

Subject: **INFORMATION**: Static Strength Substantiation
of Composite Airplane Structure; Policy
Statement PS-ACE100-2001-006

Date: December 21,
2001

From: Manager, Small Airplane Directorate, Aircraft
Certification Service, ACE-100

Reply to Lester Cheng
Attn. of: 316-946-4111

To: SEE DISTRIBUTION

Purpose of Policy

The purpose of this policy, which applies to 14 CFR (Code of Federal Regulations) part 23 airplanes, is threefold. First, it provides general guidance on large-scale tests and when they are needed to meet the certification requirements. Second, it reviews the critical factors that affect the static strength of composite airplane structures and how they can be addressed. Third, it describes some commonly accepted engineering practices used for structural substantiation, including the engineering rationale for various means of showing compliance. This document also provides further clarification of AC 20-107A.

This policy on static strength substantiation for composite structures is consistent with small airplane and business jet certification programs completed. Note that most of these airplanes have been constructed with pre-impregnated, laminated composite material forms. As service databases expand and new composite material forms and manufacturing processes continue to evolve, future applications may need to consider other critical factors important to static strength.

This document describes policy for static strength substantiation of primary composite airplane structures that are critical to safety of flight. Other structures, whose failure can be shown not to affect airplane safety (secondary structures), may not require the same level of rigor in engineering analysis and test assessment to ensure structural integrity.

Table of Contents

1.0 Introduction

- 1.1 General Background
- 1.2 Factors to Consider

2.0 Related Regulatory and Guidance Materials

- 2.1 Federal Regulations
- 2.2 Advisory Circulars

3.0 Building Block Approach

- 3.1 Purpose and Application
- 3.2 Analysis Validation of Load Paths

- 3.3 Damage, Defects, Repeated Load, and Environmental Effects
- 3.4 MIL-HDBK-17

4.0 Environmental Exposure and Repeated Load

- 4.1 Long-Term Time Related Degradation
- 4.2 Solar/Thermal Design Criteria
- 4.3 Peak Temperature Analysis
- 4.4 Peak Moisture Content
- 4.5 Analyses and Tests
- 4.6 Full Scale Test Considerations
- 4.7 Other Exposures

5.0 Static Strength Analysis - "A" and "B" Basis Allowables

- 5.1 General
- 5.2 Policy on Material Qualification and Equivalency
- 5.3 Detail Design and Notch Sensitivity

6.0 Static Test Article Fabrication and Assembly

- 6.1 General
- 6.2 Design and Manufacturing Detail Definition
- 6.3 Conformity Inspections
- 6.4 Defects and Damage

7.0 Effects of Impact Damage and Minor Discrete Source Damage

- 7.1 Damage at the Threshold of Detectability and Allowed Damages
- 7.2 Impact Considerations
- 7.3 Damage Tolerance

8.0 Material and Process Variability

- 8.1 General
- 8.2 Analytical Substantiation Supported by Tests
- 8.3 Substantiation Primarily by Tests with Minimal Analyses
- 8.4 Overload Factors
- 8.5 Other Considerations

9.0 Conclusion

10.0 References

-- POLICY --

1.0 Introduction

Static strength substantiation is an important milestone in the certification of composite airplane structure. In the past, different approaches have been used to meet the associated Federal Aviation Administration airworthiness regulations.

1.1 General Background

Many factors contribute to the strength exhibited by built-up composite structure, which utilizes bonding and other manufacturing technologies to minimize parts count and achieve performance goals. Traditionally, applicants used large-scale structural tests at the component level to evaluate the complex load paths and failure mechanisms of such structure. As in the case of new metal structural designs, such tests are often used to ensure sufficient ultimate strength. However, it becomes unwieldy to address all issues affecting composite static strength in large-scale tests.

The combination of lower-scale tests and analyses has proven useful to quantify many static strength issues, minimize uncertainties, and mitigate risks before large-scale tests. These tests may also prove essential in addressing common manufacturing and service issues that should be expected following type design certification.

1.2 Factors to Consider

When substantiating the static strength of a composite design, applicants should consider the following:

- Critical load cases and associated failure modes;
- Effects of environment, repeated loading, manufacturing tolerance, and material and process variability;
- Manufacturing defects and service damage that are not detectable by the anticipated inspection methods (as well as those defects or damage that are permitted by the quality control or maintenance documents of the product); and
- Desired repair scenarios.

The static strength demonstration should include an ultimate load test for each major structural component, unless the adequacy of the analysis is substantiated by sub-component tests or component tests to appropriate lower load levels. These tests should include, but are not limited to, configured wing, empennage and fuselage structure. The necessary experience to validate an analysis should include previous component tests with similar designs, material systems, and load cases.

Although not specifically discussed in this memo, factors that affect static strength may also impact the vibration characteristics (stiffness, damping, and mass) of the composite structure. For this reason, applicants need to be aware of these factors when they verify the integrity of the composite structure against flutter and other aeroelastic mechanisms.

2.0 Related Regulatory and Guidance Materials

2.1 Federal Regulations

The regulations that are directly related to this policy include the following:

14 CFR Part 23 Subpart C – Structure

Section 23.305	Strength and deformation
Section 23.307	Proof of structure
Section 23.573(a)(1)	Damage tolerance and fatigue evaluation of structure

14 CFR Part 23 Subpart D - Design and Construction

Section 23.601	General
Section 23.603	Materials and workmanship
Section 23.605	Fabrication methods
Section 23.609	Protection of Structure
Section 23.613	Material strength properties and design values
Section 23.619	Special factors

Section 23.573(a) specifically sets forth the requirements for substantiating the primary composite airframe structures, including considerations for damage tolerance, fatigue, and bonded joints. Paragraph (a)(1), which prescribes "that the structure is cable of carrying ultimate load with damage up to the threshold of detectability considering the inspection procedure employed," is particularly pertinent.

