Understanding the Materials – Manufacturing – Structural Performance Hierarchy for Composite Materials and Structures

Dr. Doug Cairns

Lysle A. Wood Distinguished Professor

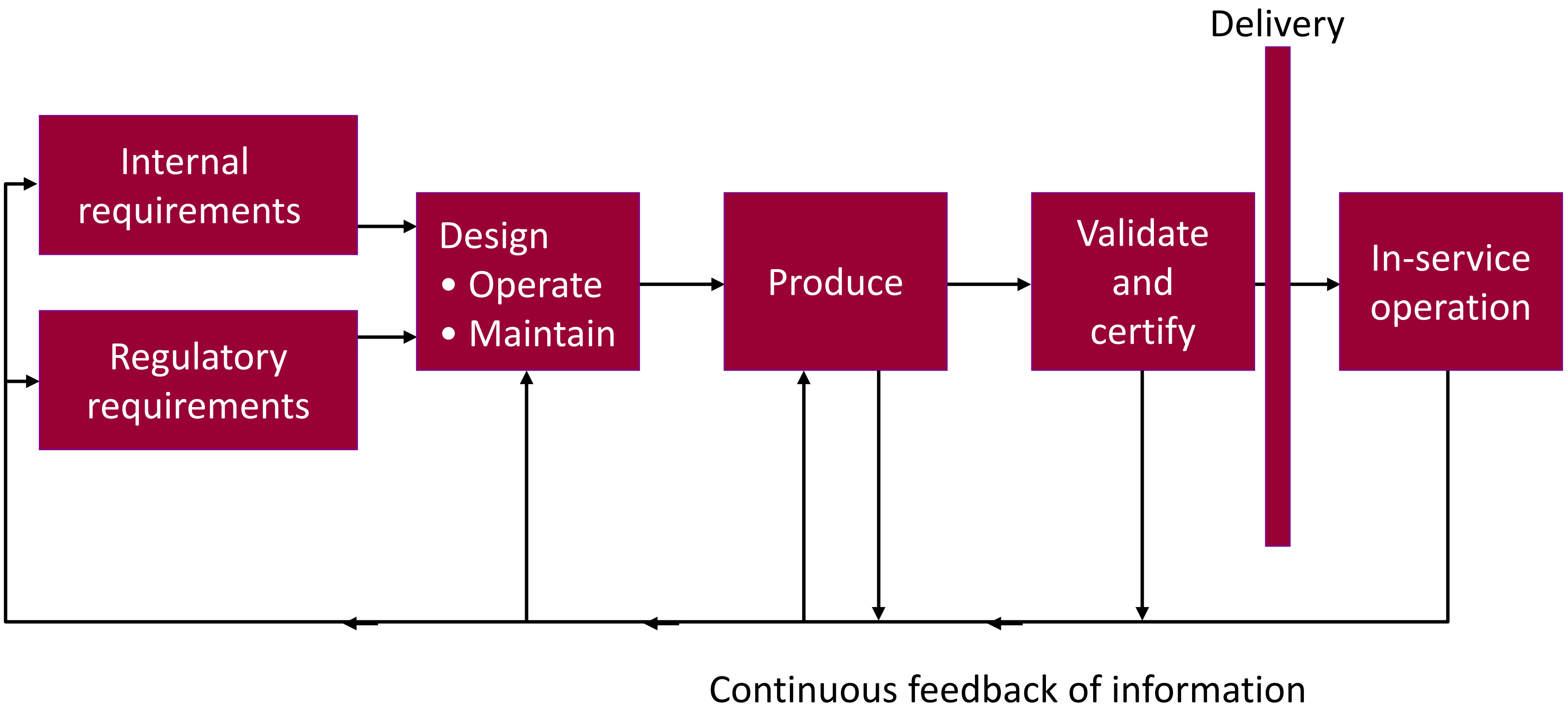
MONTANA STATE UNIVERSITY
✦ BOZEMAN ✦
Mountains & Minds

Cairns' Background (to calibrate perspective)

- Ph.D. in Aeronautics and Astronautics, MIT, thesis on damage resistance and damage tolerance due to impact damage in carbon/epoxy and kevlar/epoxy structures, research sponsored by FAA
- Joined Mechanical and Industrial Engineering at Montana State University in 1995, began working on wind turbine blade structures, <$10/lb final part cost target
- Dr. Cairns has over thirty three (38) years of experience in academia and industry as a researcher in composite materials for primary structure (beginning in 1979 for research on compression-compression fatigue of the F/A 18 vertical stabilizer). He has over 18 years of concentration on composite wind turbine blades (materials, manufacturing, structural performance)
- DOE award, wind energy program "Outstanding Research and Development Partnership Award," 2003 (first time given for wind energy; Other MSU and Sandia National Laboratory partners recognized as well)
- Lysle A. Wood Distinguished Professor in Mechanical & Industrial Engineering, 2007-present.
- Co-Chairman Damage Tolerance Committee FAA HDBK 17 Composite Materials Handbook

  "Composite Materials Handbook will be the authoritative worldwide focal point for technical information on composite materials and structures."
- Chairman, Charter Committee for the North American Wind Energy Academy (inspired by European Wind Energy Academy)
- Chairman (2012-2016) ASME Wind Energy Technical Committee

How Does a Commercial Aircraft Manufacturer Do It?



