Introduction to Fracture Mechanics in Composite Structures

ME 7502 – Lecture 14

Dr. B.J. Sullivan
Fracture Mechanics of Composite Structures

- Introduction to Fracture Mechanics
- Brief History of Fracture Mechanics
- Fundamental Development of Fracture Mechanics
- Definition of Fracture Toughness
- Description of Fracture Toughness Test Methods
- Analytical Methods of Fracture Mechanics
  - Virtual Crack Closure Technique (VCCT)
  - Examples of use of VCCT is Aerospace Structures
  - FEA Assessment of Delamination Growth in Composite Structures: Thermal Protection System Repair Components for Space Shuttle Orbiter
- Concluding Remarks
Motivation: Why is Fracture Important?

Fracture: Key damage mechanism of composites

Composite torsion tube

Skin subjected to edgewise compression

Impacted plate

Delamination

Matrix-crack

Delamination may occur under many loading scenarios, both mechanical and thermal.
When is Fracture Mechanics Needed?

1. **Design and certification.** Damage tolerance may be required for several reasons:

   - Inspection limitations / blind spots
   - Stress singularities/concentrations affecting design margins

   - **Adverse loading conditions**
   - **Damage threats**

2. **Manufacturing**
3. **Repair**
4. **Life extension**
Consequences of Fracture: Case #1

Mid-flight rudder failure
Consequences of Fracture: Case #1

Mid-flight rudder failure

1. Improper repair led to disbond between facesheet and core in rudder
2. Cruising altitude caused a critical pressure differential between honeycomb cell cavities and outside
3. Resulting deformation propagated existing disbond
4. Loss of rudder’s structural integrity
The Accident

On November 12, 2001, American Airlines Flight 587 crashed shortly after takeoff, killing 260 people on board and 5 on the ground.
The probable cause of this accident was the in-flight separation of the vertical stabilizer as a result of the loads beyond ultimate design.

Recovery of Vertical Tail

Right Rear Lug
Consequences of Fracture: Case #2

- Complex 200 ply laminate
- Numerous plies in form of tape and fabric
- Numerous curvilinear ply drops
Consequences of Fracture: Case #3

X33 tank failure

LH2 tank (sandwich structure) failed due to cryo pumping
Consequences of Fracture: Case #3

X33 tank failure

- Tank was primed for cryopumping:
  - Void in the form of honeycomb cells
  - Reall cold (-423°F) test conditions (air in cells liquefies: vacuum)
  - Leak paths (cracks in inner and outer facsheets)
  - Fluids available to pump (nitrogen purge and liquid hydrogen)
  - Warm up
Consequences of Fracture: Case #3

X33 tank failure: Most probable cause

- Microcracking of the inner skin allowed hydrogen infiltration into the core
- The nitrogen purge gas was cryopumped through the outer skin and thrust buster areas into the core
- The presence of nitrogen and hydrogen in the core produced higher than expected core pressures
- Core bondline strength was lower than the original design allowable (a known condition prior to test)
- The presence of a 1/2-inch-wide by 3-inch-long piece of PTFE tape at the inner skin to core bondline created a critical disbond area. The same effect can be shown for the other manufacturing flaws of comparable size. These may have been critical flaws due to size, shape and location within the core
- The most probable cause of the incident was a combination of the above factors
- Program cancelled….. But not necessarily because of this.
Consequences of Fracture: Case #4

Columbia Orbiter re-entry incident

On February 3, 2003, Space Shuttle Columbia crashed killing its seven member crew. Insulating foam was separated from the external tank, which caused damage that resulted in the loss of the Orbiter.

Potential damage scenarios include through-crack, front-side coating loss, backside damage.
What Can Fracture Mechanics Accomplish?