Following § 23.573(a)(1) ensures sufficient ultimate load capability with undetected manufacturing defects, as well as impact damage, that can be realistically expected from production and service. Do not confuse it with damage tolerance requirements that ensure sufficient residual strength at limit loads.

Section 23.613 contains specific requirements for material strength properties and design values. An earlier policy document issued by the Small Airplane Directorate contains detailed discussion of these requirements (see reference (1) under 10.0).

Sections 23.603(a)(3) and 23.613(c) address the requirements relating to the effects of environmental conditions, which includes both the temperature and humidity expected in service. These requirements are of particular significance to composite aircraft structures.

2.2 Advisory Circulars

The following two FAA advisory circulars (AC's) present recommendations for showing compliance with FAA regulations associated with composite aircraft structure:

AC 20-107A	Composite Aircraft Structure
AC 21-26	Quality Control for the Manufacture of Composite Structures

AC 20-107A sets forth an acceptable means, but not the only means, of showing compliance with the provisions of 14 CFR parts 23, 25, 27, and 29 regarding airworthiness type certification requirements for composite aircraft structures. Section 6 (Proof of Structure – Static) is particularly relevant to this policy where the general guidance for conducting the component ultimate load tests is presented. Section 6 also describes the factors important to composite structure, which include:

- Material and process variability;
- Strength degradation due to repeated loading and environmental exposure; and
- Impact damage expected from manufacturing and service.

AC 21-26 provides information and guidance pertaining to an acceptable means, but not the only means, of demonstrating compliance with the requirements of 14 CFR part 21 regarding quality control systems for the manufacture of composite structures. This AC also provides guidance regarding the essential features of quality control systems for composites as mentioned in AC 20-107A.

3.0 Building Block Approach

3.1 Purpose and Application

Within the composite engineering community, the structural substantiation process, which uses testing and analysis at increasingly complex levels, has become known as the “building block approach.” Traditionally, such an approach has been used to address durability and damage tolerance as well as static strength for both metal and composite aircraft structure.

Figure A provides a conceptual schematic of tests included in a building block approach for wing structure. As suggested by the figure, lower levels of testing are more generic and likely to apply to other airplane parts and products. Generally, more lower-level test repetitions provide a statistical basis for material performance.

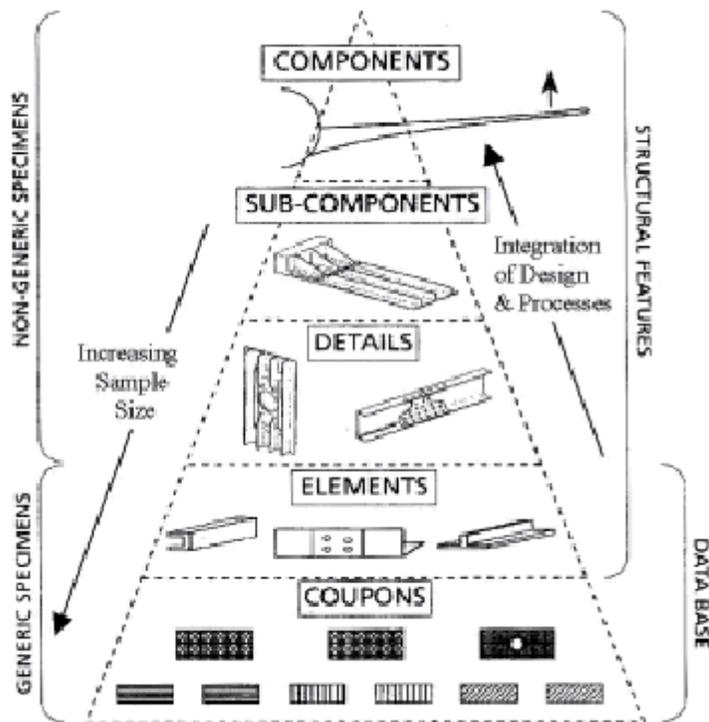


Figure A. Schematic Diagram of Building Block Tests.

Since some lower levels of building block tests can be considered generic, the concept of databases shared between programs is reasonable. Engineering protocol for base material qualification and the equivalency testing to use shared composite databases has been published previously (see references (1) and (2) under 10.0). As discussed in these references, each certification project will have its own certification plan and methods approved by the local Aircraft Certification Office.

The integration of the design and manufacturing process becomes evident in building block levels, which are above coupons and elements. The larger scales of testing are needed to address the effects of more complex loads and geometry.

As implied by Figure A, fewer tests are performed at larger scales. These tests are relevant because they address specific structural details.

Applicants should place design attention on avoiding out-of-plane loads and related failure modes, which may occur with significant loss of local stability. Small out-of-plane load conditions, which have little impact on bolted structures, can be significant for bonded structure. These conditions are often not easily analyzed.

3.2 Analysis Validation of Load Paths

Analysis validation is an important part of the building block process because it provides a basis to expand beyond the specific tests performed in development and certification. This validation starts with prediction of the structural stiffness, internal load paths, and stability.

