AIRCRAFT DAMAGE TOLERANCE

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Abstract

The introduction of advanced composite materials leads to not only new attributes for aerospace structures, but also leads to the introduction of new technological elements to be considered. From a historical prospective, structural aircraft design has transgressed from wood structures (homogenous, anisotropic materials), to metallic structures (homogenous, isotopic materials), to advanced composite structures (homogenous, anisotropic materials). While a review of the above structural materials suggests a full circle progression, our knowledge in characterizing and modeling the behavior of these materials has increased significantly. As an example, the Wright Brothers used wood, a homogeneous, anisotropic material, without understanding the intricacies of anisotropy. As design experience progressed to the next generation of metallic based structures, our understanding of characterizing and modeling homogeneous and isotropic material behavior at the phenomenological level in design practice became documented. With the introduction of advanced composite materials, the inherent anisotropy of such materials has led to new failure mechanisms unlike our historical experience with metallic materials. In addition to the characteristic and inherent anisotropy, the brittle nature of such materials, coupled with the initiation and growth of damage, remains to a degree uncharted territory. This has led to a design approach which can at best be described as semi-empirical and relies on experience for design/certification. In this talk, we will explore damage tolerance issues based upon design requirements, current state of the art design and analysis, some selected examples, and concluding remarks

1 Introduction

Issues related to the structural integrity of composite materials have found attention in the subject area of damage tolerance. In this paper, issues related to the methodology, design, and state of the art of damage tolerance are examined. A key element is related to the definition of damage tolerance. The key features associated with a definition for composite structures can be summarized as follows:

- The damage tolerance evaluation of structure is intended to ensure, that should fatigue, intrinsic/discrete damage, large area manufacturing flaws, or severe accidental damage occur within the operational life of the aircraft, the remaining structure will withstand reasonable loads without failure of excessive structural deformation until the damage is detected.

From this definition come the following considerations:

- The acceptance that damage will occur
- An adequate system of inspection so the damage may be detected
- An adequate strength maintained in the damaged structure.
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These considerations lead to the following goal:

- Composite structure should maintain lifetime design loads in a damaged condition up to the condition where a barely visible damage state is detectable.

2 Damage Tolerance Methodology

The considerations delineated above lead to the following design requirement for composite structures:

- Will not accept composite structures that are less damage tolerant than metals.

Based upon the above statement, requirements as shown below follow:

- Mature design practices

- Extensive tests to support analysis
- Robust in-service experience

3 Design Issues

From in-service experience, the most dangerous loading mode to aircraft structures appears to be impact damage. Associated with this mode of loading is the requirement for sustained strength after impact, specifically retained compression strength. Thus follows that

- <u>Compressive strength retention</u> after impact is the most critical condition for composites.

While impact damage is considered the key source of damage, a number of sources of damage are indicated below:

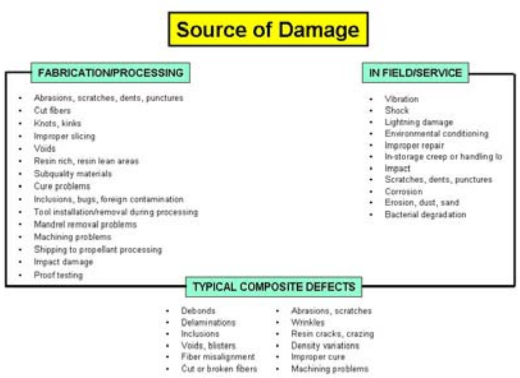


Fig. 1. Source of Damage

The recognition of damage sources has led to the introduction of damage categories. These indexes have been introduced as important categories for primary structural components. As defined at a recent damage tolerance and maintenance workshop held in Chicago in 2006, the damage categories delineated have been summarized below:

- Category 1 – Damage that may go undetected by field inspection methods
- Category 2 – Damage detected by field inspection
- Category 3 – Obvious damage detected within a few flights by operations
- Category 4 – Discrete source damage and pilot limits flight maneuvers
- Category 5 – Severe damage created by anomalous ground or flight events

As indicated above, damage identification is a key factor in cataloging the damage categories. It has been noted that approximately 80-90 percent of inspections for damage are visual. This begs the need for diagnostic tools to catalog and characterize damage particularly for internal damage in composites.

