Damage Tolerance of Composite Laminates from an Empirical Perspective

Alan T. Nettles, PhD

Composite Materials Engineer

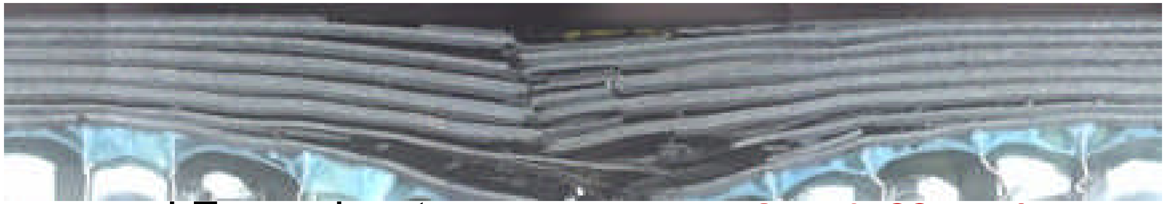
NASA, Marshall Space Flight Center

Alan.t.nettles@nasa.gov

Plenty of controversy on analyzing undamaged laminates

Undamaged Face sheet

Difficult to predict failure



Impact Damaged Face sheet

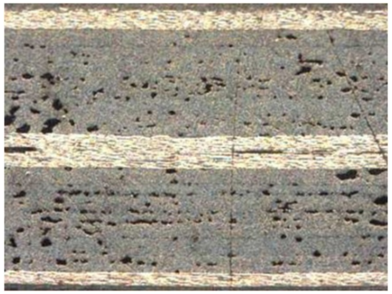
Extremely difficult to predict failure

See for example the World Wide Failure Exercise (WWFE)

Composite Laminates can be "damaged" in many ways:

Manufacturing Defects (porosity, debris between plies…)

Porosity



Burns (runaway heat blanket light fixture too close for too long…)

(Extreme cases)