In order to perform these analyses, applicants need to establish the material stress-strain curve to failure (or a strain cutoff in the test methods) for each composite material used in the design. Analysis has proven reliable to minimize the number of tests needed to define this characteristic for laminated composite material forms.

Verifying internal load paths may require additional building block tests, which are designed to evaluate load share between bonded and mechanically attached elements of a design. As failure is approached, some nonlinear behavior can be expected. Combined load effects can further complicate the problem of analytical predictions.

3.3 Damage, Defects, Repeated Load, and Environmental Effects

Predicting the effect of multiple influences (environment, repeated loads, damage, and manufacturing defects) on the failure modes that affect structural strength traditionally relies on the building block tests. Often, semi-empirical analyses have been adopted for composite strength. Special consideration is given to structural discontinuity (for example, joints, cutouts or other stress risers) and other design or process-specific details.

One of the most important parts of the building block analysis and test development comes in providing engineering databases to deal with the manufacturing defects, field damages, and repairs likely to occur in production and service. Traditionally, not enough attention was given to these issues during composite product development and certification. This has caused significant work slowdowns and increased costs for subsequent product manufacturing and maintenance.

Without sufficient analysis and test database to cover commonly allowed manufacturing defects, damages, and repairs, engineers will be forced to either adopt conservative assumptions (part rejections or expensive repairs) or generate the data as it is needed (leading to down time and associated cost or lost revenue).

It is difficult to plan for unanticipated defects and damage. Production and service experiences with new technologies such as composite materials are often needed to completely define the problems. Nevertheless, an awareness of the likely production and service issues will help define practical levels of building block tests and analyses to be performed as part of structural substantiation.

3.4 MIL-HDBK-17

MIL-HDBK-17 (Composite Material Handbooks) is available at <http://www.mil17.org/>. This handbook provides detailed background on the engineering practices that have been successfully applied with composite materials used in airplane structures. Chapters on the building block approach for substantiation of composite structures are most useful for the

current discussion. Chapter 2.1 from Volume 1 of the Polymer Matrix Composite (PMC) provides some introduction to this subject, including a synopsis of test levels and data uses.

There is more information on the building block approach that can be found in Chapter 4, Volume 3 of PMC for the most recent revision of MIL-HDBK-17 (Revision F). This chapter outlines rationale for the traditional multi-level testing and analysis development approach used for metallic and composite structures, particularly in the aerospace industry. It also contains guidance and example test programs for various applications.

Many of the engineering practices outlined in MIL-HDBK-17 were derived from composite applications to military and commercial transport structures. The composite material types, structural design details, and associated manufacturing processes selected for such applications may have significant differences from those used for small airplanes.

4.0 Environmental Exposure and Repeated Load

4.1 Long-Term Time Related Degradation

The effects of environmental exposure and repeated loading, which may result in static strength degradation, should be addressed. Reduction in composite static strength as a function of environmental exposure and repeated loads can occur over long periods of time. For purposes of this policy, these considerations will be limited to reductions in static strength, which come without detectable damage. As a result, damage tolerance evaluation methods and maintenance practices cannot cover such degradation. Instead, sufficient static strength must be shown following exposures to environmental effects and repeated loads.

The effect of repeated loads on base composite material properties is typically not as severe as metal fatigue (relatively flat curves for critical fatigue stress versus number of cycles). Degradation mechanisms for a composite subjected to repeated loads are typically not the same as self-similar crack growth behavior in metals. Instead, the composite damage associated with repeated loads can be more dispersed with minimal drop in local stiffness and residual strength until immediately prior to failure. As a result, composite structures are usually designed to working stress levels (highest loads in the spectrum) below that where significant damage accumulation occurs. In adopting such design practice, the degradation in residual strength with repeated loads should be minimal.

Fatigue tests with open hole and impact damaged specimens may be used to determine damage accumulation stress levels for laminated composite materials. Some static strength testing following repeated loads can also demonstrate long-term resistance for specific materials and design details.

Typical environmental exposures, which reduce static strength, include high temperatures and long-term moisture conditioning (often referred to as a hot/wet condition). Composite airplane structures absorb moisture in the service environment and tend to reach an equilibrium condition after some period of time, which depends on design details (for example, part thickness) and exposure.

Composite structural properties greatly affected by hot/wet conditioning include those that decrease with matrix stiffness (for example, compression strength). Other composite properties may be more strongly affected by cold/dry conditions. Coupon data generated for material allowables are generally a good basis for understanding the critical environments for different load types.

4.2 Solar/Thermal Design Criteria

In 1990, the Small Airplane Directorate issued an FAA internal policy letter presenting the solar/thermal design criteria to be used for composite aircraft certification. This guidance supports the determination of the peak temperature for a particular composite airplane structure (Section 4.2 of this document) ¹.

The "Guidance for Composite Aircraft Solar and Thermal Design Certification Criteria" is presented below:

Applicants may base the thermal environmental analysis on a parametric study of the following data to identify the highest structural temperature:

Hour	Ambient Temperature	Solar Radiation
1100	111°F	330 Btu/ft ² /hr
1200	114	355
1300	119	355
1400	122	330
1500	123	291
1600	124	231
1700	123	160

The above temperature values would not be exceeded 99.9 percent of the time, as derived from MIL-STD-210C statistical data. For the above data, the wind speed was 14 feet per second (for consideration of heat dissipation by convection). The relative humidity was 3 percent.

