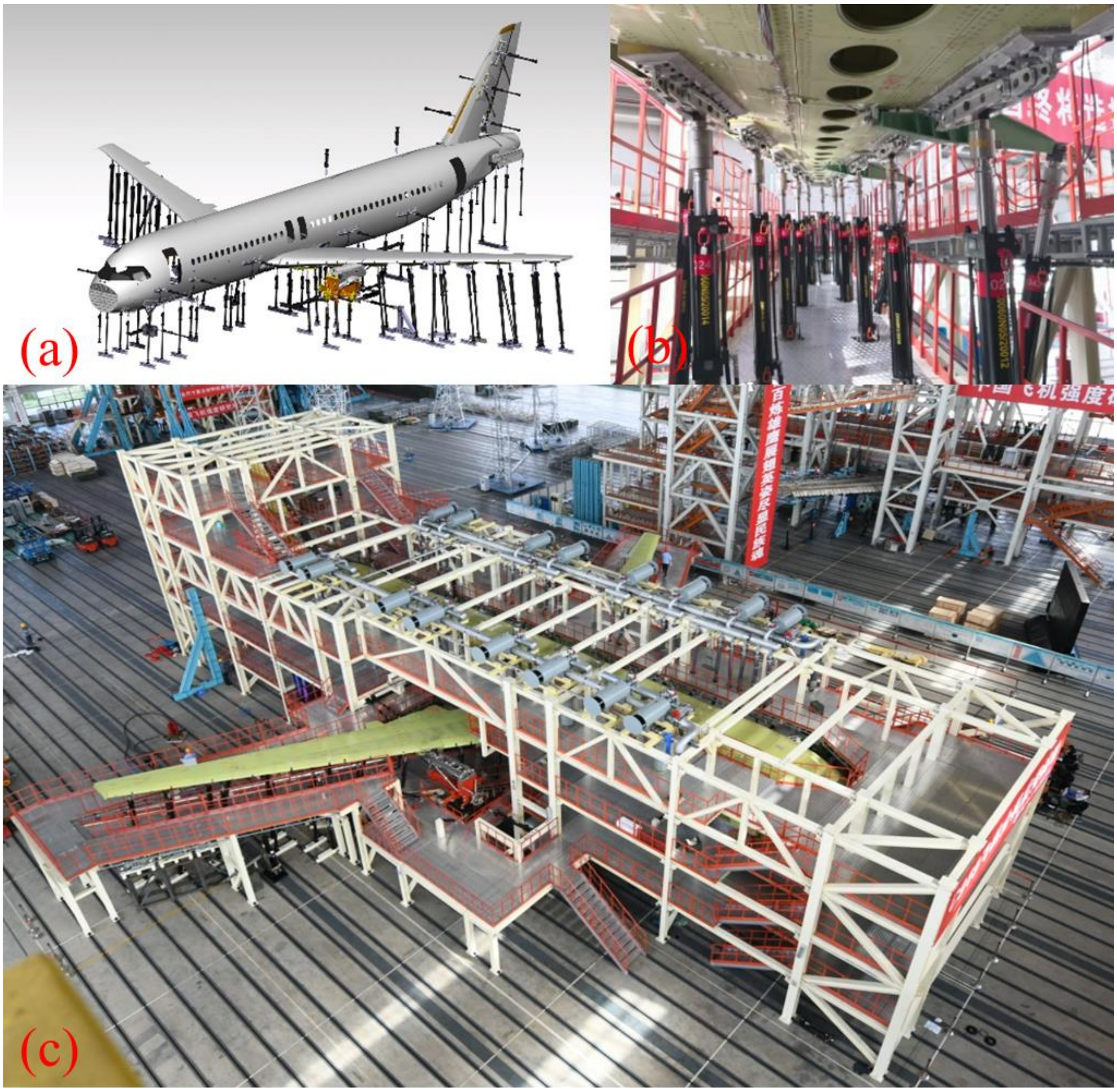

Fig. 7 Tension pad-lever system application ((a):Tension pad design application position. (b): Photograph of the wing application. (c): C919 aircraft full aircraft fatigue test.).

