PRINCIPLES FOR ACHIEVING DAMAGE TOLERANT PRIMARY COMPOSITE AIRCRAFT STRUCTURES

H. Razi and S. Ward
The Boeing Company
Boeing Commercial Airplane Group
Seattle, Washington

ABSTRACT

This paper presents an analysis and testing methodology to support certification and maintenance of composite structures based on: a) establishment of residual strength versus damage size relationships; b) establishing methods of damage detection and minimum detectable damage sizes; and c) determination of allowable ultimate load damage limits and limit load capability damage thresholds. Flow charts outlining an approach for achieving damage tolerant and fail safe designs are also presented.

INTRODUCTION

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 [1]. This service experience as well as component testing [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.

In-service damage resistance and repair of thin gage composite has become a major issue for the commercial airlines. In order to make composites cost effective for the airlines, allowable damage limits (ADLs) must be set at their maximum allowable size while still meeting regulatory ultimate load requirements. To achieve this goal, test data and analytical methods encompassing the complete range of potential damage sizes and types are required.

This paper presents a design approach to ensure that composite structures have low in-service maintenance costs as well as adequate damage tolerance. Several damage sizes based on detectability levels are described and requirements for each damage size relative to FAA and JAA regulations are discussed. Suggestions are made for developing
appropriate databases to satisfy regulatory damage tolerance requirements and achieve low maintenance costs.

**ACRONYMS**

- **ADL** Allowable Damage Limit (damage size and state which reduces strength to design ultimate load)
- **BVID** Barely Visible Impact Damage
- **CDT** Critical Damage Threshold (damage size and state which reduces strength to design limit load)
- **DLL** Design Limit Load
- **DUL** Design Ultimate Load
- **MDD** Maximum Design Damage
- **RDD** Readily Detectable Damage (damage of a size and state such that it will be detected within a small number of flights during routine aircraft servicing)

**DAMAGE TOLERANCE DEFINITIONS**

Damage tolerance assessments involve the application of known damage threats to the aircraft structure during its typical service usage and demonstration that this damage will not alter the safe operation of the aircraft prior to detection. Damage tolerance builds upon fail-safe analysis by including determinations of damage growth characteristics and by establishing damage detection methods and inspection plans.

The minimal environmental deterioration and fatigue damage [2-5] leaves accidental damage as a primary damage source in composite structures. Several methods for improving the performance of impacted composite panels and components have been proposed [6,7]. One approach is to increase the inherent toughness of the composite by using tougher resin matrices. Although this method improves damage resistance and reduces maintenance costs, material costs and reductions in stiffness limit application of "toughened" material systems for thin honeycomb sandwich composite panels.

In metallic structures, damage tolerance has been demonstrated using fracture mechanics to characterize crack growth under cyclic loading, predict the rate of crack growth in the structure under anticipated service loads, and establish inspection intervals based on realistic damage detection reliability considerations[8]. Since typical CFRP composites have relatively flat S-N curves, and because these damages do not propagate under aircraft wing/empennage operational loading spectra, the above method cannot be used to establish inspection plans. Therefore, a no-growth approach has been used to
demonstrate compliance with damage tolerance requirements for composite primary structures on commercial aircraft for current composite structures.

For damage larger than BVID sizes, damage types and sizes are classified into several groups based on the likelihood of damage detection as shown in Figure 1. The selection of damage sizes must be consistent with the established inspection program and with the corresponding reduction in static strength. The following paragraphs describe the different damage types and sizes:

(a) Barely visible impact damage (BVID) is defined as damage that establishes the strength design values to be used in analyses demonstrating compliance with the regulatory ultimate load requirements of FAR 25.305. The extent of such damage is established prior to the design phase. The term visible is used since the primary inspection method in current use involves visual observation.

(b) Allowable damage limits (ADL), defined as damage that reduces the residual strength to the regulatory ultimate load requirements of FAR 25.305, are determined to support maintenance documents. Given that the structure’s strength with BVID damage will result in positive margins at design ultimate load (DUL), the corresponding ADL will be larger than the BVID (see Figure 1). Characteristics describing the detectability of the ADL as well as the type and extent of the damage are documented to support maintenance programs.