The effect of cooling airflow may be considered. The FAA recommends the following:

After heat soak at the critical condition, the airplane taxis, takes off, and climbs to 1,000 feet above sea level. The airplane then accelerates in level flight to:

(1) The lesser of the design maneuvering speed (V_A), or the aircraft operating speed limit (in § 91.117(b)) if maneuver loads are critical;

or

¹ Other sources of heat and temperature limitations (for example, flying temperature limits for avionics equipment or other limitations specified in the flight manual) may lead to higher or lower structural temperatures, respectively.

(2) The lesser of the design cruise speed (V_C), or the aircraft operating speed limit (in § 91.117(b)) if gust loads are critical.

In the case of a commuter category airplane, the design speed for maximum gust intensity, (V_B), applies instead of the design cruise speed (V_C).

Per § 91.117(b), the aircraft operating speed limit is 200 knots or the applicable maximum airspeed of the aircraft, whichever is lower. This applies to major structure and may not be applicable to certain structures such as flaps and landing gear doors, which would be subject to limit loads at an earlier time in the flight profile. For a small airplane, a maximum taxi speed of 10 miles per hour is recommended. A four-minute taxi time would be reasonable.

4.3 Peak Temperature Analysis

Applicants may use analyses, tests, published data or some combination of the three to obtain the peak temperature for a particular composite airplane structure. Thermal analysis should use the environmental conditions outlined previously in Section 4.2. Tests for conditions other than those described in this section may also be used to validate the analysis, which would then need to be applied for the critical conditions.

Structural temperatures typically rise well above the ambient conditions under high solar radiation. In performing thermal analysis for a structure, consider allowed paint colors that provide the highest temperature. Account for the combined effect of structural orientation and the reflection from adjacent structures and the ground. For example, adjacent structure painted with a light color may reflect radiation and increase the temperature of adjacent structure with dark colored paint.

For most paint colors, a default critical structural temperature of 180 °F can be assumed without supporting tests or analyses. Dark colors or black, which may yield higher structural temperatures, are an exception.

In addition to the solar/thermal consideration outlined above, consider other thermal sources when assessing the temperature effect to the composite airplane structure. Depending on the design configuration and installation arrangement, these thermal sources may require attention. For example:

- (1) Business jets may have air cycle machines for air conditioning, and there may be high temperature exhaust from the heat exchangers.
- (2) Engine bleed air is used for anti-ice. Consider system insulation and failure conditions. Operational experience indicates that bleed air leaks can cause severe local damage to composite structure.
- (3) Engine nacelles and cowlings may have higher operating temperatures due to the heat from the engine.

(4) Other structure in the proximity of engine exhaust.

4.4 Peak Moisture Content

Applicants may use analysis, tests, published data or some combination of the three to determine peak moisture content for a particular composite airplane structure. Moisture diffusion analysis and test conditioning should assume a relative humidity on the order of 85 percent as characteristic of past studies from long term service exposure, which includes ground time in humid environments from around the world. Engineering guidelines for moisture conditioning test samples to equilibrium can be found in MIL-HDBK-17.

Relief from assumptions of an equilibrium moisture content condition may be possible for thick structures. These structures would not reach equilibrium during the specified useful service lifetime of an airplane. The surface layers would approach the equilibrium in a reasonable time, but the full thickness of the structure would not attain equilibrium moisture content prior to retirement.

In conditioning test specimens, elements, sub-components or components to evaluate the effects of moisture on material or structural properties, it may be desirable to increase the conditioning temperature to accelerate the moisture diffusion process. However, conditioning temperatures should not be increased to the extent that the material degrades or changes due to thermal exposure. This is critical for composite materials cured at lower temperatures, where high temperature conditioning can either break down the matrix or advance the cure.

Elements such as sandwich panels and secondarily bonded structures may also have temperature limits for moisture conditioning. Extreme environmental conditioning can result in material or structural properties that are not characteristic of real service exposures.

When performing mechanical tests with conditioned specimens or structures, avoid excessive loss of moisture during the test. This is particularly important for hot/wet tests performed with relatively thin specimens, where timing is critical to ensure moisture desorption is not dominant. In some cases, the test chamber humidity may need to be controlled to get the desired data. A traveler coupon may also be placed in the test chamber and moisture content determined after the test.

4.5 Analyses and Tests

Static strength substantiation for environmental exposures and repeated loads may use building block tests, analyses supported by test evidence, relevant existing data or some combination of the three. As discussed previously, perform component ultimate load tests unless sufficient experience exists to rely on analysis supported by sub-component tests or component tests taken to appropriate lower load levels. For component test articles without prior exposure, some options exist when considering the effects of environment and repeated loads in the structural substantiation.

4.6 Full Scale Test Considerations

For critical loads testing, use one of two main approaches to account for either prior repeated loading or environmental exposure, or both.

In the first approach, conduct the static test on structure with prior repeated loading or with damage that simulates prior repeated loading. Furthermore, perform the static test with structure representative of the minimum accepted manufacturing quality and impact damage at the threshold of detectability. These will be discussed later in this document. Condition the test article to simulate the environmental exposure and then test in that environment.

The second approach relies upon coupon, element, and sub-component test data to assess the possible degradation of static strength after application of repeated loading and environmental exposure. Account for degradation characterized by these tests in the full-scale, static test or in the analysis of results of the static test. An example of the former is to use a load enhancement factor in the full-scale, static test. An example of the latter is to analytically show a positive margin of safety with allowables that include the degrading effects of environment and repeated load. In either case, the component static test may be performed in an ambient atmosphere.