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*

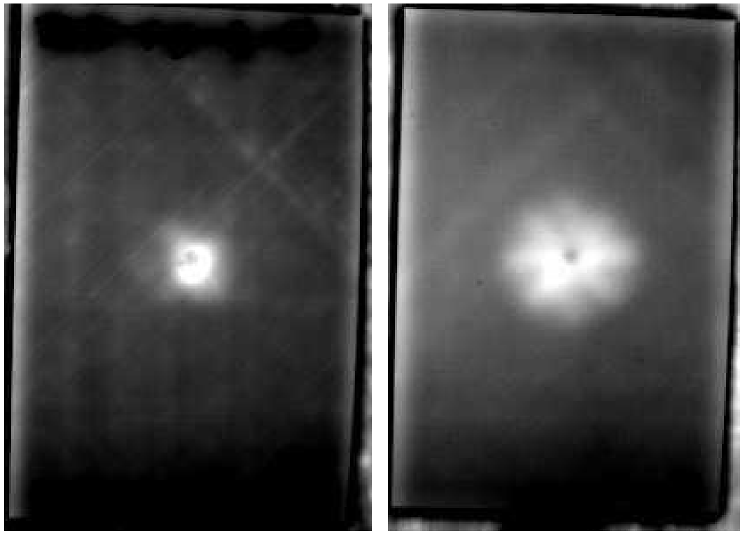
Ex. Damaged tabletop

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

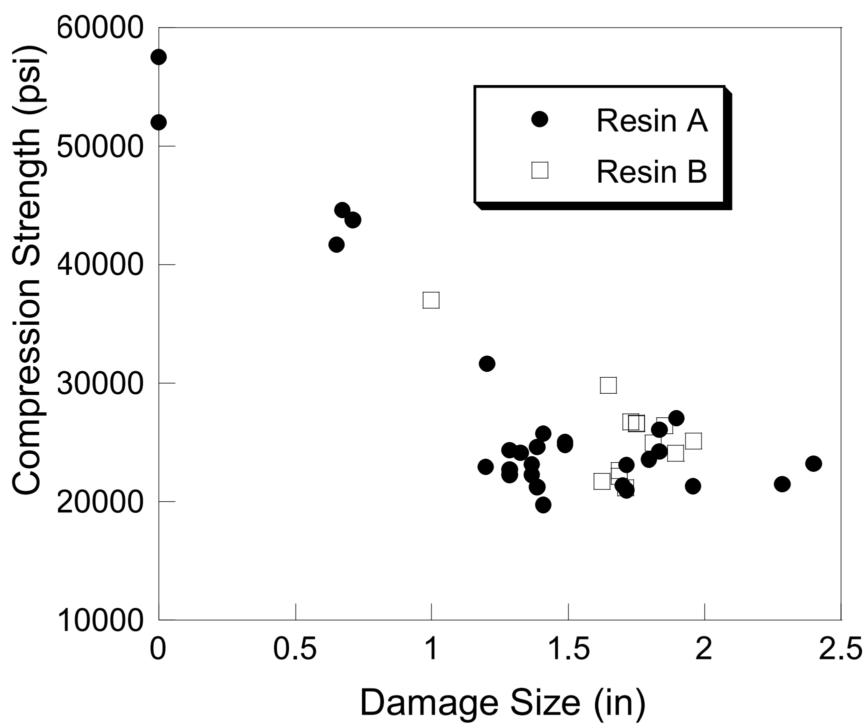
Identical impact conditions



Resin A

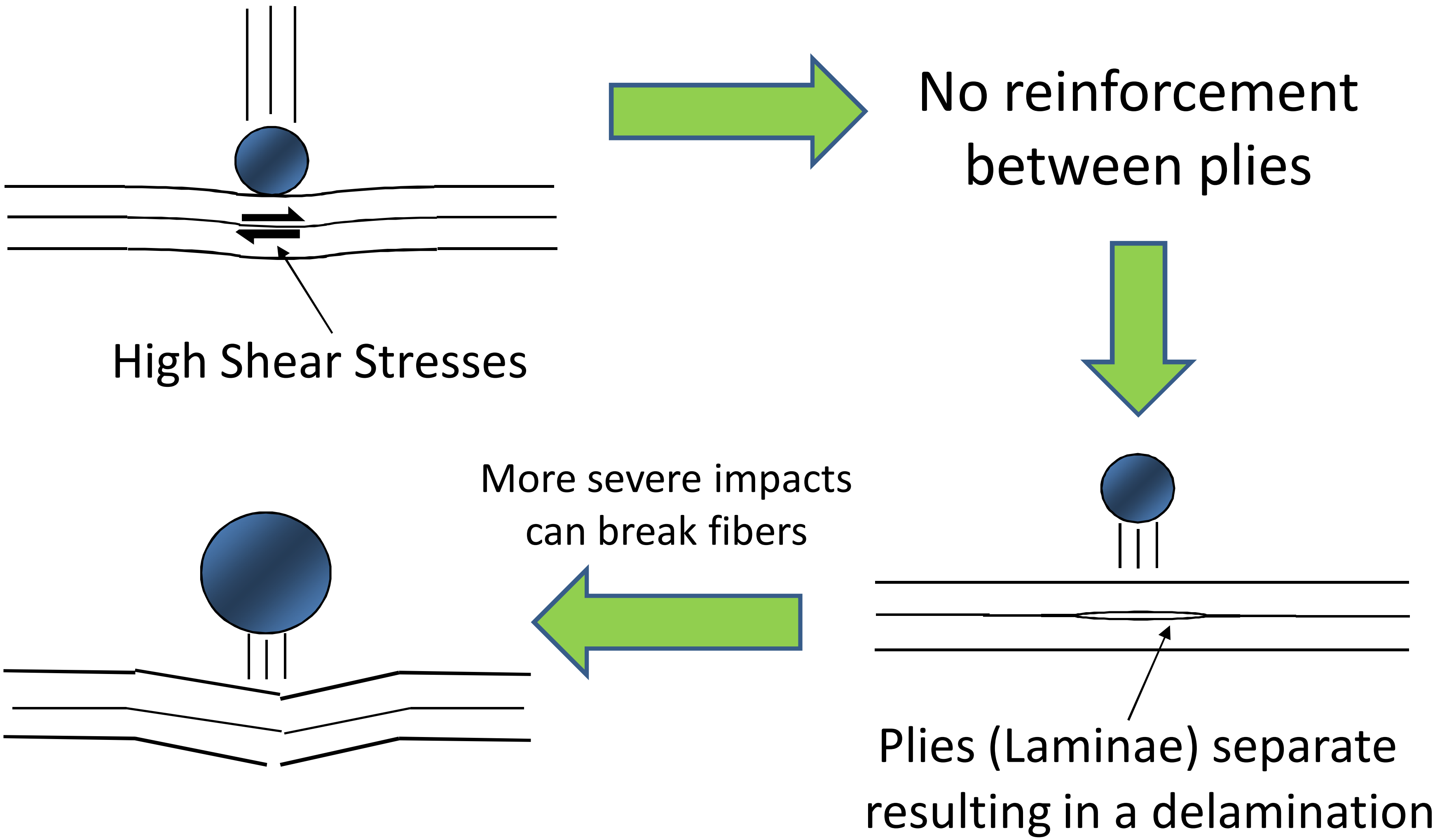
Resin B

Resin A more damage resistant than resin B



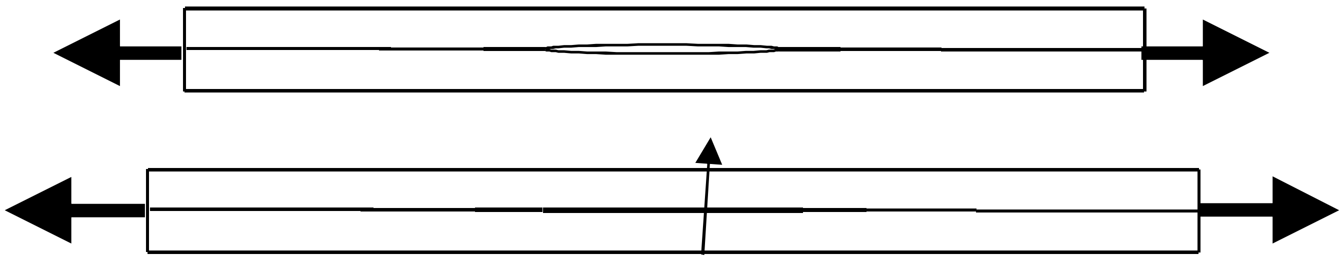
Equal damage tolerance

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



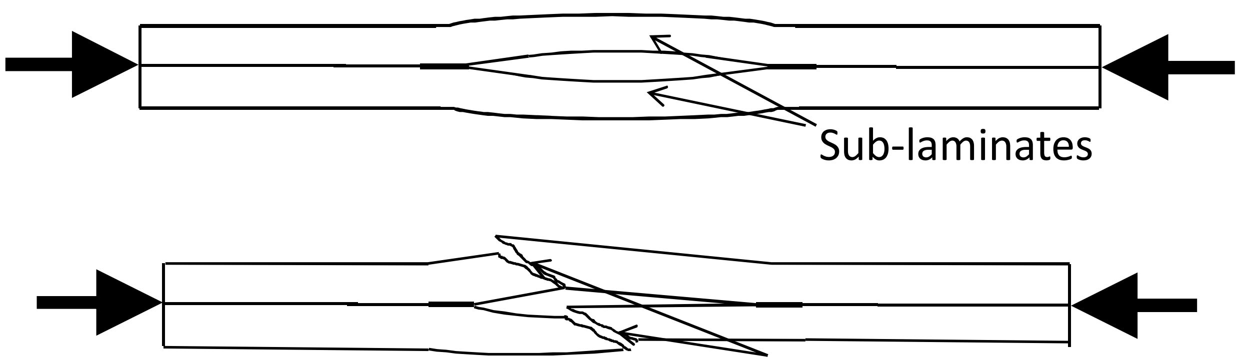
Compression Strength After Impact (CSAI) is of particular concern