We want to be able to provide quantitative answers to one or more of the following questions which might be asked of a particular design or material:

- Given that a crack exists in a component or structure, what load can be applied without the crack extending in an unstable manner?
- Knowing the service loads (design stresses) on a component or structure, what is the maximum crack size that the component or structure can sustain without risk of failure?
- For a component with a preexisting crack, how long does it take for that crack to grow from its initial size to a critical size from which fracture may occur?
- What is the anticipated service life of a component or structure which contains preexisting defects of known size arising from manufacturing defects or material inhomogeneities?
- For a component or structure with a pre-existing defect, what frequency of inspection is appropriate to ensure that this defect does not grow to a critical size during operation?
Modern Origins of Fracture

- A single, notorious case motivated the modern study of fracture.
- It was not until the 1940s when a series of catastrophic failures of steel structures gave sufficient impetus that attention was turned to attempting to answer the far more fundamental questions of “why and how does it break?”.
- As part of the wartime Lend-Lease agreement between the US and UK it became obvious that the UK did not have enough commercial shipping capacity to be able to transport the quantities of materiel required from the US to UK ports. The US government therefore called for tenders to build a large number of general purpose cargo ships and tankers with the express purpose of transporting weapons, food and oil from the Eastern seaboard of the US to the UK. The tender required that these vessels should be built in a matter of a few months rather the years required by conventional riveted plate construction.
The majority of North American shipyards said it was impossible but a Californian civil engineer, curiously enough called Kaiser, claimed that he could meet the deadlines using a novel construction method of a ship assembly line and all welded construction. The history of these so-called ‘Liberty’ ships is well known. Suffice it to say that of the ~2500 ships built, over 140 broke in two and nearly 700 suffered serious cracking problems, some when lying in port but invariably in cold weather.
Modern Origins of Fracture

At the end of WWII, a commission was set up to try to answer the question as to why these ships had failed. Tests on plates from the fractured ships showed that in order not to fail by catastrophic cleavage fracture the ships plate had to have a minimum value of Charpy Energy of about 35 J at 0°C and exhibit less than 70% crystallinity. It was further determined that all the serious cracking was by brittle fracture from either preexistent flaws or stress concentrations in steel plates which did not meet this criterion.
The ‘Briefest’ History of Fracture Mechanics

1921
A.A. Griffith:  
Failure of brittle materials

1920s-1950s

1953
R.S. Rivlin and A.G. Thomas:  
Characteristic energy for tearing

1957
G.R. Irwin:  
Plasticity plays role in fracture of ductile materials

Stress intensity factor  
Strain energy release rate

1960s
A.A. Wells  
Crack tip opening displacement/angle (CTOD / CTOA)

G.R. Irwin  
Crack resistance curve (R-curve)

G.P. Cherepanov, J.R. Rice  
J-Integral

G.I. Barenblatt, D.S. Dugdale  
Cohesive zone models

1970s-1980s
E. Rybicki

W. Elber

1990s
T. Belytschko

2000s
E. Greenhalg, M. Czabaj

Extended finite element method (XFEM)

Crack containment
Fundamental Development

- Consider an infinite plate containing a central through thickness crack of length “2a” and subjected to a remotely applied uniform tensile stress of magnitude $\sigma$.

- We consider what happens to the total energy as we extend the crack length by an infinitesimal amount.
Imagine it is possible to reproduce the load-displacement diagram for the condition where the crack length is “a” and then superimpose on it the load-displacement diagram for the condition when the crack length is “a+δa”.

As the crack extends the stiffness of the plate decreases and for a constant displacement the load will drop as the crack extends.
Fundamental Development

- For a crack length “a”, the elastic strain energy = \(\frac{1}{2}P_1u_1\)
- For a crack length “a+\(\delta a\)”, the elastic energy = \(\frac{1}{2}P_2u_1\)
- Therefore, the release or decrease of elastic strain energy as the crack extends for “a” to “a+\(\delta a\)” is \(\frac{1}{2}(P_1-P_2)u_1\) due to the plate becoming more compliant

If the load is kept constant as the crack grows, the stored strain energy for a crack of length “a+\(\delta a\)” is \(\frac{1}{2}P_1u_2\)
In achieving the increase in crack length, $P$ has moved through the distance $u_2-u_1$ and we have done the work $P_1(u_2-u_1)$ on the system.

Overall change in potential energy is expressed as

$$
\Delta U_E = P_1(u_2-u_1)-(1/2)P_1(u_2-u_1) = (1/2)P_1(u_2-u_1)
$$

which is equal to the area in the cross-hatched region of the load-displacement curve.