In practice, the two approaches may be combined to get the desired result. For example, a large-scale static test may be performed at temperature with a load enhancement factor to account for moisture absorbed over the airplane structure's life. In developing load enhancement factors to account for the environment, more statistical confidence is gained from a difference in the means between critical and test environments rather than between basis values.

4.7 Other Exposures

The ground temperature exposure of composite airplane structure is often higher than is possible when subjected to operating conditions. For example, the cooling effects of taxi and takeoff tend to reduce the temperature of structure. The structure is not required to meet critical loads at the peak temperatures possible in ground exposure. However, account for any time-related changes in material properties due to such exposure. This issue is usually dealt with by selecting materials with properties that are invariant to temperatures possible in ground exposure.

Other exposures that can degrade the static strength of composite structure include exposure to aviation fluids. The former is typically addressed in material screening and qualification by evaluating strength after exposure to fluids in accordance with test standards (for example, American Society for Testing and Materials). During material qualification, it is often advisable to consider even those fluids that the airplane may not have exposure to in order to support future applications of the material.

Ultraviolet rays from the sun can degrade the polymer matrix of many composites, starting with surface layers, which are directly exposed. Paints and other surface coatings that contain appropriate ultraviolet blocking compounds can eliminate this issue for composite airplane structure. When using this approach, conduct tests or obtain authenticated published data to ensure the blocking compounds are effective within the paint thickness specification limits. Maintenance practices must also be developed to ensure long-term exposure of the composite is not possible as the surface layers degrade over time.

5.0 Static Strength Analysis - “A” and “B” Basis Allowables

5.1 General

For static strength analysis, use “A” or “B” basis allowables unless lower design values are required (see Section 5.3). If lower design values are required, conduct further engineering analysis to minimize the probability of structural failure. The conditions for static strength analysis using “A” or “B” basis allowables are as follows:

- (A) The part should be designed, analyzed, and tested using “A” basis allowables whenever its failure would result in the loss of the structural integrity of the component involved (i.e., inability of the airplane structure to carry limit load). Such structure is possible when applied loads are distributed within an assembly through a single load path or a single member whose failure is catastrophic.
- (B) Damage tolerant or fail-safe structures, in which the failure of individual elements would result in applied loads being safely redistributed to other load carrying members without exceeding the limit load capability of the airplane structure, may be designed, analyzed, and tested using “B” basis allowables.

Material “A” and “B” basis allowable strength values and other basic material properties are typically determined by small-scale tests, such as coupon tests.

Property characterization requirements of all material systems (for example, pre-pregs, adhesives) and constituents (for example, fibers, resins) should be identified, documented, and approved. Include the approved requirements in all appropriate procedures and specifications that control the raw materials and the processes used to advance them to the stable state characteristic of the airplane structure. As a result, the statistical bases for composite property variations are adequately linked to the documents used to ensure repeatable material and process quality.

In developing a statistical basis in coupon tests, consider the design and manufacturing characteristics of the airframe structure. For example, some processes may produce structure with an average bondline thickness of 0.06 inch and a maximum permissible bond up to 0.10 inch thick. Coupon testing should include bonded joints with similar characteristics. If sufficient data exists to determine the bondline thickness yielding the lowest strength, most of the coupon testing could assume the worst case permitted.

5.2 Policy on Material Qualification and Equivalency

Engineering protocol to generate base composite material allowables and the equivalency testing to share such databases has been documented previously (see references (1) and (2) under 10.0). The test methods, data reduction, and statistical procedures are based on those documented in MIL-HDBK-17, which provides details on commonly accepted engineering practices. Typically, environmental effects are also considered as part of the program to generate “A” or “B” allowables.

5.3 Detail Design and Notch Sensitivity

Some factors that lead to design values, which are lower than base material properties, include the following:

- Point design considerations (stress risers, joints, and so forth);
- Stiffness requirements (flutter or vibration margins);
- Fatigue;
- Manufacturing defects and damage; and
- Other overriding issues.

Often, such considerations cannot be addressed in simple coupon or element testing. As a result, higher levels of the building block tests are needed to assess the strength that can be achieved at the structural scale. Engineering judgment is then needed to apply a statistical basis generated with coupons to the smaller sample used in static strength tests performed with structural details characteristic of the design. When evaluating sub-component tests, which have no repetition, it is generally assumed that the results represent the mean of the population.

6.0 Static Test Article Fabrication and Assembly

6.1 General

Fabricate and assemble the static test articles in accordance with production specifications and processes such that they are representative of the production structure. Without such practice, technical issues will arise before and after certification as production tools are developed and manufacturing processes evolve.

It is important to ensure the test hardware fabricated for type certification does not use tools and process steps that are likely to change in production. Production process changes and improvements often require additional testing to ensure they have not led to differences in structural performance. To help minimize such issues, integrate design and manufacturing development during building block tests and analyses, culminating in final structural tests with hardware processed using production tools, fabrication, and assembly steps. A structural substantiation approach, which includes analysis, can also help minimize the numbers of tests that need to be repeated when the inevitable process changes are sought.

6.2 Design and Manufacturing Detail Definition

During the course of composite structural design and manufacturing detail definition, create sufficient records to ensure that parts and assemblies remain invariant with time. Although such records are not unique to composites, there are issues that go beyond basic material type and form call-outs and part geometry definition. These include definition of part contour, cure process parameters, and ply lay-up details for laminated composites.