Tension After Impact



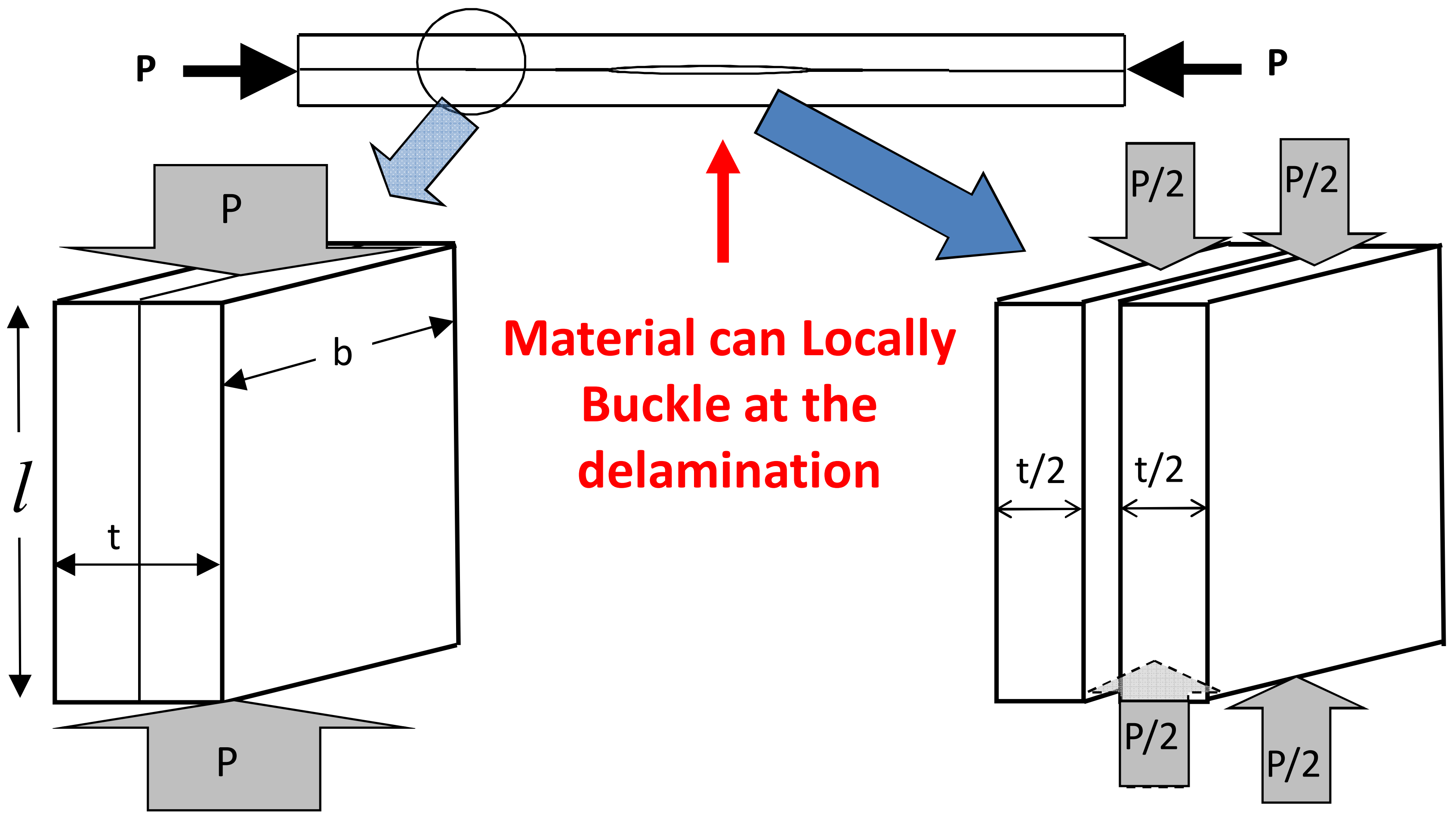
Delamination Simply "Closes-Up"

Compression After Impact



Sub-laminates buckle

Buckling Load (P_B) is proportionate to t^3



$P_B \propto t^3$

$P_B \propto 2t^3/8 = t^3/4$

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……

Leakage due to impact

Disposition of Impacted Laminates

If a laminate is damaged:

- If damage is not found (undetectable): Part must perform as if undamaged

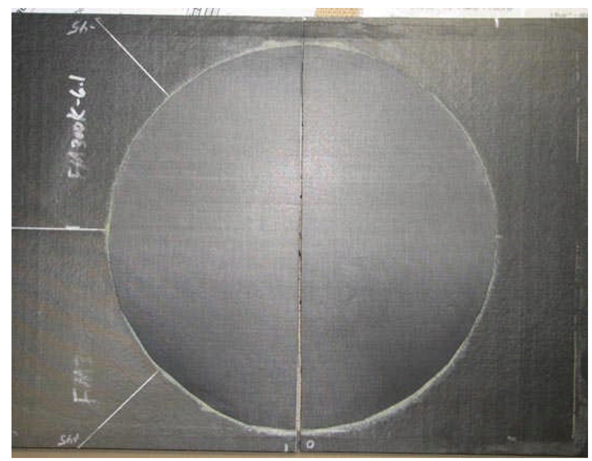
“If you can’t see it, you must prove that it can’t hurt performance”

- 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)

CMH-17 COMPOSITE MATERIALS HANDBOOK

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)

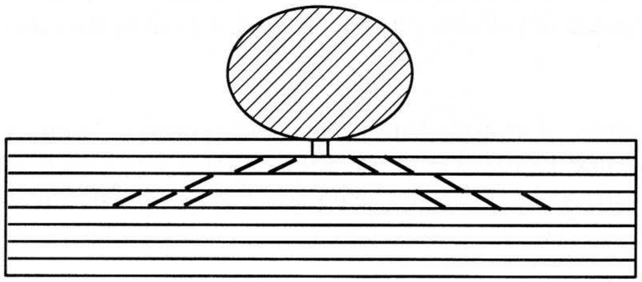
For some programs the philosophy is **"make sure it doesn't get hit"**

Observations from Impact Testing

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

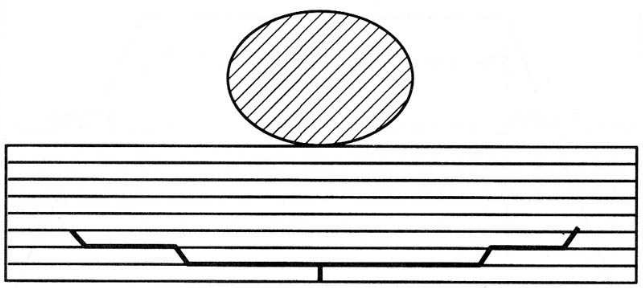
For a given impacting object (impactor)