Let $\delta u = u_2 - u_1$ and $\delta P = P_1 - P_2$

- Strain energy release (fixed displacement) = $-(1/2)(\delta P)u$
- Potential energy release (fixed load) = $-(1/2)P(\delta u)$
We can relate the displacement to the load by mean of the stiffness $K$ or the compliance $C$ (and we choose the latter) here:

$$P = Ku \text{ or inversely } u = CP \text{ so that } \delta u = C \delta P \quad (C = 1/K)$$

Strain energy release (fixed displ) = \(-\frac{1}{2}(\delta P)u\) = \(-\frac{1}{2}CP\delta P\)

Potential energy release (fixed load) = \(-\frac{1}{2}P(\delta u)\) = \(-\frac{1}{2}CP\delta P\)

Therefore, there is no difference in the energy released when an infinitesimally small increment of crack growth occurs under conditions of fixed load or conditions of fixed displacement.

Griffith made an important connection in recognizing that the driving force for crack extension is the energy which can be released and that this is used up as the energy required to create the two new surfaces as the crack grows.

Griffith postulated that the change in energy of a body as a function of crack growth can be expressed as

$$\frac{\delta U}{\delta a} = G = \text{strain energy release rate}$$
The strain or potential energy release for an increment of crack growth $\delta a$ is therefore $G\delta a$ per unit thickness.

If $B = \text{plate thickness}$, then

$$G\delta a B = (1/2)P\delta u$$

$$GB\delta a = (1/2)P^2\delta C$$

or finally the \textit{Critical Strain Energy Release Rate} $G_c$, also called the \textit{Fracture Toughness}, is

$$G_c = \frac{P^2}{2B} \frac{\partial C}{\partial a}$$

Units of $G_c$ are energy per unit (cracked) area.
In monolithic (and isotropic) material, the analysis of fracture is also approached via elastic analysis around a sharp-tipped crack.

Stress intensity factor $K$ is a single parameter which identifies the amplitude of a stress field in the vicinity of a crack:

$$ K = Y \sigma \sqrt{a} $$

where $Y$ = shape factor and is a function of the body geometry.
Fundamental Development

- The only parameter distinguishing one crack situation from another is $K$.
- Therefore, if fracture is controlled by conditions in the vicinity of the crack tip, failure must be associated with the attainment of a critical stress intensity: $K_{ic}$.

At fracture, $K_{IC} = Y\sigma_c \sqrt{a}$

In practice we may attain $K_{ic}$ by increasing either $\sigma$ or $a$. For a defect of fixed length $a$, $\sigma_c$ is the critical value of the applied stress for fracture. Alternatively, for a constant applied stress $\sigma$, $a_c$ is the critical defect size for fracture.
**Fundamental Development**

- K is a stress field parameter independent of the material, whereas $K_{lc}$ is a material property, the fracture toughness. (Compare stress $\sigma$ which can have any value, and $\sigma_y$ which is a specific material property).

- The units of K are $(\text{stress})\sqrt{\text{distance}}$. This may be written most clearly as MPa$\sqrt{\text{m}}$ but usually appears as MN m$^{-3/2}$ or occasionally as N mm$^{-3/2}$.

- A measured value of $K_{1c}$ can be converted to a value of $G_{lc}$ and vice-versa, the main underlying assumption being that linear elasticity describes the stress/strain field adequately.
  - Both $G_{lc}$ and $K_{lc}$ are called the fracture toughness of a material.

$$K_c^2 = EG_c \text{ under plane stress loading conditions}$$


Fracture Methodology

- Strain energy release rate, $G$: Energy dissipation per unit area of crack formation.
- Flaw propagation occurs when $G$ exceeds a critical value, $G_c$ (fracture toughness).

$G_c$ is a **material property** independent of mechanical loading and geometry but can depend on mode of loading, temperature and manufacturing processes.
Three modes of fracture possible in composites

**Mode I**
Direct stress normal to delamination plane

**Mode II**
Shear stress perpendicular to delamination front

**Mode III**
Shear stress parallel to delamination front

Mixed-mode strain energy release rate:
\[ G = G_I + G_{II} + G_{III} \]

Delamination growth onset occurs when \( G \) exceeds \( G_c \)
Why is shear-driven delamination a consideration?