There are two common approaches for defining the contour of a composite part. One uses engineering drawings or data sets that define loft lines for the mold. The other relies on either a master model or a mold to define the contour.

When a master model or mold is used to define the part contour, include enough provisions in drawings to check for warpage and contour changes in the master model or mold throughout their lives. Known locations for fixed reference points are often used at reasonable spacing when combined with a contour board. The approach chosen by an applicant must detect geometric changes in both the parts and the tools used. When tools are changed or modified, possibly to accommodate derivative models, keep records of the changes so that it is possible to determine the contour of previously delivered aircraft and to support the production of spare parts.

During type design definition, establish tolerances for the parameters affecting strength and durability characteristics of the structure. Examples of these parameters include ply orientation, stacking sequence, cure time, temperature, pressure, and ply drop off locations. There is no fixed standard for the magnitude of these tolerances, but they should be selected based on sound engineering judgment and criteria that ensures the parts manufactured within tolerance limits will be capable of meeting the certification requirements.

Where tolerances are chosen in excess of those that were demonstrated to provide adequate control in the past, additional testing may be required to show that the structure can sustain the design loads and is safe from flutter within the tolerance envelope. For example, an applicant wishing to make ply orientations optional for a structural component should demonstrate, either by test or by analysis, or both, that the structure is capable of sustaining the design loads and is free of flutter at the most adverse orientation possible.

The shape of each ply used in the airplane should be established through the drawings and specifications. When this is accomplished through the use of templates or electronic data sets, these templates or data sets then become part of the type design and must be controlled as such.

6.3 Conformity Inspections

Due to the nature of many composite materials and processes, it is often necessary to conduct conformity inspections during the fabrication of components to a greater extent than in the case of metallic components where inspection can be conducted after assembly. For

example, type certificate applicants should plan on conducting conformity inspections of the lay-up processes and bonded assemblies early in the program.

Once a fabrication inspection system has been established, it is possible to rely on that system to verify the orientation of hidden plies as well as other processing steps, so that conformity inspections can be done on subsequent components after lay-up and cure is complete. It is usually in the applicant's best interest to establish this system and the appropriate process specifications as early in the type certification process as possible.

During development of the drawings and process specifications, when major changes are made to the type design, it is often necessary to re-conform the test articles. The extent to which changes need to be re-conformed is left to the Aircraft Certification Office.

6.4 Defects and Damage

The static test article should consider manufacturing defects, field damages and repairs likely to occur in production and service. From a safety perspective, include in critical structure areas the defects and field damages that will likely not be detected by the inspections specified in manufacturing or maintenance. From the economic perspective of airplane manufacturers and users, include in testing any defects and field damages that can be detected by inspection, but are allowed because the required levels of strength and durability are maintained. The level of allowed manufacturing defects should be included in either specifications or drawings, or both. Finally, validate a complete range of repair scenarios that are anticipated to fix manufacturing defects and service damage.

Note: Damage repaired in the field by secondary bonding is generally limited in size. The damaged structure should have limit load capability, without the bonded repair, just as other bonded structural details are expected to be redundant². Although this issue is one that is more commonly considered under damage tolerance substantiation, repair capabilities are often demonstrated in static strength testing to ultimate loads.

7.0 Effects of Impact Damage and Minor Discrete Source Damage

7.1 Damage at the Threshold of Detectability and Allowed Damages

Impact damage (or other minor discrete source damage) can significantly reduce the static strength of composite structures by causing matrix cracking, delamination, and fiber failure, which locally alters the load path. Depending on the impact event and inspection procedure, specified inspection methods may not detect the resulting damage. In the case of the lower levels of impact damage, which are not detectable, demonstrate sufficient static strength capability.

² Per § 23.573, there are other means of compliance for bonded structural details (for example, NDE and proof testing); however, neither are believed to be appropriate for field repairs.

Impact damage that can be realistically expected from manufacturing and service, but not more than the established threshold of detectability for the selected inspection procedure, should not reduce the structural strength below ultimate load capability. The load level differs for damage that is detectable (limit load) because maintenance inspection and repair practices can be relied on to return the structure to sufficient strength.

As discussed previously, include in test and analysis substantiation any detectable damage that does not reduce the strength of a particular composite structural design below ultimate loads. This data can benefit manufacturing and maintenance activities for a certificated product. In the case of most past composite aircraft structure, detectable damage implies clearly visible damage because the inspections used in service rely on a mechanic finding the damage without sophisticated equipment.

7.2 Impact Considerations

Show the static strength capability of structure with impact damage by analysis supported by test evidence, or by a combination of tests at the coupon, element, sub-component, and component levels. The complex nature of impact damage in composite structures is such that there is a general dependence on tests to evaluate its effect on static strength.

Typical impact threats include runway debris, dropped tools, hail, ground vehicle or equipment collisions, and handling damage. Much of this impact damage can be considered in the scope of composite damage tolerance (detectable damage, specified inspection, no significant growth, and a limit residual strength requirement). However, impact damage up to the threshold of detectability that can be realistically expected from manufacturing and service has a static strength requirement for ultimate loads (§ 23.573(a)(1)).

