Principles for determining material allowable and design allowable values of composite aircraft structures

LIU Wencheng a*

Airworthiness Engineering Center, COMAC, Shanghai 200232, China

Abstract

In this paper, the determining methods of composite structure material and design allowable values are presented. The characterization and application of material allowable, examining and statistical analysis ways of test data are described, and the determining methods for design allowable values of static strength, fatigue strength, damage tolerance and repair are also analyzed. The research results can be used for design and certification of aircraft composite structure, and have a high reference value on the research and development of composite structures of large civil transport aircrafts.

Keywords: Aircraft structures; Composite; Material allowable; Design value

1. Introduction

Material allowable value is defined, under a certain type of load and environmental conditions, as a material characterization value with some confidence and reliability which is mainly determined by statistical analysis of the sample test data. Allowable value of structural design is defined, according to the requirements of specific project, on the basis of the material allowable value and the test results of the typical samples, components (including the typical structural element) represent structural characteristic, and the experience of design and use, as a design limit value [1-3] which is intent to ensure the integrity of the entire structure. In the design and certification of composites aircraft structural at static strength,
fatigue strength, damage tolerance and repair, etc, the Material and Design Allowable Values will be the foundation and key for design and certification. Therefore, to determine the material and design allowable values reasonably, is the basis to ensure the reliability and security of composites structures.

The ability to be designed for structural performance and the special mechanism in damage and failure for composite aircraft, which makes the determination principles and methods for composites is different from the metal materials in material allowable and design allowable values. Review the composite Aircraft Structures progress of the past 50 years, the determination principles of the composite material allowable and design allowable values were constantly improved by the development of the composite structure design technology, expansion of the application, the accumulation of experience [4-9]. In this paper, with the research work on the certification technology of composite Aircraft Structures by the author, clarify the representation and application of the composites allowable value, and analyze the methods for determining about the static strength, fatigue strength, damage tolerance and design values of repair.

2. Material Allowable Value

2.1. The characterization and application of application of the material allowable value

Material allowable value is a material property value obtained by the statistical analysis of test data (for example, modulus, strain or stress, etc.). Material allowable values usually represented by mean (for the modulus), B-basis (for the statically indeterminate structure) and the A-basis (for the statically determinate structures). For composite materials, usually using the material strain value represents the material allowable value [10].

Composite material allowable value used to evaluate the dispersion of the material, environmental impact (including the identification of the environmental compensation factor), and determines the basis of the design allowable values, and gives modulus value of the design and analysis. Except the modulus, the material allowable value is not directly used for the structural design of composite materials.

2.2. Tests for material allowable value

The tests Used to determine the allowable value is mainly sample-level tests. It’s necessary to take the thickness and overlay design, environmental impact, and the gap effect and extrusion damage of the mechanical fastening connection into account, to determine the number of samples respectively, and to form a reasonable test matrix.

During the determination of the design allowable value, for tensile loaded situation, the design allowable values are based on the tests results of the specimens contain the hole with a radius of 6.35mm (between the filled and unfilled holes, choose the lesser); For the compression loaded situation, the design allowable values are based on the tests results of the specimens containing gap or impact damage (choose the lesser). In general, the design allowable value was given based on the test results contains impact damage [11].

2.3. Statistical analysis of test data

Compared with metallic materials, the composites test data of static strength, residual strength and fatigue life have high dispersion. In order to ensure that composite structures and metal structures have a considerable level of reliability, we need a statistical analysis of the composite performance test data, and
give a statistics-based material allowable value, thus bring the differences in composite performance data into the design allowable value of composite structures.

Before the statistical analysis of test data, you should first distinguish and discard the abnormal test data (in addition to use quantitative judgments, but also use engineering judgments); and normalize the performance data for the fiber control. In the statistical analysis of unstructured data, you can use Weibull distribution, normal distribution and lognormal distribution for statistical analysis. However, it should use Weibull distribution firstly for statistical analysis, because it gives conservative results. If the test data is the collection of several batches of material test data, variance analysis methods can be used for statistical analysis; If the test data is the collection of different temperature or humidity, simple linear regression method and combined Weibull analysis method can be used for statistical analysis [12].

3. Design Allowable Value

In the process of composite structures research and development, before determine the design allowable value ultimately, the design allowable value of development process need to be given first to use in design analysis and determine the geometry. The final design allowable value will be used for the certification of composites structures.

When determining the structural design allowable value of composite materials, it is related to the static strength, fatigue strength, damage tolerance and repair and so on of the composite structure. First, you need to determine the related static strength design allowable value, fatigue strength design allowable value, damage tolerance design allowable value and repair design allowable value. Then, comprehensive analysis those design allowable values, and give the structural design allowable value. Require associate with design experience, and go through experimental verification to determine the allowable design value.