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

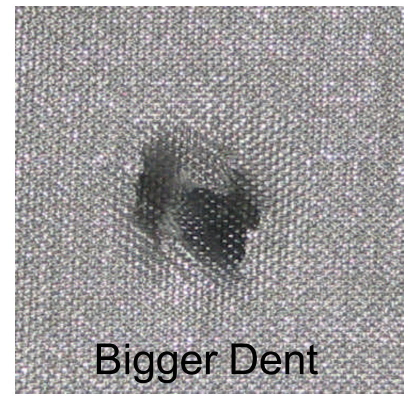


Damage may not be simple to characterize

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

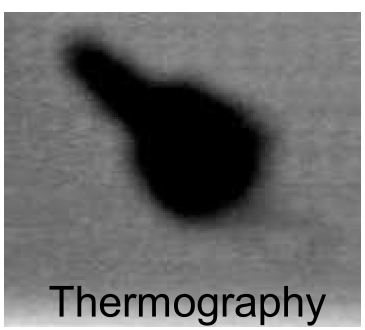
Most Common is Visual, which can be subjective

Small Dent



Bigger Dent

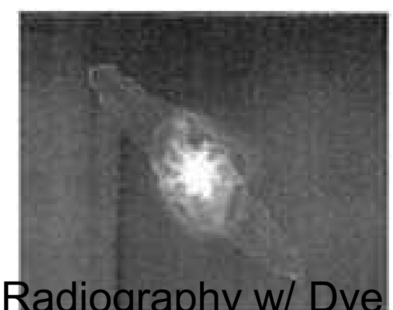
NDE techniques are often employed.



Thermography

Shearography

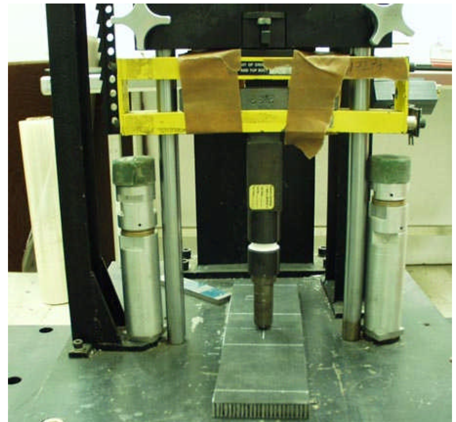
Zinc Iodide used as an opaque dye penetrant



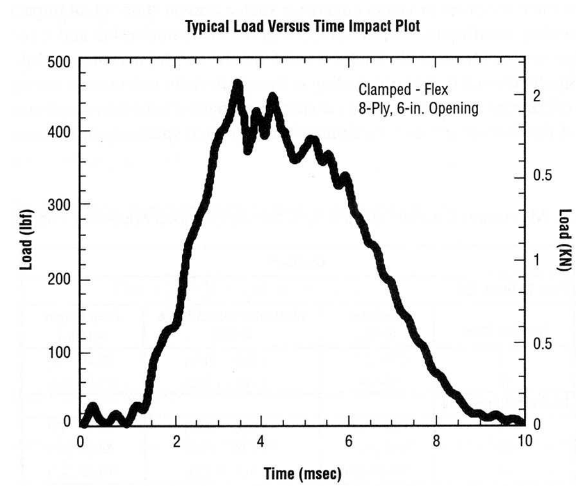
Radiography w/ Dye

Laboratory characterization (coupon testing) helps to better understand impact events

Impact can be controlled with instrumented impactors.

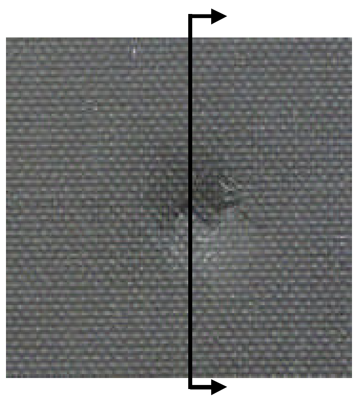


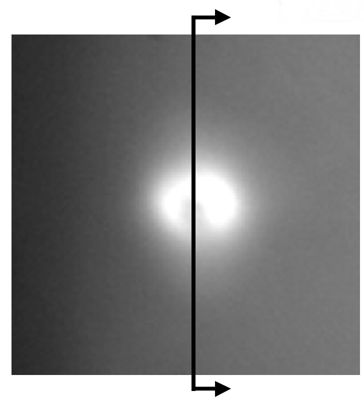
Instrumented Impact apparatus

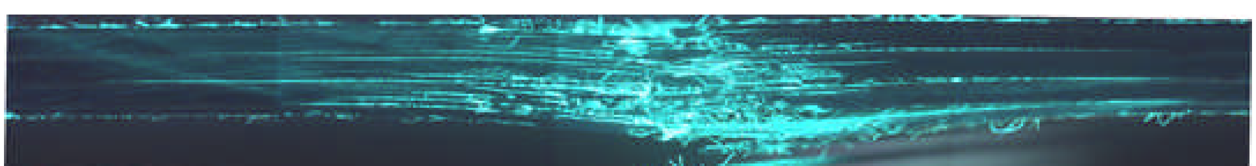


Load-time output from impact

Can relate internal damage to NDE via Cross-Sectional Microscopy.





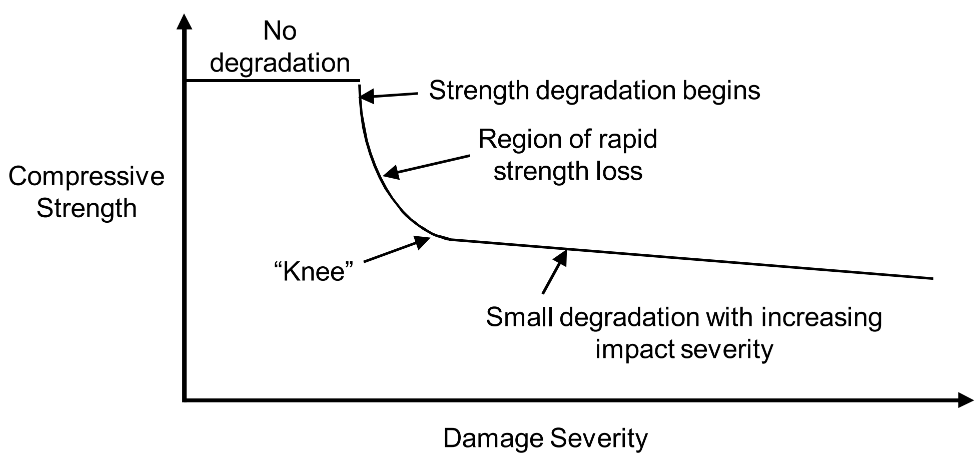


Ultimately the Goal is to Predict Laminate Performance with a given damage state

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



- Used to aid in defining critical damage levels

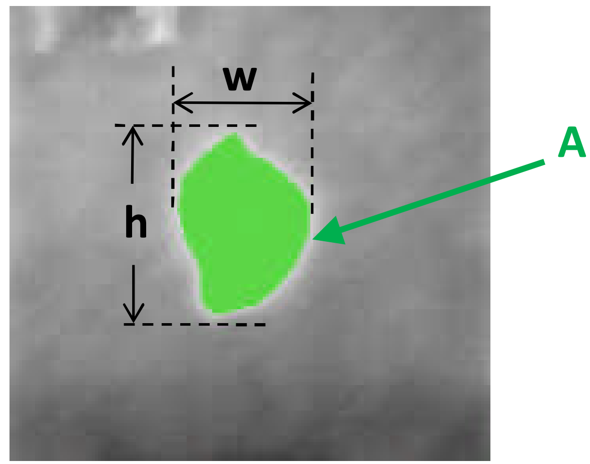
Damage Severity can be quantifiably measured in different ways