(c) Maximum design damage (MDD) is defined as damage that establishes the strength design values to be used in analyses demonstrating compliance with the regulatory damage tolerance requirements of FAR 25.571(b). The extent of such damage is established prior to the design phase.

(d) Critical damage thresholds (CDT) are defined as damages that reduce the residual strength to the regulatory requirements of FAR 25.571(b). Given that the structure’s strength with MDD size damage will result in positive margins at design limit load (DLL), the corresponding CDT will be larger than the MDD. Characteristics describing the detectability of the CDT as well as the type and extent of the damage are documented to support the establishment of required inspection methods and intervals. Using the selected inspection technique, realistic damages smaller than the corresponding CDT are shown to be detectable with high probability before any growth causes it to exceed the CDT.

(e) Readily detectable damage (RDD) is defined as damage that can be detected within a small number of flights during routine aircraft servicing. For damage that is not readily detectable, the structure should be evaluated for all possible damage growth mechanisms. The maximum extent of damage that is considered readily detectable, but which is not immediately obvious, should be
established. The advisory circular for damage tolerance, AC 25.571 (a), allows the residual strength of RDD to be confirmed at load levels less than the regulatory loads specified in FAR/JAR 25.571 (b) [9].

Damages larger than the maximum readily detectable damage are considered to be immediately obvious. Except for damage resulting from in-flight discrete sources (rotor burst, bird strike, etc.), no residual strength analysis is required for obvious damage.

The residual strength curve in Figure 1 starts near ultimate strength and spans the range to discrete source damage sizes. This range encompasses damage conditions critical to meeting all requirements such as:

a) Damage sizes and states which support the allowable damage limits (ultimate load levels) and repairable damage sizes to be placed into the Structural Repair Manual;

b) CDT damages for limit load design values;

c) Readily detectable damage for less than limit load but greater than continued safe flight load design values; and

d) "Discrete source" damage for continued safe flight load design values.

Test data and analysis methods developed by the Boeing-NASA/ACT program [10-12] shows that the inspection methodologies and damage growth mechanisms should be established to ensure accidental damage occurring in-service can be found and repaired before compromising limit strength capabilities. Visual inspection is the preferred damage detection method, and the no-growth approach for damages less than limit load size has been the basis for certification. For new composite primary structure application these approaches will require revalidation.

Figures 2 and 3 identify the inspection decision points, requirements, development tasks, analyses and actions required to meet the damage tolerance requirements of a principal structural element (PSE). Figure 2 outlines the levels of damage tolerance requirements and can be used for test, analysis and maintenance planning. Figure 3 defines the flow of events and actions to be used to develop the data required for damage tolerance certification.

**DESIGN VALIDATION APPROACHES FOR DAMAGE TOLERANCE**

The following two approaches to certifying composite principal structural elements for damage tolerance have been used:

**Method 1:** This method is based on two sets of testing and analysis. The first set of testing and analysis is designed to show positive margins of safety at design ultimate load with BVID size damages. This testing includes mostly coupons and subcomponents containing BVID. The second set of testing is designed to show
positive margins of safety with large damage at design limit load. This testing includes subcomponent (e.g. five-stringer panels) and component structures with through-the-thickness damage, skin-stiffener debonds, large impact damages, etc. These types of damage are considered to be maximum design damage (MDD). Tests are used to show MDD size damage are easily detectable, and that damage of this size and smaller does not grow under operational loads.

Method 2: This method involves a probabilistic assessment of the occurrence of impact damage at a given impact energy level, probability of occurrence of a load level, and the likelihood of detection of a given impact damage. The inspection intervals and methods are defined such that the cumulative probability of failure risk will be lower than $10^{-9}$ per flight hour [13]. This method, in addition to the ultimate and limit load tests described for method 1, requires tests to be conducted for intermediate damage sizes. Also required is detailed knowledge of damage threats and their probabilities of occurrence, as well as detailed detectability characteristics for the range of damages between BVID and MDD. This method involves a series of analyses at various load levels between DUL and DLL to verify the probability of failure based on the probability of a given damage and its corresponding detectability.