Delamination is preferred mode

Matrix cracking is preferred mode

Principal tensile stress plane

Locally, composites often fail in tension
3D Delamination Growth Criterion

**MODE I**
- Double cantilever beam test (ASTM D5528)
- End-notched flexure test (ASTM D7905)

**MODE II**
- Mixed-mode bending test (ASTM D6671)

**MODE III**
- Edge-crack torsion test

Shear-torsion-bending test

Fracture Mechanics for Delamination
1. Load specimen until required delamination growth achieved
2. Record force/displacement response and monitor delamination growth
3. Determine change in specimen stiffness (compliance) with respect to delamination growth
4. Compute interfacial fracture toughness, $G_c$ (initiation and propagation values)
Mode I Interlaminar Fracture Test

- Double cantilever beam (DCB) test: ASTM D5528
- Specimen loaded, applying direct normal stress to delamination plane
- Measure of $G_{lc}$ associated with ‘initiation’ and ‘propagation’
Mode I Interfacial Fracture Test

- Single cantilever beam (SCB) test: Draft ASTM standard / CMH-17 guidelines
- Specimen loaded to peel facesheet from core
- Measure of mode-I dominated $G_c$ of the facesheet/core interface

\[ G_c = \frac{3P_c \delta_c}{2b(a + \Delta)} \]

\[ C(a) = m(a + \Delta)^3 \]
Candidate Mode II Test Methods

(a) 3 ENF test

(b) Stabilised ENF test

(c) 4 point ENF test

(d) ELS test
## Candidate Mode II Test Methods

<table>
<thead>
<tr>
<th>Test Method</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>3ENF</td>
<td>Simplest possible fixture – no concerns with fixture compliance</td>
<td>Crack growth is not stable for organic matrix composites; Therefore only one data point per specimen can be obtained</td>
<td>Crack growth may also not be stable for CMC materials</td>
</tr>
<tr>
<td>Stabilized 3ENF</td>
<td>Simple fixturing</td>
<td>Crack shear displacement must be measured for control of real-time loading of specimen</td>
<td>Test procedure is too complex for adoption as int’l standard</td>
</tr>
<tr>
<td>4ENF</td>
<td>Crack growth is stable; one specimen can be used for multiple data points</td>
<td>Compliance of the internal span load platen must be accounted for in data reduction process</td>
<td>Crack growth is expected to be stable for CMC materials also.</td>
</tr>
<tr>
<td>ELS</td>
<td>Single load point makes load fixture simple</td>
<td>Clamping of the specimen may introduce variability in test results</td>
<td>This technique is less mature than either 3ENF or 4ENF and deserves serious attention</td>
</tr>
</tbody>
</table>
## Crack Measurement Methods

<table>
<thead>
<tr>
<th>Measurement method</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual</td>
<td>Simple, requiring no special instruments</td>
<td>Very difficult to discern precise location of crack tip; requires cool down from elevated temperature; crack length may be affected by specimen cool down; unloading of specimen may also affect perceived crack length</td>
<td>Most likely the least accurate method for CMCs; time consuming and therefore costly for elevated temperature measurement of $G_{II}$</td>
</tr>
<tr>
<td>NDE</td>
<td>Potentially the most accurate method for room temperature tests</td>
<td>Requires cool down from elevated temperature; crack length may be affected by specimen cool down; unloading of specimen may also affect perceived crack length</td>
<td>May be sufficiently accurate, but only if NDE can be performed in presence of load; time consuming and therefore costly for elevated temperature measurement of $G_{II}$</td>
</tr>
<tr>
<td>Compliance Calibration</td>
<td>No measurement of crack length is actually required during fracture toughness tests</td>
<td>If crack front does not advance in same plane as initial notch, inferred crack length and $dC/da$ will not be accurate</td>
<td>Most cost effective approach for elevated temperature tests; cool down, specimen unloading and removal, and actual crack measurement are not required</td>
</tr>
</tbody>
</table>
Two techniques used commonly with FEMs:

- 2D and 3D analysis
- Nonlinear FEA
- Arbitrary shaped cracks

(1) Virtual Crack Closure Technique
- $G$ computed externally to FEM / more efficient
- Crack growth only
- Mesh independent

\[ G_I = \frac{1}{ba} \left( \frac{F_y \Delta y}{2} \right) \]

(2) Cohesive zone model
- $G$ computed internally to FEM
- Initiation and crack growth
- Mesh dependent

\[ \int_0^{\delta_F} \sigma(\delta) d\delta = G_C \]
Applying Fracture Mechanics to Composite Materials

**Step 1:** Identify flaw size and location

Where’s the crack?