Another integrated application case is the C919 aircraft tail/rear fuselage static/fatigue and damage tolerance test, which adopts the same design principles as the C919 full-scale aircraft fatigue test, in which 21 sets of tension pad-lever systems are used, mainly applied to the load application in the rear fuselage vertical direction, rear fuselage lateral direction, vertical tail lateral direction and rudder lateral direction. The test was installed and completed in April 2021, and the 2 times life fatigue test was completed in October 2021, taking 100 days to complete, with an average of 700 cycles per day during the test, and all static/fatigue and damage tolerance tests were completed by March 2023, thus breaking the record for the fastest test of its kind in China. The C919 EF3 test site is shown in Figure 8.

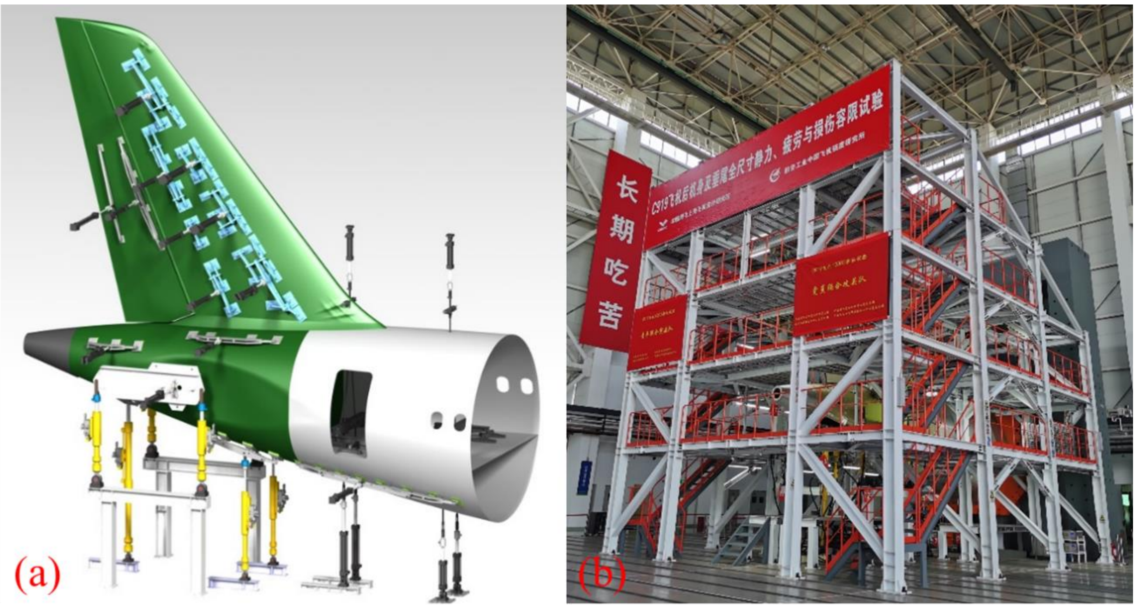

Fig. 8 C919 aircraft EF3 test tension pad-lever system application schematic and field photo.

CONCLUSION

Test acceleration is a constant pursuit for efficient aircraft development, and ASRI continues to work on efficient verification of aircraft design results, where the development of rigid loading technology has contributed to significant improvements in fatigue test loading efficiency. The new generation of tension pad-lever system solves the challenges of vertical loading of wings and vertical/lateral loading of nose/rear fuselage hyperbolic structures, which can increase the loading rate, reduce the usage and maintenance, make the load simulation more accurate, and make the number of loading points smaller. The integrated application of rigid loading technology shows that the two loading methods work well in the C919 full-scale structural fatigue test and the full-scale structural static/fatigue and damage tolerance test of the tail/rear fuselage, and the C919 full-scale structural fatigue test has achieved a good result of 2000 cycles in the first month of the test while ensuring test safety and test accuracy. The C919 full-scale structural static/fatigue and damage tolerance test has achieved the test results of completing 2 times the fatigue life in 100 days and zero failure of the loading system during the whole test. The successful application of these technologies can provide important reference and support for the subsequent full-scale fatigue tests of other aircraft.

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