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]

1. Wardle and Lagace, JRPC, 16: 1093-1110, (1997)

2. Nettles and Jackson, JCM 21: 1100-1200, (2009)

Testing Laminates with Impact Damage

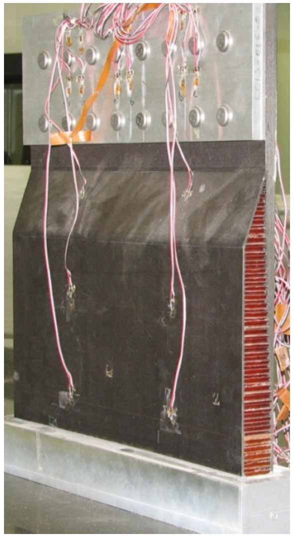
Ideally full scale test articles would be impacted and tested for residual strength*

Usually economically infeasible….Must Utilize Building Block approach

Element Level

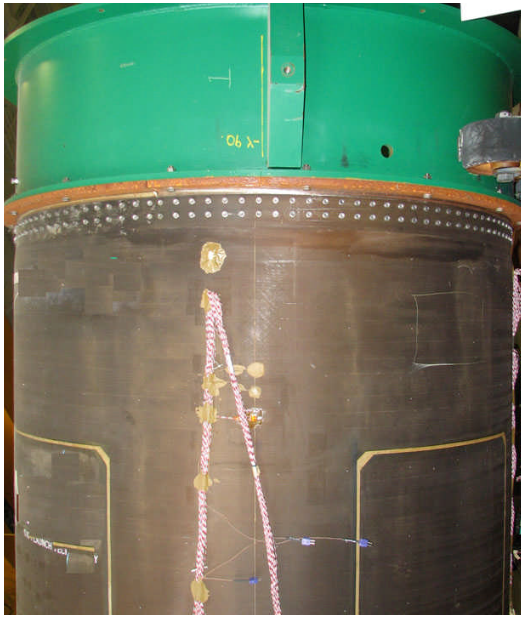
30 or more

Details



10 or less

Sub Components



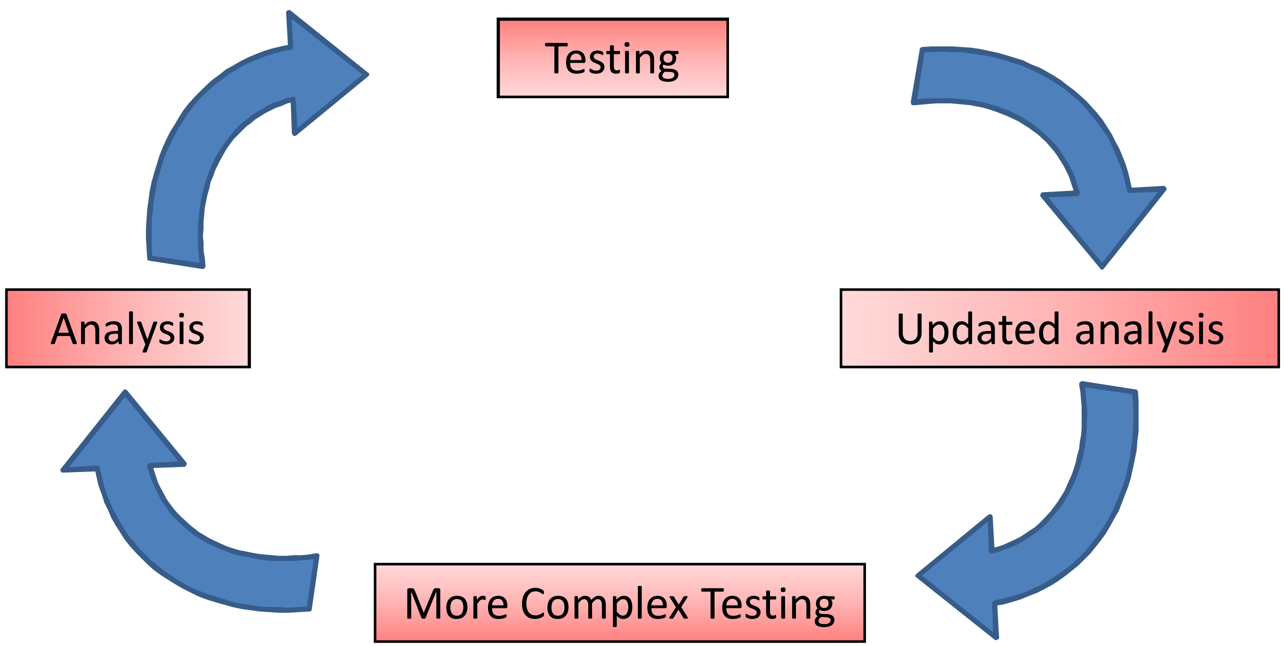
One or two

* 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.

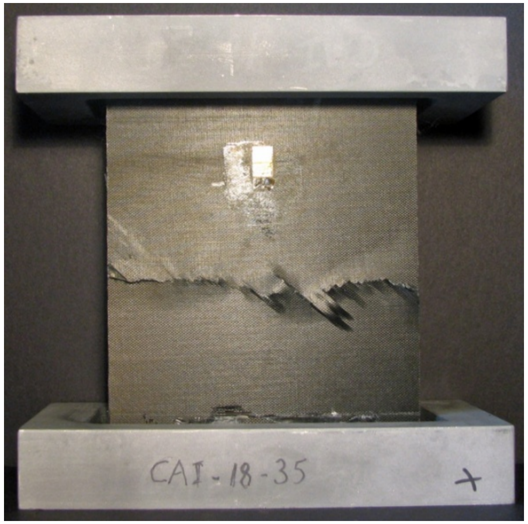
Where is Analysis?