Design allowable value used for the composite structural design, should be certification by authorities.

3.1. Static strength design allowable value

Static strength design allowable value is based on the already acquired material allowable value, gave by combined with design experience and the test result of higher levels of specimens. It is the threshold used for static strength structural design and analysis. That is to say, the design allowable value of static strength is a structure strain (or stress) limit value under the effect of design loads. It should be noted: static strength design allowable values need to be certificated by using assemblies and (or) sub-components tests. Static strength design allowable values include tensile strength allowable value, compression strength allowable value (including the design allowable value of the stability of component) and shear strength allowable value.

Because the specimens used for determining the design allowable value may be very special, unless it’s a similar structure with the design, the other design allowable value of composite structures should not be used.

The composites structures contain barely visible impact damage (BVID) and allowable manufacturing defects of process specification should be able to withstand the design limit load. Therefore, this structural design should be classified as static strength design category. That is to say, when determining the material allowable value and the design allowable value for the composites, you should take the allowable manufacturing defects of process specification and BVID into account. Currently, MIL-HDBK-17F has not given the test matrix contains BVID and manufacturing defects, the composites manufacturers could developed the appropriate test matrix freely, and submitted to certification institution for approval.
3.2. Fatigue strength design allowable value

When determining the fatigue strength design value, you should take the hot and wet environment into account. For each environmental condition, including room temperature atmosphere RTA, hot and wet ETW, and fatigue life test on at least 4 stress level, the selection of stress level need to make it close to the fatigue threshold, as the main purpose of the fatigue life test is to determine the fatigue threshold.

For each stress level, you should determine a reasonable test matrix. Because the stress level under a given environment has little effect on the dispersion of fatigue life, you can use the collection statistical analysis method of test data (for example, the combination Weibull analysis), and give out the basis of fatigue life (B-basis and A-basis).

The fatigue life test for determining the fatigue strength design allowable value, except the minimum stress level, all the fatigue tests should be carried out until the fatigue damage occurred.

Because the long time, high costs of fatigue life tests, you can choose the specimens of a representative structural configuration for fatigue test. When Boeing determining the composites structures threshold of empennage of B777 aircraft, they use the specimens of different configurations as follow: the laminates with no gap (the edge delaminat e test); the laminates with a hole; the laminates with reinforcements; bolted connections (composites- composites, composites - titanium alloy); the corner detail parts (the comer fillet with stress concentration).

In general, after the fatigue life’s B-basis and A-basis of 4 stress levels was given, you can give out the S ~ N curves corresponding to the A-basis and B-basis. You can determine the fatigue threshold of corresponding B-basis and A-basis By the S ~ N curves.

Composites have good fatigue resistance, high fatigue threshold. For the typical carbon fiber / epoxy composites, the fatigue threshold’s stress level is above the 60% average static strength. Therefore, the fatigue strength allowable value can be determined by using the method of ultimate strength (including B-basis and A-basis). It’s requires the corresponding stress level of maximum load among the fatigue load should not greater than the stress strength design allowable value, which can simplify the fatigue design process, but the method for determining the allowable value of fatigue strength is conservative.

3.3. The damage tolerance design allowable value

The design allowable value of composites structures which contains defects / damages can be divided into two categories: one is the design allowable value of composite structures which contain barely visible damage (BVID), you can also see it as static strength design allowable value. Such design allowable value is the design allowable value used for analysis of design limit load to meet FAR25.305 requirements; the other one is designed with maximum damage (MDD) the design of composite structures allowable value. Allowable value is consistent with this type of FAR25.571 (b) Analysis of damage tolerance requirements of the design used when allowable value, often called the damage tolerance design allowable value.

In the design of composite structures, the design allowable value used in most parts of the structure is damage tolerance design allowable value.

(1) Damage tolerance design allowable value with BVID

In order to determine damage tolerance design allowable values with barely visible impact damage (BVID), the residual strength tests and the "injury-free extension test" must be carried out. The residual strength of structure containing BVID should be able to achieve the load bearing capacity more than the design load. You can determine the damage tolerance design allowable values with BVID by the method of determine the allowable value of the static strength, however, BVID was "no extension" at 1.5 times (Airbus aircraft) or 2 times (Boeing series aircraft) fatigue life test need to be validated by tests.
During the development of composites structures of Boeing B777 aircraft vertical fin, except using full-size components, the following structural components and assemblies were used for a 2 times fatigue life test to confirm the injury was "no extension": ①Laminates with BVID; ②Shear panels with BVID at opening edge; ③Five-ribs panels with bond repair and BVID; ④Horizontal stabilizer skin butt joints panels with BVID; ⑤Shear beams with BVID at opening edge of web.