The impact-damaged composite requirement for static strength at ultimate loads evolved from initial applications where the specific laminated composite materials had brittle matrices. For such composites, relatively small levels of impact caused large areas of delamination, without visible surface indications. Local instability of this damage led to a drop in residual strength under compression or shear loads. The resulting ultimate load requirement is intended to ensure sufficient static strength for impact damage generated by relatively low-energy impacts.

Industry has adopted some standards for ensuring ultimate load capability for the case of impact damage up to the threshold of detectability that can be realistically expected in service. These standards have helped bound the structural substantiation for this requirement to practical limits.

Standard impactor types and geometry include weighted, spherical-shaped, metal impactors with diameters between 0.5 in. (12.7 mm) and 1.0 in. (25.4 mm). Typically, such weights are dropped to impact the structure at a perpendicular angle. Varying the height of dropped weight can attain different impact energies, which yield different levels of visibility.

Often, special towers or stands with an impacting tube are constructed and a support fixture is needed to tilt the structure for dropped weight impact. This facilitates impacting components in selected locations and at a perpendicular angle. Industry has sometimes used more sophisticated impacting devices (for example, air guns with controlled impact velocity) as an alternative to simple dropped weight impacts. These devices create normal impact to structure that is not oriented in a horizontal position; however, they generally result in higher test cost.

Typically, a test survey of varying impact energies is needed to establish the threshold of detectability for a given structural location. Alternatively, clearly visible damage can be applied for the ultimate load requirement, providing a robust design criteria, which could benefit subsequent manufacturing and maintenance activities.

In the case of thick composite structures, high energy levels may be needed to establish the threshold of detectability. When such a level is thought to exceed what is realistically expected in service, then a cut-off energy may be applied for the static strength requirement of ultimate loads. Consider those impacts that exceed the cut-off level within damage tolerance substantiation, with a residual strength requirement of limit load.

In the past, the conservative energy cut off applied as an upper level limit to the ultimate load requirement for thick structures was 1,000 inch-pounds. A value of 500 inch-pounds is a more realistic energy cutoff; however, lower impact energy levels have been justified using service data and probabilistic analyses. In most composite shell structures that are characteristic of small airplanes and business jets, the cut-off level is not applied because damage visibility is typically achieved at impact energies of 300 inch-pounds or less.

Impact test boundary conditions can significantly effect the resultant impact damage to the test specimen (test coupons, elements, sub-components, and components). This issue usually relates to the energy level needed to create some level of detectability for a given impactor geometry. As a result, some structural substantiation of the residual strength with impact damage at the component level is generally needed to adequately demonstrate compliance with the requirement.

7.3 Damage Tolerance

The purpose of § 23.573 (a)(1) is to ensure sufficient ultimate load capability with impact damage up to the threshold of detectability that can be realistically expected from manufacturing and service. This is not to be confused with damage tolerance requirements that ensure sufficient residual strength at limit loads. In addressing the damage tolerance issues for detectable damage, a range of impact variables that cause more severe damage should be considered. Some of the same test fixtures as those used for the ultimate load requirement can be used for damage tolerance substantiation, although additional impactor geometry should be considered to get a more complete range of potential threats.

There is another way of demonstrating the capability of composite structure and repairs subjected to repeated loads. Following damage tolerance substantiation, repair the detectable

damage and apply additional repeated loads before demonstrating ultimate load capability of a component.

8.0 Material and Process Variability

8.1 General

Consider the material and process variability of the composite structure in the static strength substantiation. This can be achieved in two basic ways:

- (1) Analytical Substantiation Supported by Tests: The first is achieved by establishing sufficient process and quality controls to manufacture structure and reliably substantiate the required strength in tests and analyses, which support a building block approach. The allowables and design values, which quantify material and process variability, are then applied in the analysis of the results of structural substantiation tests. This approach, which is similar to that typically applied for metal structure, is based on sufficient validation of the analyses at appropriate structural scales.
- (2) Substantiation Primarily by Tests with Minimal Analyses: The second approach relies more heavily on test results. When sufficient process and quality controls cannot be achieved, it may be necessary to account for greater variability with special factors (similar to those discussed in § 23.619, but with values derived for a given composite application) applied to the design. Account for these factors in the component static tests or analyses.

8.2 Analytical Substantiation Supported by Tests

A number of engineering guidelines can be used to decide whether it is sufficient to use allowables, design values, and analysis to account for material and process variability in structural substantiation. First, materials and fabrication processes used to make test samples, which establish a statistical basis for structural analysis, must be sufficiently controlled to ensure the allowables and design values that are derived represent those achieved in the structural components. Second, all analyses must be validated through the course of testing at different structural scales, including predictions of deflections, load paths, and overall strength.

Predictions of deflections and load paths are typically achieved through correlation with test results from strain gauges and other test instrumentation. In the case where a finite element model (FEM) is being used for analysis, the FEM is also being validated by test to meet the requirement of § 23.307. Model validation is required to establish confidence that model and modeling techniques are satisfactory to allow them to be used to show compliance for static strength conditions that are not tested. It is also necessary for model revisions needed in other analyses (for example, rotor burst, fire, and other discrete source failure conditions).

Validation of the strength prediction requires that critical locations are identified and the anticipated failure loads and modes are confirmed by tests. Such substantiation should include methods to account for the reduction in static strength associated with design details (for example, attachments, joints and cutouts), environmental effects, manufacturing defects and damage.

Although the numbers of tests and analyses increase with this approach to structural substantiation, generally more efficient structure and lighter weights are possible. This approach also yields a test and analysis database that tends to prove useful for engineers involved in solving subsequent manufacturing and maintenance problems.