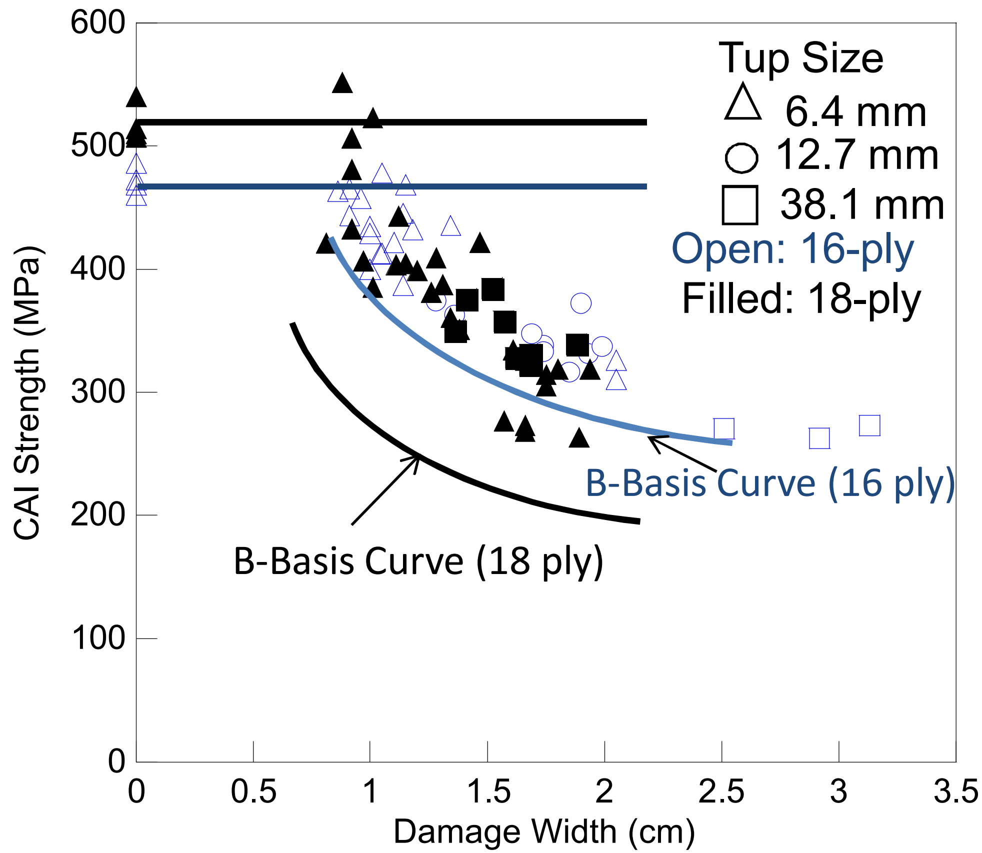
From CMH-17…

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.