Delivery

Internal requirements

Regulatory requirements

Design
- Operate
- Maintain

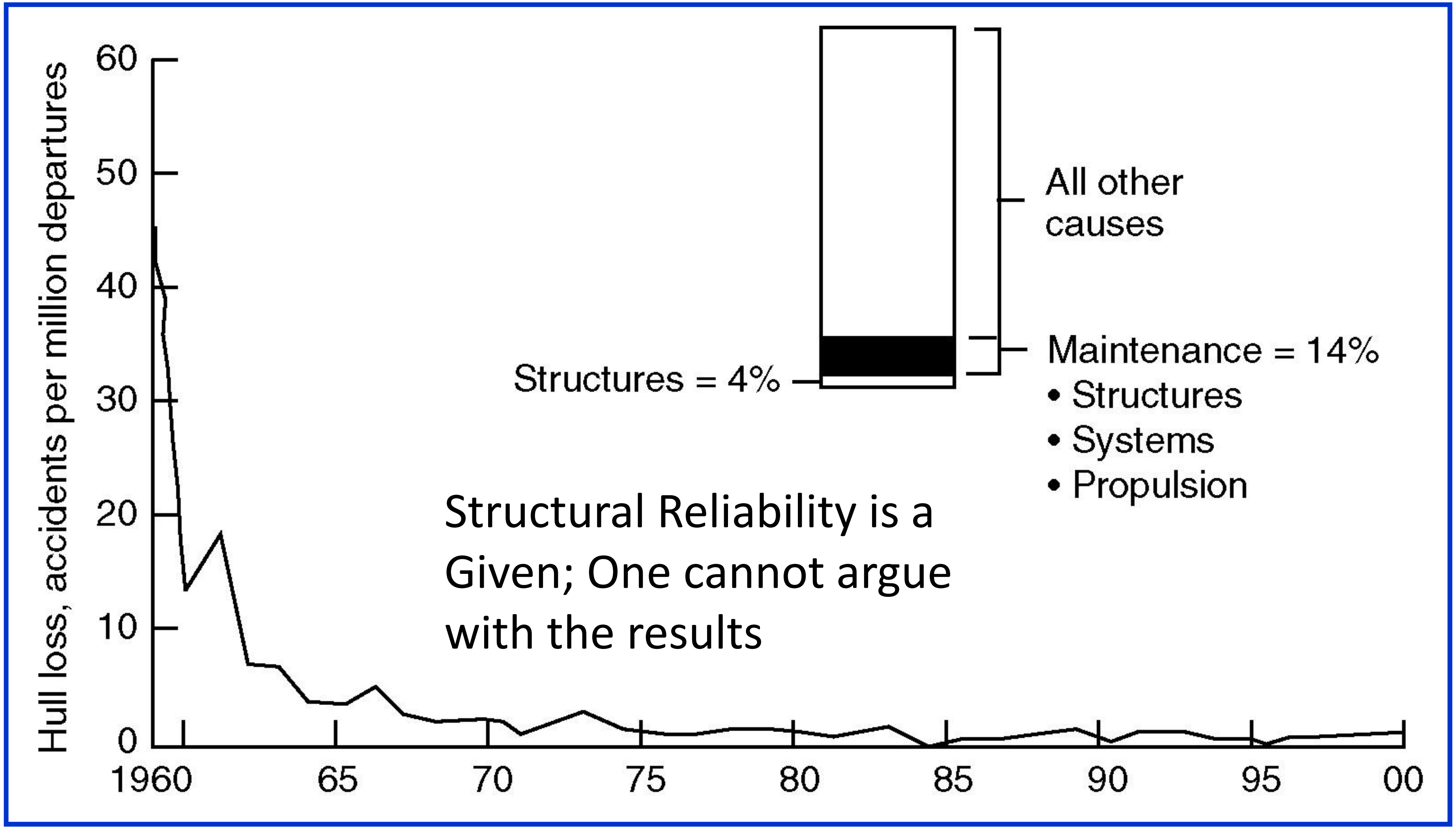
Produce

Validate and certify

In-service operation

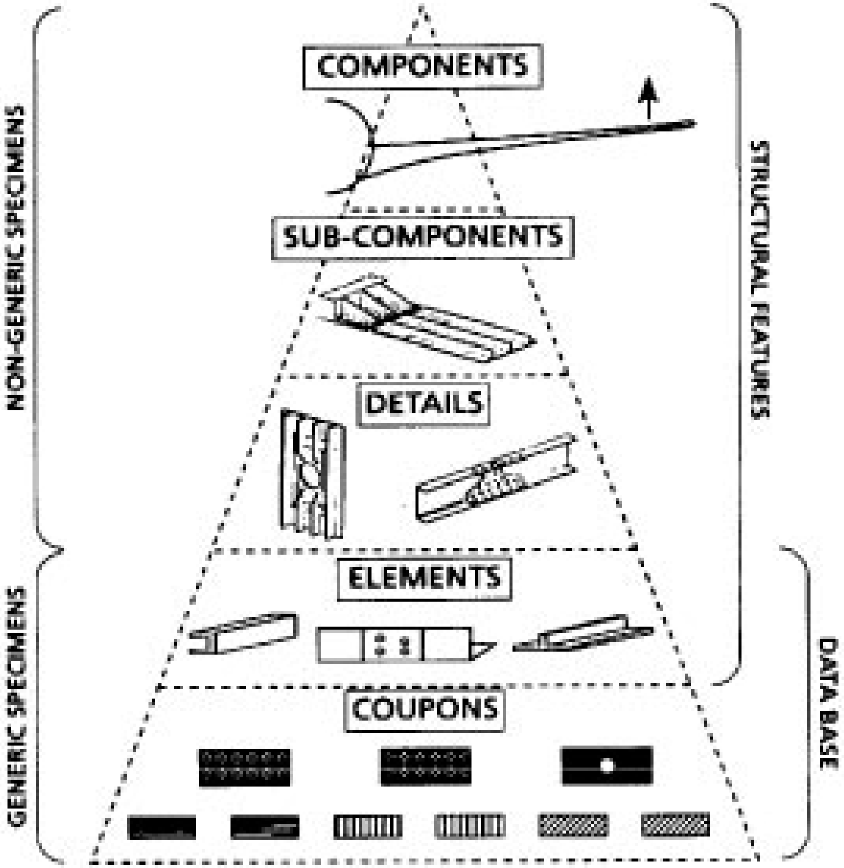
Continuous feedback of information

