Study on Airworthiness Requirements of Composite Aircraft Structure for Transport Category Aircraft in FAA

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Abstract

This article focus on the introduction of composite structure characteristics and background of usage in civil aviation, also on airworthiness requirements in FAR 25 which include raw materials, manufacturing processes, structure static strength, fatigue property and damage tolerance. The building block approach, AGATE and NCAMP program are studied to improve the sharing of database furnished by material suppliers and to reduce cost in airworthiness certification. This article presents an analysis and testing methodology to support certification and maintenance of composite structures based on establishment of residual strength versus damage size relationships, determination of allowable ultimate load damage limits and limit load capability damage thresholds to insure that residual strength of composite structure is higher than the limit load strength. Other airworthiness considerations such as lightning protection, crashworthiness, fire protection and so on, are finally introduced for composite structure. A reference is provided to native composite structural airworthiness certification for transport category aircraft.

1. Introduction

The application of composite structure which provides redundant load paths and high specific bending stiffness without a significant increase in structural weight in commercial aviation and is changed from

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small, simple structures to huge, complex supporting structures in civil aircrafts, is developed very quickly recently with from just 1~3% usage of composite structure in 1960s to 50% usage today in B787 and A350. Several composite primary structures, such as the Boeing 777 empennage and NASA-ACEE/Boeing 737 horizontal stabilizers, have been certified per FAR 25 and JAR 25. The 737 stabilizers have demonstrated excellent service performance\(^\text{[1]}\), this service experience as well as component testing \(^\text{[2-5]}\) has shown that current composite aircraft structure has excellent resistance to environmental deterioration and fatigue damage. This leaves accidental damage as a primary consideration for composite damage tolerance design and maintenance planning.

Structural performances between composite and metal are different, with exhibitions of environment (temperature and humidity) sensitivities in envelop of usage, sensitivities of low energy impact and out-of-plane loads. The latest airworthiness certification standards for composite structure occurred on May 24th 2011 with the issuance of FAR 25 and Advisory Circular \(^\text{[10]}\) on September 8th 2009 which was published to aid in the evaluation of certification programs for composite applications and to reflect the current status of composite technology. Other corresponding Advisory Circulars \(^\text{[6-9]}\) were also issued to provide acceptable means of showing compliance with FAR 25 involving damage tolerance and fatigue evaluation, raw materials, fabrication, sampling, lightning, quality control, fire protection and so on.

This article analyses airworthiness certification requirements for composite aircraft structure in FAR 25 and corresponding compliance methods which are about validation raw materials, certification of procedure, static strength, fatigue and damage tolerance, aeroelastic instabilities and other considerations focusing on composite aircraft structure certification for transport category aircraft. This article is intended to provide technical support to airworthiness certification of composite structure for native transport category aircraft relating to applying TC, also intended to put forward new directions of structural design, analysis and experimental verification in china.

## 2. REQUIREMENTS FOR MATERIALS AND PROCESSES

### 2.1. CERTIFICATION REQUIREMENT

Airworthiness certification of composite materials and manufacturing processes for transport category aircraft should be implemented per §25.603, §25.605, §25.609, §25.613 and §25.619 which require that all composite materials and processes used in structures are qualified through enough fabrication trials and tests to demonstrate a reproducible and reliable design. The depth and detail of certification are related with function of components and degree of importance. The following aspects of airworthiness certification about material performance should be considered:

Thermal analysis and moisture absorption analysis including environmental top design temperature; thermal parameters during analysis, such as heat absorption rate, reflectivity and heat conduction coefficient of coating; parameters used in moisture absorption analysis, such as wet spread rate and so on; the selecting of adjustable parameter in accelerating environment; confirming materials including material and processes specifications which depend on mechanics, physical tests, chemical tests and so on; the requirement for candidate material suppliers; relater manuals \(^\text{[11]}\) should be used in handing tests data; ASTM or equivalent methods; detail design features and so on. Material Specifications covering processing procedures which should be developed to ensure that repeatable and reliable structure is being manufactured are required to ensure consistent material is being procured. Once the fabrication processes have been established, changes should not occur unless additional qualification, including testing of differences is completed. Environmental effects on critical properties of the material systems and associated processes should be established.
2.2. AGATE AND NCAMP PROGRAM

The materials and processes should be accepted as part of a particular aircraft product certification. In some cases, material and processing information may become part of accepted shared databases used throughout the industry when the same materials and processes are used in similar applications subject to substantiation and applicability.

