Damage Tolerance of Composite Laminates from an Empirical Perspective

Alan T. Nettles, PhD
Composite Materials Engineer
NASA, Marshall Space Flight Center

Alan.t.nettles@nasa.gov
Plenty of controversy on analyzing undamaged laminates

Undamaged Face sheet  Difficult to predict failure

Impact Damaged Face sheet  Extremely difficult to predict failure

See for example the World Wide Failure Exercise (WWFE)
Composite Laminates can be “damaged” in many ways:

- **Manufacturing Defects** (porosity, debris between plies...)
- **Burns** (runaway heat blanket light fixture too close for too long...)

The most common is **Impact**
“Damage Tolerance” consists of two parts.....

**Damage resistance**: The ability of a material to not permanently change due to a loading event outside the design envelope.

Ex. Dropping a bowling ball on floor.......  
  Rubberized gymnasium floor => Damage resistant  
  Ceramic tile kitchen floor => Not damage Resistant

**Damage tolerance**: The ability of a material to function after a permanent change has taken place.

Ex. Damaged tabletop  
  Wood => Damage tolerant (can hit with axe but still hold heavy computer)  
  Glass => Not damage tolerant (don’t put heavy computer on if cracked)
Damage Tolerance and Damage Resistance are not necessarily related

Identical impact conditions

Resin A more damage resistant than resin B

Equal damage tolerance
For Laminated Composites, damage due to foreign object impacts is of great concern.

- High Shear Stresses
- More severe impacts can break fibers
- No reinforcement between plies
- Plies (Laminae) separate resulting in a delamination
Compression Strength After Impact (CSAI) is of particular concern.

**Tension After Impact**

**Delamination Simply “Closes-Up”**

**Compression After Impact**

Sub-laminates buckle
Buckling Load ($P_B$) is proportionate to $t^3$

$$P_B \propto t^3$$

Material can locally buckle at the delamination

$$P_B \propto \frac{2t^3}{8} = \frac{t^3}{4}$$
Tension Strength After Impact (TSAI) is of concern for structures such as pressure vessels (rocket motor cases)

Shear Strength After Impact (SSAI) is of concern for some structures such as cylinders that twist (airplane fuselage)

Difficult to test
Other Properties After Impact may be of concern for certain structures

Permeability (leakage) after impact
Aerodynamic Smoothness
Localized Stiffness
CTE (telescope tubes)

......Others......
Disposition of Impacted Laminates

If a laminate is damaged:

• If damage is not found (undetectable): Part must perform as if undamaged
  
  “If you can’t see it, you must prove that it can’t hurt performance”
  
• If found, then the damage must be assessed and 3 options exists

  1. Use part “as is”
  2. Repair
  3. Scrap part
Comment on the damage tolerance philosophy

Many programs follow Composite Materials Handbook-17 (formerly MIL-17)

Authors recognize *document is airplane specific*

“This information is presented from the perspective of aircraft structures, since that is the authors’ background;…”

It is **not** requirements…no “shall statements”, it is a guide!

“Damage Tolerance” is unique to each industry

Aircraft have most stringent requirements….most composite laminates will probably not need this high level, and you probably cannot afford it (unless you are building an aircraft)

For some programs the philosophy is “make sure it doesn't get hit”
Many factors influence how much damage is incurred by a given fiber/resin laminate from a foreign object impact event...most of these are obvious

For a given impacting object (impactor)

- Higher velocity => more damage
- Thinner laminate => more damage
- Boundary Conditions of laminate have large influence
- Incident angle of impact => Higher angle, less damage

For a given impacting velocity

- Heavier impactor=> more damage
- Sharper Shape=> more damage (usually)
- Boundary Conditions of laminate have large influence
- Rigidity of impactor => more rigid, more damage
Damage may not be simple to characterize

Characterizing the level of damage is performed a number of ways depending upon application, costs, ease of access, etc...

Most Common is Visual, which can be subjective

NDE techniques are often employed.