**Step 2:** Fracture-based life prediction / design mod.

- Calculate energy available for crack growth (VCCT, cohesive zone, global energy approaches)
- Compare with critical strain energy release rate, $G_c$

**Step 3:** Build structure and conduct performance (proof) test
FEA Assessment of Delamination Growth

- Delaminations can occur in composite structures from:
  - Residual stresses from processing
  - Overstress conditions from operation of composite structure
- Computational, finite element based methods are available to make an assessment of the likelihood of the delaminations to grow in an unstable fashion.
- The strain energy release rate (SERR) is calculated at the “front” of the delamination or crack.
  - SERR is then compared to the critical strain energy release rate (i.e., the Fracture Toughness) within a specific fracture mode ($G_{xc}$) of the material.
    - If $\text{SEER} > G_{xc}$, delaminations will grow.
    - If $\text{SEER} < G_{xc}$, delaminations are stable and will not continue to grow under the applied loads.
Initially developed FEA method was *Finite Crack Extension Technique* for calculating $dU/da$ (or *SERR*).

- This method requires two FE analyses: one using the original flaw size, and another using a marginally increased flaw size (+1%).
- The strain energy $U$ is calculated for both cases $\Rightarrow dU = U^{(2)} - U^{(1)}$.
  - $U$ is a solution quantity calculated by the FE code.
  - The change in the flaw size is known $\Rightarrow da = a^{(2)} - a^{(1)}$.

Subsequently, the *Virtual Crack Closure Technique* (VCCT) was developed, which is more robust, requires only one FE analysis, does not require user-defined quarter-point elements, and has been shown to yield good agreement with the closed form solution for a plate with a central crack.

VCCT essentially replaced Finite Crack Extension Technique

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Delamination Growth Analysis Method

- Delaminations in composite structures frequently result from excessive ILS stresses.
- Accordingly, fracture propagation (if it occurs) would most likely occur in Mode II, but could also occur in Modes I or III.

![Diagram of delamination modes](image)

- Delamination grows if $SERR_X \geq G_{X,c}$ where $SERR_X$ = strain energy release rate in Mode X and $G_{X,c}$ = Mode X critical strain energy release rate.
- While Mode II ILS may be the primary mode of concern, VCCT allows SERR to be easily calculated for all three modes to obtain a more complete assessment of the likelihood of propagation.
Delamination Growth Analysis Method

- VCCT uses the forces at the crack front (red arrows) and relative crack opening displacements (green arrows) immediately behind the crack front to enable direct calculation of SERR for each mode, for each node along the crack front.

Therefore, VCCT readily provides SERR for all three modes.

\[
SERR_{I} = \frac{1}{2\Delta A} \cdot Z_{Li} \cdot (w_{Ll} - w_{Ll*})
\]

\[
SERR_{II} = \frac{1}{2\Delta A} \cdot X_{Li} \cdot (u_{Ll} - u_{Ll*})
\]

\[
SERR_{III} = \frac{1}{2\Delta A} \cdot Y_{Li} \cdot (v_{Ll} - v_{Ll*})
\]

where \(\Delta A = \Delta a \cdot b\)

If \(SERR_{X} \geq G_{X,c}\), delamination is expected to propagate.

If \(SERR_{X} < G_{X,c}\), delamination is stable.
VCCT vs. Closed Form Solution

Simple Plate with Central Crack
- Plate Dimensions: 5” x 8” x 1”
- Crack Width (a): 0.50”
- Applied Load: 100 psi (on top face)
- Material: Aluminum (E = 10 Msi)
- Closed Form Solution:

\[
SERR = \frac{\pi \cdot \sigma^2 \cdot a}{E} = 1.57 \cdot 10^{-3} \text{in} \cdot \text{lb/} \text{in}^2
\]

Two Mesh Sizes
- Model 1: All elements are 0.1” x 0.1” x 0.1”
  - 11 Nodes through-the-thickness
- Model 2: All elements are 0.25” x 0.25” x 0.25”
  - 5 Nodes through-the-thickness

- Take Y-dirn displacements from these nodes…
- Take Y-dirn forces from these nodes…

For each pair of nodes TTT, complete the \( SERR_i \) calculation defined previously on slide 12.
VCCT vs. Closed Form Solution

- VCCT results agree very well with closed form solution
  - Model 1 (10 elements TTT) yields a maximum error of 6.4%.
  - Model 2 (4 elements TTT) yields a maximum error of 12.7%.
Example: Finite Element Model Overview

Original GTOR Plate Model

Submodel of Hole

Applied boundary conditions derived from full GTOR plate model.