8.3 Substantiation Primarily by Tests with Minimal Analyses

A number of engineering guidelines can be used to decide whether it is appropriate to use overload factors for structural substantiation in component tests. If the desired materials and manufacturing processes are not sufficiently mature to rely on accurate determination of structural strength margins, then it may be appropriate to overload test articles to account for the effects of material and process variability when this variability is greater than that in conventional metallic structure. This greater manufacturing and process variability is accounted for through the use of an overload factor.

Component test overload factors may also be appropriate when the structure being certificated is known to have sufficiently higher strengths than needed. In such a case, an overload testing approach may be used to avoid the more rigorous analysis validation, which is needed to substantiate the use of low margins of safety. Under such circumstances, some savings in development costs may be possible with an overload approach to structural substantiation, as opposed to an investment in the rigorous analysis and test correlation of a building block approach.

Applicants who use an overload approach to static strength test substantiation are relying on the structure to be sufficiently over-designed to ensure failure is not likely to occur below ultimate load levels due to material and process variations. Since these overload factors are in addition to those used to account for the environmental effects or repeated loads, the component hardware may be loaded well above ultimate loads.

An overload approach must also include the effects of design details, manufacturing defects, and damage as part of the component test hardware. Unfortunately, the types, location, and extent of defects covered in component tests, without validated analyses, may prove limited as applied to subsequent manufacturing and maintenance problems.

The conservatism applied to structure that is not strength critical is another concern in using overload factors. For example, structure failing in stability modes, which are not strongly affected by material and process variations in strength, would fit in this category. If analysis is able to predict stability failure, then an overload factor based on variation in material stiffness may be more appropriate.

8.4 Overload Factors

Derivation of the overload factors used to account for the effects of material and process variability in static strength substantiation tests should come from a rational engineering basis, which includes a statistically significant number of tests. Data from coupon tests of base material properties for multiple material batches and processing cycles generally provides such a basis.

Experience with composite materials and structures suggests that such coupon data should prove conservative in quantifying variations at structural scales, unless there is reason to believe processes used in manufacturing airplane components or structural failure modes yield greater variation. Conformity of the certification test hardware should provide the necessary data to make such engineering judgments. The overload factor should be sufficiently high to ensure it is extremely unlikely that material and process variations could yield structural components that fail below ultimate load.

Typically, overload factors for material and process variability may be based on the ratio between the mean and statistical “A” or “B” basis values of key material properties for single load path or damage tolerant structures, respectively. Such values indicate minimal attempts to validate analyses and associated structural margins of safety.

Lower overload factors may be appropriate in cases where some analysis validation is achieved in building block testing. For example, some analysis validation of the stiffness and internal loads could be used to reduce the overload factor such that the material variability characteristic of metal structures is subtracted from the difference between the mean and basis values. Overload factors discussed in this paragraph may not be sufficient if processes used to manufacture airplane structure are found to vary more than those used to manufacture panels for coupon tests.

8.5 Other Considerations

Using the overload approach to account for material and process variability in composite structural substantiation is more difficult when metal structure is part of the component design. Since overload factors are derived from composite properties, the capability of metal parts may not be sufficient unless a conservative design practice is adopted. In these cases, additional metal reinforcement may be used for test purposes to allow the overall structure to reach the higher loads selected for composite structural substantiation.

Any metal reinforcement used for test purposes must not change the load share between metal and composite parts. The reinforcement may also have to occur in steps during the sequence of testing if the metal part must first be included in static strength tests that substantiate their capability at lower load levels.

9.0 Conclusion

Several means of compliance in the static strength substantiation of composite airplane structure have been described in this document. The importance of performing large-scale tests to validate sufficient ultimate strength in the presence of complex load paths and failure mechanisms has been highlighted. The use of lower-level tests and validated analyses to address the critical issues, which includes the effects of environment, variability, manufacturing defects, service damage, and repair has also been discussed.

Building block tests and analyses at coupon, element, and sub-component levels also help minimize the number of large-scale tests. These engineering practices, which include rigorous structural analysis validation, more complete testing, and thorough quality control practices, may be used to avoid overloading large-scale structures to levels that force conservative design practices or cause failures in any integrated metal parts. On the other hand, overload factors may be used to successfully expedite static strength substantiation, provided the composite structure has sufficient strength when overloaded to levels accepted by the appropriate Aircraft Certification Office.

Analysis and test technologies as well as material and manufacturing quality controls are likely to advance, providing more confidence in scaling results from lower levels of study to configured airplane structure. As a result, the joint efforts of regulatory agencies, other government groups, industry, and academia will no doubt extend the state-of-the-art, reducing the burden in composite static strength substantiation in the future. When sufficient advancement in the field is achieved, this policy document will be updated accordingly.

10.0 References

- (1) Memorandum entitled "Material Qualification and Equivalency for Polymer Matrix Composite Material Systems," ACE-100 Proposed Policy, May 2000.
- (2) "Material Qualification and Equivalency for Polymer Matrix Composite Material Systems," FAA Technical Report - DOT/FAA/AR-00/47, April 2001.

If you have any questions or comments, please contact Mr. Lester Cheng, Regulations and Policy Section either by telephone at 316-946-4111, by fax at 316-946-4407, or by email at lester.cheng@faa.gov.

S/ Scott Sedgwick
for

Michael Gallagher
Manager, Small Airplane Directorate
Aircraft Certification Service