Although both methods meet FAA requirements for damage tolerance, they may not provide enough data to support large allowable damage limits in structural repair manuals. Consequently, allowable damage sizes are set to conservative smaller values. This has the effect of increasing in-service repair costs of thin composite honeycomb sandwich panels in commercial aircraft.

Figure 4 shows ranges of typical data generated in both methods 1 and 2 to design and certify commercial aircraft structures. It can be seen that only a small band of the residual strength curve is defined. Since residual strength of in-service damage sizes are not available, often BVID sizes are used for ADL sizes in structural repair manuals. These are conservative sizes and can result in increasing maintenance costs.

The following are recommended approaches for developing data to support certification and to allow for reduced maintenance costs of composite aircraft structures:

a) The residual strength curve for each significant type of potential damage on each principal structural element should be determined by analysis and/or test.

b) Characteristics describing the inspectability of the CDT as well as the type and extent of the damage should be documented to support maintenance planning activities.

c) For readily detectable damage, the magnitude of the threats that should be considered, similar to those in FAR 25.571 (e), should include impact damage by ground vehicles and ground handling equipment, impact with jet gates,
runway debris and thrown tire treads. Service experience has shown that damage associated with such events may persist for a few flights before the damage is detected and the structure repaired. The extent of damage that should be considered must be established by taking into account susceptibility to each type of accident.

**SUMMARY**

Structural damage design should be coupled with development of the aircraft maintenance plan in order to reduce in-service damage occurrences and repair costs. Test validation and analyses should address design ultimate strength, damage growth, residual strength, and maintenance issues for composite structures. Independent studies of design ultimate load or limit load strength without data and analyses at intermediate load levels will not provide a balanced design that supports cost-effective maintenance. For example, damage considered for ultimate strength analyses is more likely to occur in-service while the associated loads are very unlikely. The reverse is true for limit strength analyses. A database that covers a range of damage scenarios increasing in severity will allow for more cost effective use of composite structures in commercial aircraft service.

**ACKNOWLEDGMENTS**

The authors would like to gratefully acknowledge the contributions to this effort of B. Backman, E. Dost, L. Ilcewicz and M. Miller of the Boeing Commercial Airplane Group.

**REFERENCES**


Figure 1. Residual Strength Versus Damage Size

- **BVID**: Barely visible impact damage
- **DUL**: Design ultimate load
- **MDD**: Maximum design damage
- **ADL**: Allowable damage limit
- **CDT**: Critical damage threshold

- **DLL**: Designing limit load
- **DSD**: Discrete source damage
- **RDD**: Readily detectable damage
- **MS**: Margin of safety
Figure 2. Levels of Damage Tolerance Assessments

Damage Type

Is Damage Result of In-flight Discrete Source Event?
  Yes
  Residual Strength with “Get-Home” Loads per FAR 25.571(e)
  No

Is Damage Immediately Obvious?
  Yes
  Immediate Repair
  No

Is Damage Readily Detectable?
  Yes
  Residual Strength with Loads Between FAR 25.571(b) and 25.571(e) (see ACJ 25.571(a), Section 2.1.2)
  No

Is Damage Detectable By Planned Inspections?
  Yes
  Residual Strength with Loads per FAR 25.571(b)
  No

Does Undetectable Damage Grow?
  Yes
  Becomes Detectable?
    Yes
    Safe-Life Assessment per FAR 25.571(c)
    No
    Residual Strength with Ultimate Loads
  No

Residual Strength with “Get-Home” Loads per FAR 25.571(e)
Immediate Repair
Residual Strength with Loads Between FAR 25.571(b) and 25.571(e) (see ACJ 25.571(a), Section 2.1.2)
Residual Strength with Loads per FAR 25.571(b)
Safe-Life Assessment per FAR 25.571(c)
Residual Strength with Ultimate Loads
Figure 3. Damage Tolerance Assessment Flowchart for Fail-Safe Loads
Figure 4. Residual Strength Versus Damage Size Relationship