As depicted in Figure 1 and Figure 2, the advanced general aviation transport experiments (AGATE) and the national center for advanced materials performance (NCAMP) which takes the AGATE shared database approach to the next level, focused towards “low-cost” composite material systems and funded by NASA aim to create a shared database program for traditional materials, to design airframe based upon a combination of material vendors (minimum B-basis criteria), to provide statistical materials management and control, to accelerate advanced materials usage and to monitor material stability.

![Fig. 1. Traditional Process (left) and AGATE Process (right)](image1)

![Fig. 2. NCAMP Shared Database Process](image2)
As depicted in Figure 2 and Figure 3, material suppliers and aircraft companies cooperate to monitor material property variations over time to establish policy for those composite databases that can be shared by OEM & product users in development, certification and maintenance. Firstly, multi-batch material qualification should be done to generate the database and set specifications. Secondly, equivalency (mini-qualification) should be made to sample and show you process the material to fall within the database population and, if desired, update specifications per your specific use of material as allowed with guidelines. Finally, database should be applied to your product to control the material continuously.

Fig. 3. Material Property Monitoring

Base material qualification provides a representative database of key properties and characteristics for use in design and subsequent quality control (repeatable raw material production). Raw composite material is significantly advanced in fabricating the OEM product and a material equivalency exercise is required to use the qualification database in certification.

3. REQUIREMENTS FOR STATIC STRENGTH

Airworthiness certification of static strength of composite aircraft structure for transport category aircraft should be implemented per § 25.305 and § 25.307 which should consider all critical load cases and associated failure modes and be demonstrated through a program of component ultimate load tests in the appropriate environment. The strength of the composite structure should be reliably established, incrementally, through a program which referred to in industry as the “building block approach” of analysis and a series of tests conducted using specimens of varying levels of complexity.

Fig. 4 shows a typical Building Block program flow whose philosophy is to make the design development process more effective in assessing technology risks early in a program schedule. Cost efficiency is achieved by designing a program in which greater numbers of less expensive small specimens are tested and fewer of the more expensive component and full scale articles are required. Using analyses in place of tests where possible also tends to reduce cost.

At the lowest Building Block level, small specimen and element tests are most widely used to characterize basic unnotched static material properties, generic notch sensitivity, environmental factors, material operational limit and laminate fatigue response. Analysis in the second level uses the basic information obtained at the first level to calculate internal loads, identify critical areas, and predict critical failure modes. At subsequent levels, even more complex static and fatigue loadings are analyzed and verified, with particular attention directed toward assessing out-of-plane loads and identifying unanticipated failure modes. Variabilities introduced by scale-up and response of the structure as a whole
are also addressed. The final building Block level involves full scale static and fatigue testing (as required). This testing validates predicted internal loads, deflections, and failure modes of the entire structure. It also serves to verify that no significant unpredicted secondary loads have appeared.

Fig. 4. Typical building block program flow

Fig. 5. Block approach for commercial aircraft primary structure

As illustrated in Fig. 5, the typical composite structure certification approach is primarily analytical, supported by test evidence at the coupon, element, subcomponent and component level, and full-scale limit load test at ambient environment. The environmental effects on the composite structure are characterized at the coupon, element and subcomponent levels and are accounted for in the structural analysis. Supporting evidence includes testing through a “building block” approach where material
characterization, allowables and analysis methods development, design concept verification, and final proof of structure are obtained.

4. REQUIREMENTS FOR FATIGUE AND DAMAGE TOLERANCE

Airworthiness certification of fatigue and damage tolerance of composite aircraft structure for transport category aircraft starting with identification of structure whose failure would reduce the structural integrity of the aircraft should be implemented per § 25.571 which requires that catastrophic failure due to fatigue, environmental effects, manufacturing defects, or accidental damage will be avoided throughout the operational life of the aircraft.

Five categories of damage as described in Fig. 6 which shows the relationship between design load levels and damage severity. All damages have associated repair scenarios except for category 1. Ultimate strength and damage tolerance design philosophies are used to help maintain the reliable and safe operation of composite structure. Design requirements of residual strength for relatively small damage, which are likely to occur in service, are matched with very high (unlikely) load scenarios (ultimate). The design requirement for more severe damage states, such as those caused by impact events that have a very low probability of occurrence, are evaluated for the upper end of realistic load conditions (limit). The most severe damage states considered in design are those occurring in flight (e.g., engine burst). The flight crew generally has knowledge of such events and they limit maneuvers for continued safe flight. Depending on the specific structure and an associated load case, continued safe flight load requirements may be as high as limit (e.g., pressure loads for fuselage).