As a design strategy for developing design criteria, both an experimental and analytical tool box are needed. The test pyramid below indicated a strategy for experimental testing, while the analytical is captured in the accompanying design.

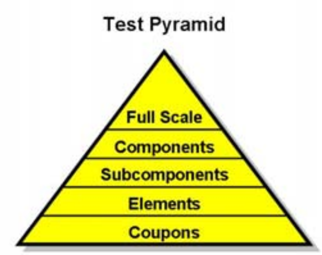


Fig. 2. Test Pyramid

4 Analytical Approach

Final Validation

- Verify analysis methods
- Verify FEM or other tools used to stress/strain distributions

Methodology & Computing Validation

- Allowable validation against coupon and smaller specimens

- At detail level, critical values are determined if test results are used in the analysis

State of the Art

The current state of the art is based upon knowledge of the sources of damage (See Figure 3) and the types and degree of the damage state as shown below:

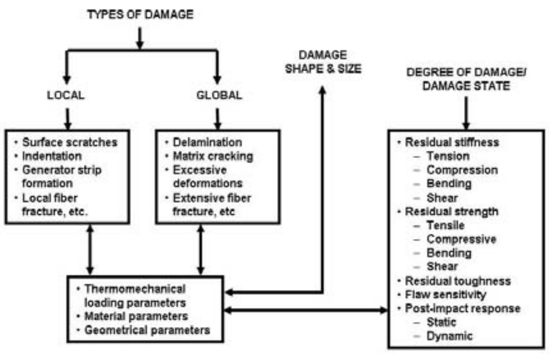
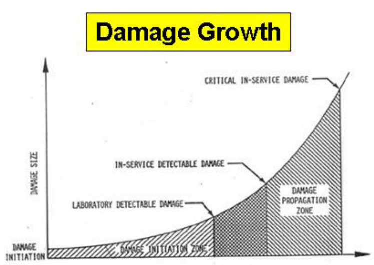


Fig. 3. Sources of Damage

The above information leads to models for evaluating damage growth and the resulting retained strength for in-service use. Both experimental and analytical issues are noted in the following figure:



Experimental Issues

Detection of damage size

Analytical Issues

- **Establishing damage metrics, i.e., time to grow to critical size**

Fig. 4. Damage Growth

As noted earlier, the most important source of damage has been identified as impact damage. This is shown in the figure below:

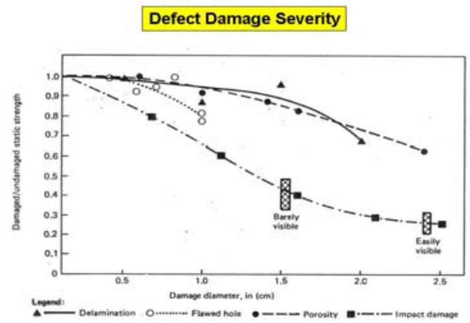


Fig. 5. Defect Damage Severity

This figure also shows the various types of damage including matrix cracking, delaminisation and fiber fracture. This leads to requirements for design criteria starting with the damage threat assessment and the structural category, safety assurance, and technology control as noted in the accompanying figure:

Structural Category	Safety Assurance	Technology Control
Secondary Structure	Redundancy	Functional Performance
Primary Structure (obvious damage)	Adequate Residual Strength	Residual Strength
Primary Structure (damage detection)	Damage Detection	Residual Strength Crack Growth

Fig. 6. Types of Damage

This can be accompanied by a table which reflects upon defect damage size:

Flaw/Damage Type	Flaw Damage Size
Scratches	Assume presence of a surface scratch 4.0" (12cm) long and .02" (.05cm) deep
Delamination	Assume presence of interply delamination area equivalent to 2.0" (5.1cm) diameter circle
Impact Damage	Assume presence of impact induced damage caused by hemispherical compactor of 1.0" (2.5cm) diameter with 100 ft.-lb. KE (136J) causing a .10" (.25cm) dent

Fig. 7. Defect Damage Size

5 Concluding Remarks

- The use of Advanced Composites is expanding in aircraft
- Damage Tolerance is a key aspect of safety in composite primary structure
- Understanding composite behavior to diverse loading conditions is evolving
- Need to communicate and coordinate composite use experiences between aircraft users, maintenance personnel, and regulatory agencies.