During the determination of damage tolerance design allowable value with BVID, you can refer to the above type of test to confirm BVID is "no extension". Because the method of compression loading is critical, damage "no extension" validation test should select the method of compression loading.

(2) Damage tolerance design allowable values with maximum design damage (MDD)

Composite structures with MDD must have the capacity to bear the load above the limit load, and the damage with "no extension" at the double check interval fatigue test (Airbus company uses 0.5 times the fatigue life test).

By the residual strength test of MDD Assembly level and (or) sub-component level, and along with design experience, you can determine the residual strength design allowable values of composite structures with MDD, and validate the limit load of structure through full-scale tests, and damage no extension at the above check intervals.

(3) Damage with discrete source

Composite material structure with discrete source damage (for example, bird strike damage) should have "continued safe flight" capability. Therefore, in the determination of the damage tolerance design allowable value, this damage condition should be considered through the assembly or sub-component test.

In the design of B777 aircraft composite empennage, the design allowable values of consideration of the impact damage effects are mainly given by assembly tests. This is because the impact damage of critical position usually occurs in the position of stress concentration (for example, the edge of the checking hole) or the top of the frame components (for example, the skin at reinforced bar).

3.4. The design allowable value for repair

The Composite structure repair program is usually using specimens of simulated repair position configurations, materials and processes for testing. For the repair design, the material allowable value which is based on statistical is not need. However, the difference of material performance should be given, especially for the case of the wet ply repair.

In general, the material allowable value of original composite structure can be multiplied by the allowable reduction coefficient (given by the lower complexity test of specimens) to give the material allowable value under the repair condition, and to reflect the condition which the repair material and the curing temperature and pressure is lower than the original structure.

After material allowable value has been given by using the above method, a small amount of assembly and (or) sub-component test should be carried out, and design allowable value used for repair design combine with the repair design experience was given out.

Specimens used for the repair design usually with bolted or bond connection. Such tests usually are two-dimensional tests. The bolted specimens can be single-row or double-row bolted connections, these tests can obtained the test values of extrusion, extrusion / bypass and net tensile. The bond connecting specimens usually use overlap form to get the connection strength of the bond junction.

3.5. The typical design allowable value of domestic and foreign aircraft composite structures
In general, the design allowable strain value of aircraft composite structures should be limited between 3000 and 5000 με. Table 1 shows the typical composite Aircraft Structures design allowable value of domestic and foreign manufacturers.

Table 1. Typical design allowable of national and foreign aircraft manufacturers[13-15]

<table>
<thead>
<tr>
<th>Company</th>
<th>Component name</th>
<th>Material system</th>
<th>Stretch design allowable value (με)</th>
<th>Compression design allowable value (με)</th>
<th>Shear design allowable value (με)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lockheed</td>
<td>L-1011 vertical stabilizer</td>
<td>T300/5208</td>
<td>4500</td>
<td>4000</td>
<td></td>
</tr>
<tr>
<td>Boeing</td>
<td></td>
<td></td>
<td>3200–3500</td>
<td>2700</td>
<td>5300</td>
</tr>
<tr>
<td>Airbus</td>
<td>A310 vertical stabilizer</td>
<td>T300/913C</td>
<td>2800</td>
<td>2800</td>
<td></td>
</tr>
<tr>
<td>Airbus</td>
<td>A320 vertical stabilizer</td>
<td>T300/913C</td>
<td>3200</td>
<td>3200</td>
<td></td>
</tr>
<tr>
<td>Airbus</td>
<td>A330/340 outboard wing</td>
<td>HTA/6376</td>
<td></td>
<td>5000</td>
<td></td>
</tr>
<tr>
<td>Xi'an aircraft Design and Research Institute</td>
<td>Y7 vertical stabilizer</td>
<td>T300/913C</td>
<td>3200</td>
<td>3200</td>
<td></td>
</tr>
</tbody>
</table>

4. Conclusions

In this paper, there are some comprehensive and systematic discussion of the determination principles and methods for material allowable value and design allowable value of the composite Aircraft Structures, which referred to the design and certification process, the methods for confirming material and design allowable values of composite structures, the indication and application, test and statistical analysis methods of material allowable value were clarified, and analyzing the method of determining static strength, fatigue strength, damage tolerance and repair design allowable value.

References