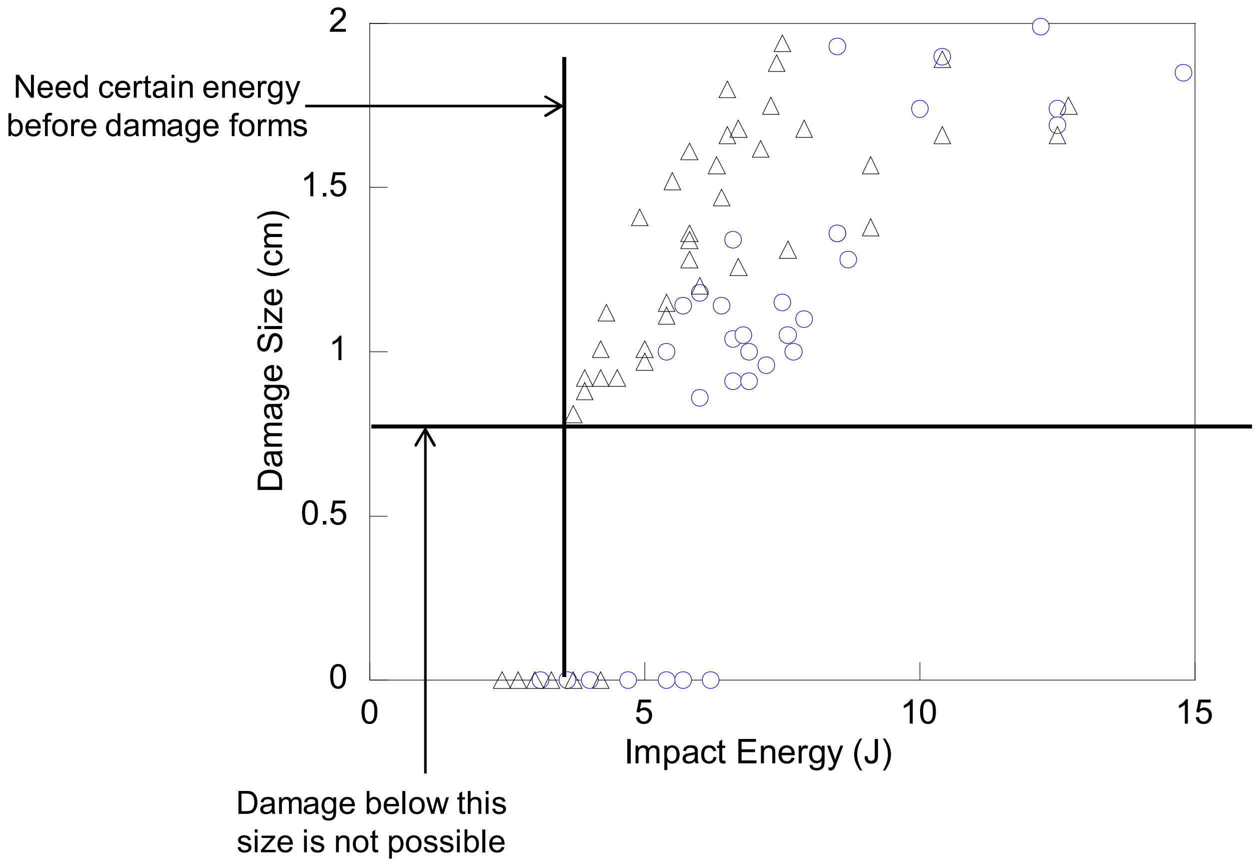
Example of CAI results for Carbon/Epoxy





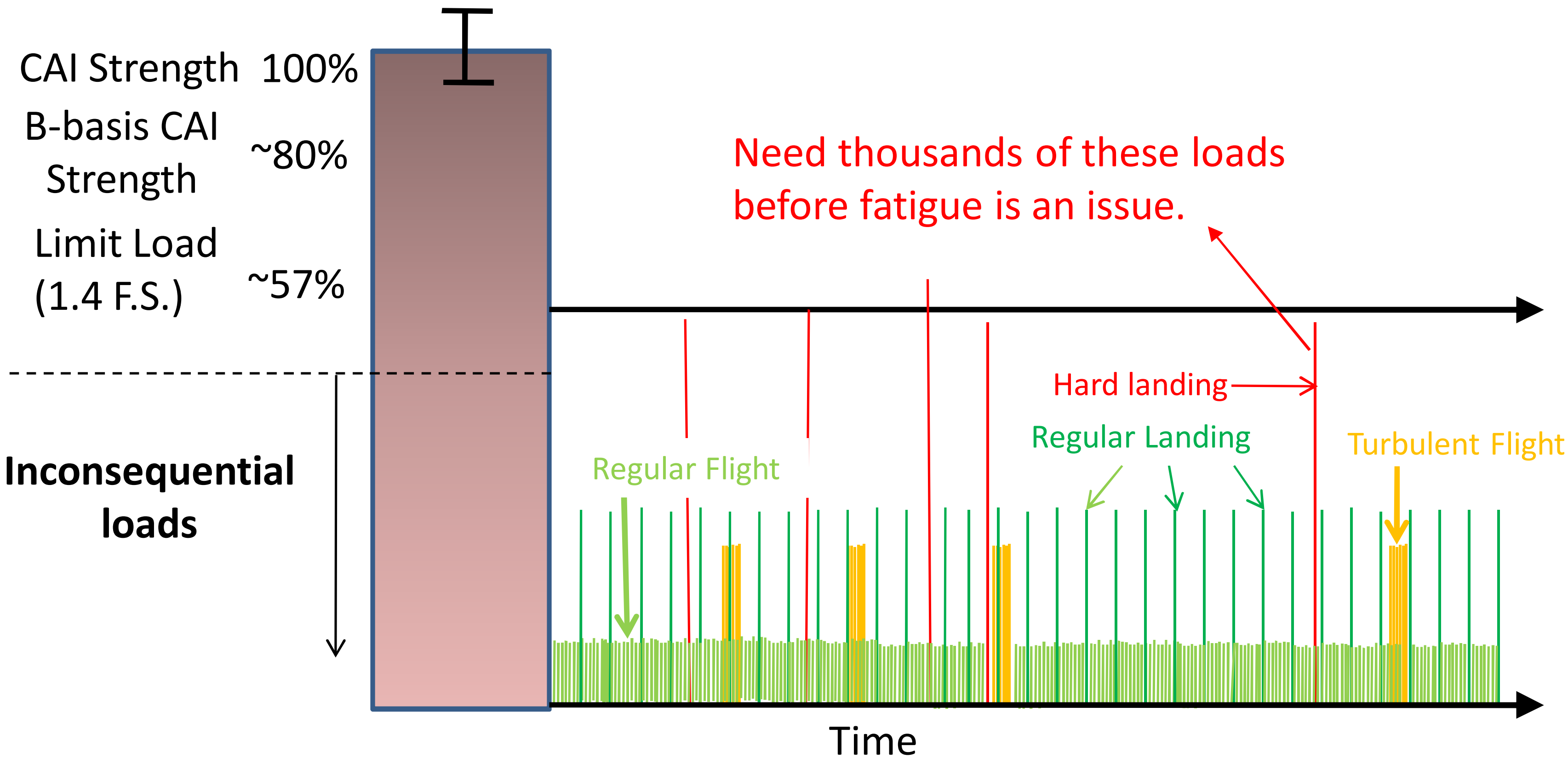
Laminates typically demonstrate a damage threshold

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



For most applications, Static = Fatigue*

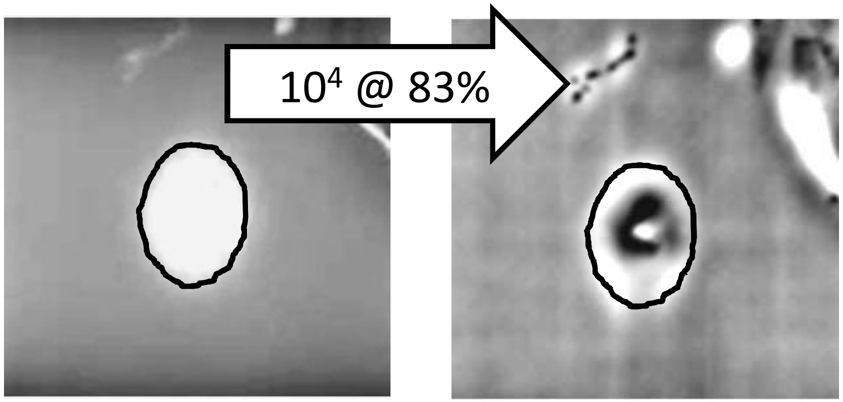
Run out typically occurs for 10^5 cycles at any load less than ~60% of average Static CAI Strength