Zinc Iodide used as an opaque dye penetrant
Laboratory characterization (coupon testing) helps to better understand impact events.

Impact can be controlled with instrumented impactors.

Can relate internal damage to NDE via Cross-Sectional Microscopy.
Ultimately the Goal is to Predict Laminate Performance with a given damage state

The remainder of this presentation will use Compression Strength as a Performance parameter

*Keep in mind that your key performance parameter may be another property!*

Establishing a Damage Tolerance Curve (plot of performance verses damage severity) is very useful

- Compressive Strength
- No degradation
- Strength degradation begins
- Region of rapid strength loss
- "Knee"
- Small degradation with increasing impact severity

- Used to aid in defining critical damage levels
Damage Severity can be quantifiably measured in different ways

NDE Size

Can use:

- Area
- Width
- Height

Combination of above

**Difficulty is that through the thickness damage is difficult to assess**

This is where experimental experience with the laminate is needed
Damage Severity can be quantifiably measured in different ways

Dent depth is simple to measure with no specialized equipment

Unfortunately not a very good parameter for CAI Strength $^{1,2}$


Testing Laminates with Impact Damage

Ideally full scale test articles would be impacted and tested for residual strength*

Usually economically infeasible….Must Utilize Building Block approach

<table>
<thead>
<tr>
<th>Element Level</th>
<th>Details</th>
<th>Sub Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 or more</td>
<td>10 or less</td>
<td>One or two</td>
</tr>
</tbody>
</table>

* This may be done at some small aircraft manufacturers where it is less costly to make five (or so) full scale planes, impact them at critical locations and show they can survive Ultimate Load.
Where is Analysis?

*From CMH-17...*

Analysis alone is generally not considered adequate for substantiation of composite structural designs. Instead, the "building-block approach" to design development testing is used in concert with analysis. This approach is often considered essential to the qualification/certification of composite structures due to the sensitivity of composites to out-of-plane loads, the multiplicity of composite failure modes and the lack of standard analytical methods.
Example of CAI results for Carbon/Epoxy

![Image of CAI test specimen]

- **Example of CAI results for Carbon/Epoxy**
  - Tup Size:
    - 6.4 mm
    - 12.7 mm
    - 38.1 mm
  - Open: 16-ply
  - Filled: 18-ply

**Graph**
- **CAI Strength (MPa)** vs **Damage Width (cm)**
  - B-Basis Curve (16 ply)
  - B-Basis Curve (18 ply)
  - Tup Size:
    - △ 6.4 mm
    - ○ 12.7 mm
    - □ 38.1 mm

![Graph showing CAI results](image-url)
Laminates typically demonstrate a damage threshold.

As impact damage level is increased, no damage occurs until a discreet level and then a certain minimum damage will form.

Need certain energy before damage forms.

Damage below this size is not possible.
For most applications, Static = Fatigue*

Run out typically occurs for $10^5$ cycles at any load less than $\sim 60\%$ of average Static CAI Strength.

CAI Strength

- 100%
- $\sim 80\%$

B-basis CAI Strength

- Limit Load
  - $\sim 57\%$

Inconsequential loads

Need thousands of these loads before fatigue is an issue.

Regular Flight

Hard landing

Regular Landing

Turbulent Flight

Example Fatigue Spectrum

*One exception is helicopters*
Difficult to get damage to “grow” from fatigue

Cycles @ % of CAI Strength
Fatigue loading can make impacted laminates **stronger (up to a point)**

Damage zones tend to “Round-Out” decreasing stress risers
Summary

• Damage tolerance consists of analysis and experimentation working together
• Impact damage is usually of most concern for laminated composites
• Once impacted, the residual compression strength is usually of most interest
• Other properties may be of more interest than compression (application dependent)
• A damage tolerance program is application specific (not everyone is building aircraft)
• The “Building Block Approach” is suggested for damage tolerance
• Advantage can be taken of the excellent fatigue resistance of damaged laminates to save time and costs.