Fig. 7 shows all three damage growth approaches applied to composite structure. Slow growth characterization should yield conservative and reliable results and inspection program should be developed consisting of the frequency, extent and methods of inspection for inclusion in the maintenance plan. The arrested growth method is applicable when the damage growth is mechanically arrested or terminated before becoming critical (residual static strength reduced to limit load). “No-growth” approach shows that inspection intervals should be established, considering the residual strength capability associated with the arrested growth damage size (refer to the dashed lines added to Fig. 7 to conceptually show inspection intervals consistent with the slow growth basis). The arrested growth method is applicable when the damage growth is mechanically arrested or terminated before becoming critical (residual static strength reduced to limit load).

Fig. 6. Design load levels versus categories of damage severity
Fig. 7. Three different approaches to composite structural damage

Fig. 8 shows the difference that can be found between non-growing impact damage in a composite structure and a, prone to grow, fatigue crack in a metallic one. As shown with the metal curve, an inspection interval can be rationally derived such that fatigue damage in metallic structure is safely detected and repaired before the strength drops below Limit Loads. For composite, a structure with impact damage could sustain a long duration below Ultimate Load without a threat of the residual strength further dropping to the critical threshold defined by § 25.571(b) (i.e., Limit Load). A composite structure is allowed to fly a long time with residual strength just above Limit Loads. Regardless of the damage growth resistance of composite structure, damage that lowers the residual strength below Ultimate Load must be detected and repaired when found by defining a rationale inspection interval to attain equivalent or higher levels of safety than metal practice. The residual strength curve, damage growth resistance, service databases and user maintenance practices should all be considered in establishing the inspection intervals.

Fig. 8. Composite non-growing damage and metal fatigue crack damage (Ultimate Load and Limit Load)
Current airworthiness requirements for composite aircraft structures with damage should be considered from above contents. Composite designs should afford the same level of fail-safe, multiple load path structure assurance as conventional metals design. Structure containing likely damage or defects that are not detectable during manufacturing inspections and service inspections must withstand Ultimate Load and not impair operation of the aircraft for its lifetime (with appropriate factor). Structure containing damage that is detectable during maintenance inspections must withstand a once per lifetime load, which is applied following repeated service loads occurring during an inspection interval (with appropriate factor). All damage that lowers strength below Ultimate Load must be repaired when found. Structure damaged from an in-flight, discrete source that is evident to the crew must withstand loads that are consistent with continued safe flight. Any damage that is repaired must withstand Ultimate Load.

5. AEROELASTICA AND OTHER CONSIDERATIONS

Airworthiness certification of flutter and additional considerations, such as crashworthiness, fire protection, flammability, thermal issues and lightning protection of composite aircraft structure for transport category aircraft, should be implemented per § 25.629, § 25.561, § 25.863, § 25.581, § 25.954, § 25.562 and so on.

Flutter, control reversal, divergence, and any undue loss of stability and control as a result of structural loading and resulting deformation should be evaluated by analysis supported by test evidence, or by tests at the coupon, element or subcomponent level.

Occupants which must be protected during the impact event from release of items of mass must have every reasonable chance of escaping serious injury under realistic and survivable crash impact conditions. The emergency egress paths must remain following a survivable crash. The acceleration and loads experienced by occupants during a survivable crash must not exceed critical thresholds. A survivable volume of occupant space must be retained following the impact event.

The lightning protection effectiveness for composite structures should be demonstrated by tests or analysis supported by tests which are performed on panels, coupons, subassemblies, or coupons representative of the aircraft structure, or tests on full aircraft. Lightning protection should be evaluated for structural integrity, fuel Systems, electrical and electronic systems which are described in detail in DOT/FAA/CT-89/22“Aircraft Lightning Protection Handbook”.

6. CONCLUSIONS

Structural airworthiness is the first aspect in airworthiness certification for composite material structure which has particular desirable performance, togetherness of material and structure, multiplicity of potential failure modes and lack of regularity, sensitivity to out-of-plane loads and to operating environment. The items of structural airworthiness regulation are established on above key problems and have close relations with the improved knowledge of safety for aircraft structure. In the period of service life, structure must be designed to bear limit load and meet the rigidity requirement in the appropriate environment, this is not only applied to new structure and also to aging structure.

New direction of research is put forward in the current and future design and evaluation for composite materials. To improve the economic benefit and environment protection, if changing material is requested for composite materials which have been approved, alternative materials should be identified through procedure of equivalent certification. The establishment of final moisture absorption quantity must depend on the most severe environmental impact because of the drop of composite material performance after moisture absorption. The difficulty of airworthiness certification on new forming technologies (including new special resin system) of composite materials, such as resin film infusion process (RFI),
resin transfer mould process (RTM) and so on, is becoming more and harder because of required new special resin matrix and preparation of perform (perform of reinforced fiber).

References