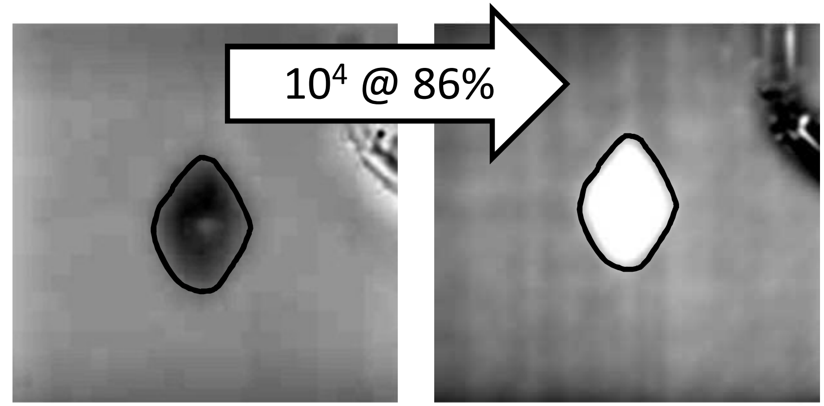


Example Fatigue Spectrum

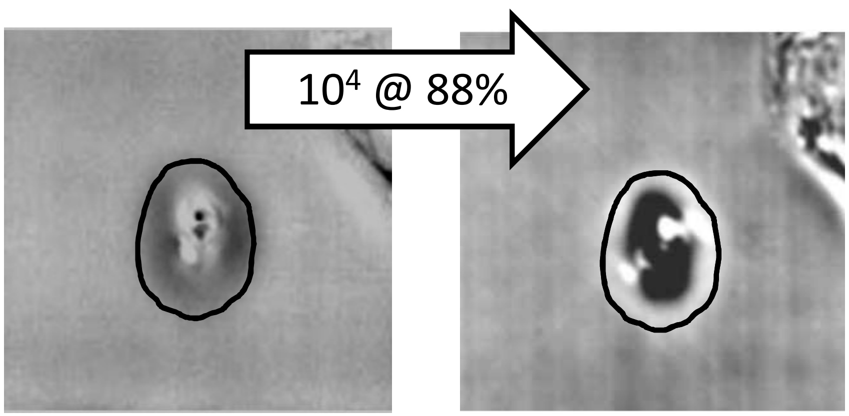
** One exception is helicopters*

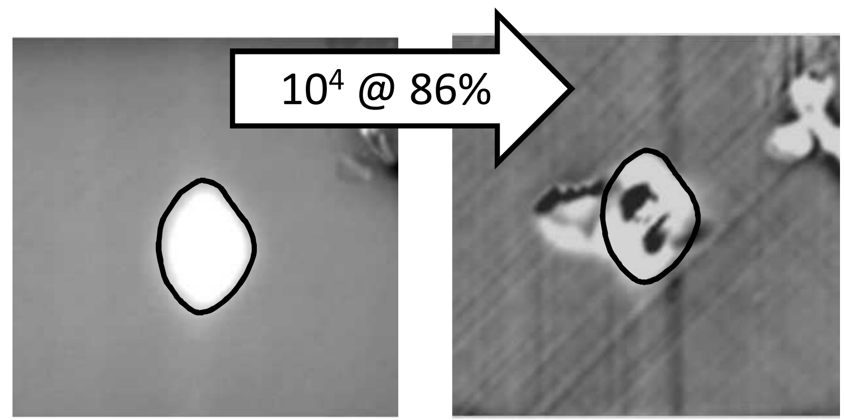
Difficult to get damage to “grow” from fatigue



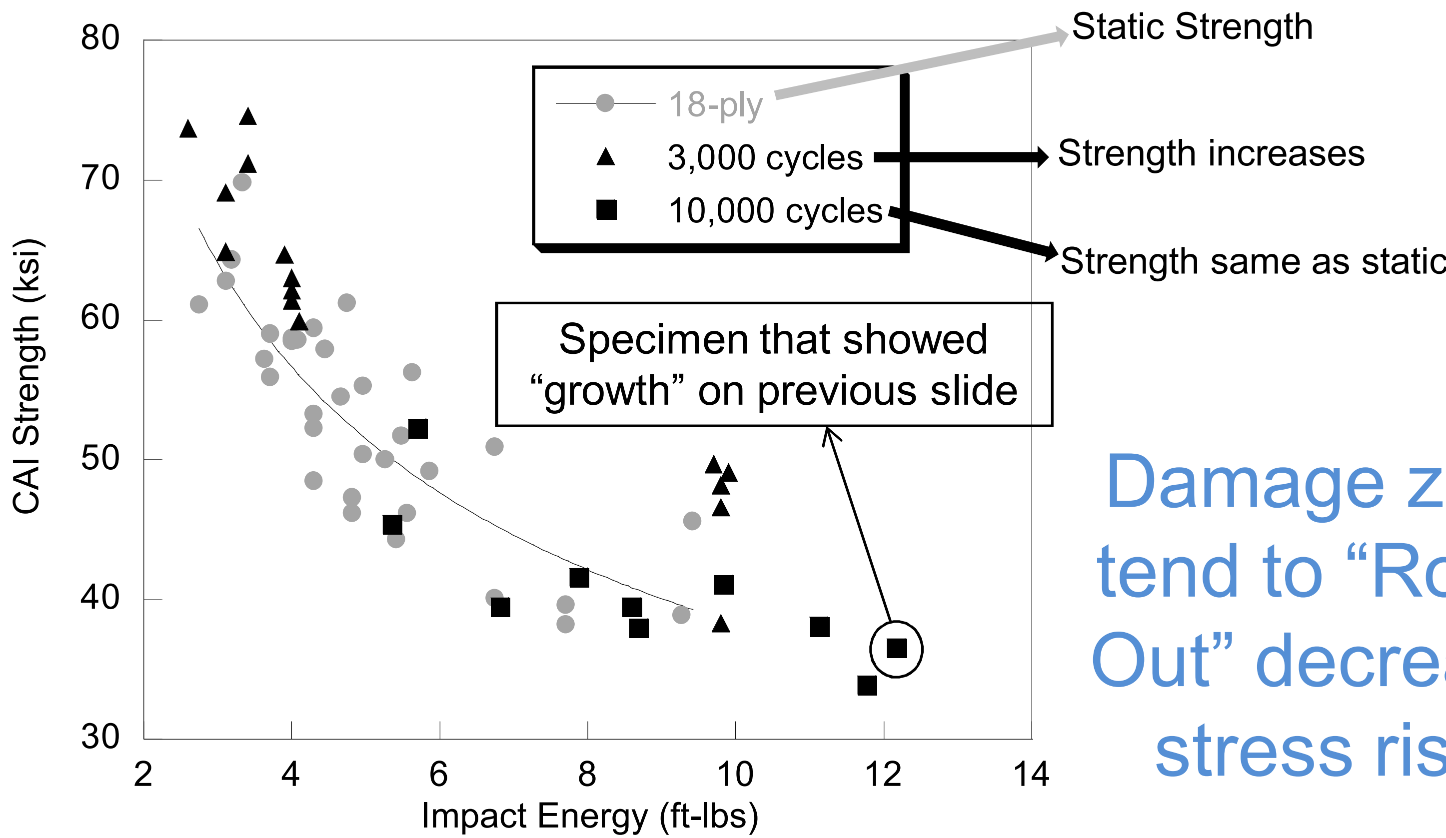


Cycles @ % of CAI Strength





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.