Coupled nodes representing the edge of the delamination (nodes inside this boundary at the midplane are unmerged).
Location and Size of Delamination in GTOR

- Delamination is centered at the location of maximum ILS stress predicted in the global analysis.

- Duplicate unmerged nodes are used at the mid-plane of the cross section over the appropriate region to physically represent the delamination.

- Approximate size of the delamination is shown at right (previous work performed by S. Caperton of NASA JSC) ~0.10” circumferentially x ~0.067” radially.
From FE analysis of GTOR plate, peak ILS stress is found to occur at Hole 5 → create submodel for this location.

First, identify the angle at which the peak ILS stress occurs → center the delamination at this location.

Next, use the GTOR plate solution to obtain the applied displacements for the boundary of the submodel.
Submodel details are shown below.

- Image on left shows outline of delamination, centered about the location of the peak ILS stress.
- Image on right shows correct application of boundary conditions as derived from complete GTOR plate model.

Delamination centered at $\theta = 325^\circ$

Displaced shape (boundary conditions interpolated from GTOR plate model)
Calculation of SERR along the Crack Front

- As discussed previously, VCCT uses forces at the crack front and relative crack opening displacement behind the crack front to calculate SERR.
  - All calculations are made in the appropriate coordinate system (normal to the crack front) as discussed below.

- There is a pair of duplicate, unmerged nodes in each green circle.
- There is a pair of duplicate, coupled nodes in each red circle.
- Coordinate System
  - X → Black Line
  - Y → Yellow Line
  - Z → Out of the page

- For each green-red circle pair (boxed in black above), calculate the relative distance between the pair of nodes in the green circle, calculate the force between the two coupled nodes in the red circle, for each direction (X, Y, Z), then complete the SERR calculations discussed previously on slide 14.
As shown in the following tables, the SERR in all three directions along the entire crack front is at least five orders of magnitude lower than the lowest C/SiC fracture toughness at any temperature.

- Minimum C/SiC fracture toughness: 40.4 \text{ in-lbf/in}^2.
- Maximum SERR: 1.785 \cdot 10^{-4} \text{ in-lb/in}^2.

### Radial (X-Direction) SERR Data – Mode II

<table>
<thead>
<tr>
<th>Node 1</th>
<th>UX1 (-)</th>
<th>UX2 (-)</th>
<th>FX3 (lb)</th>
<th>Opening Displacement (in)</th>
<th>SERR (in-lb/in^2)</th>
<th>Angle (deg)</th>
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## RT Case (Hole 5) – SERR Calculations

**Hoop (Y-Direction)**

### SERR Data – Mode III

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<th>SERR (in-lb/in²)</th>
<th>Angle (deg)</th>
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### Through-Thickness (Z-Direction) SERR Data – Mode I

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Summary

• Fracture (matrix cracking, delamination, fiber fracture) is key damage mechanism of composite materials

• Serious incidents have occurred that “may’ have been avoided by better knowledge of fracture

• Brief history of fracture revisited

• Application of fracture to compostes utilizes strain energy release rate (easily measurable and calculable).
  • This is a promising alternative allowable to that based on stress.

• Finite element analysis methods (VCCT and/or cohesive zone models) may be conveniently applied to the numerical assessment of delamination growth in composite materials and structures
Work still to be done…

1. Fatigue behavior

2. Unification of standard structural margins with fracture-based margins

3. High-fidelity simulation with ‘real’ physics and stochastics packages

4. Model validation
   I. Imaging (keep up the good work, Prof. Czabaj…)
   II. Damage mechanism control and documentation
   III. Realife loading scenarios
   IV. Statistical analysis

5. Streamlined standardized test method development

6. Improved methods of crack growth measurement
   • Use of electrical resistivity may prove promising