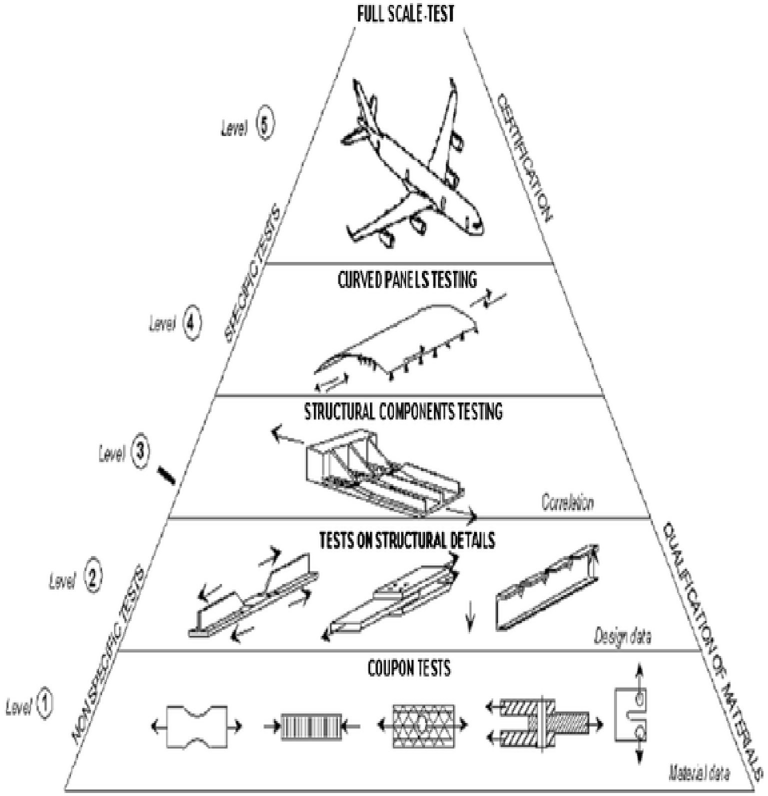
Commercial Jet Fleet Safety Record



Structural Reliability is a Given; One cannot argue with the results

Certification for Applications to Primary Structure





$Up to $350 Million for such a database (2.33 B DKK)

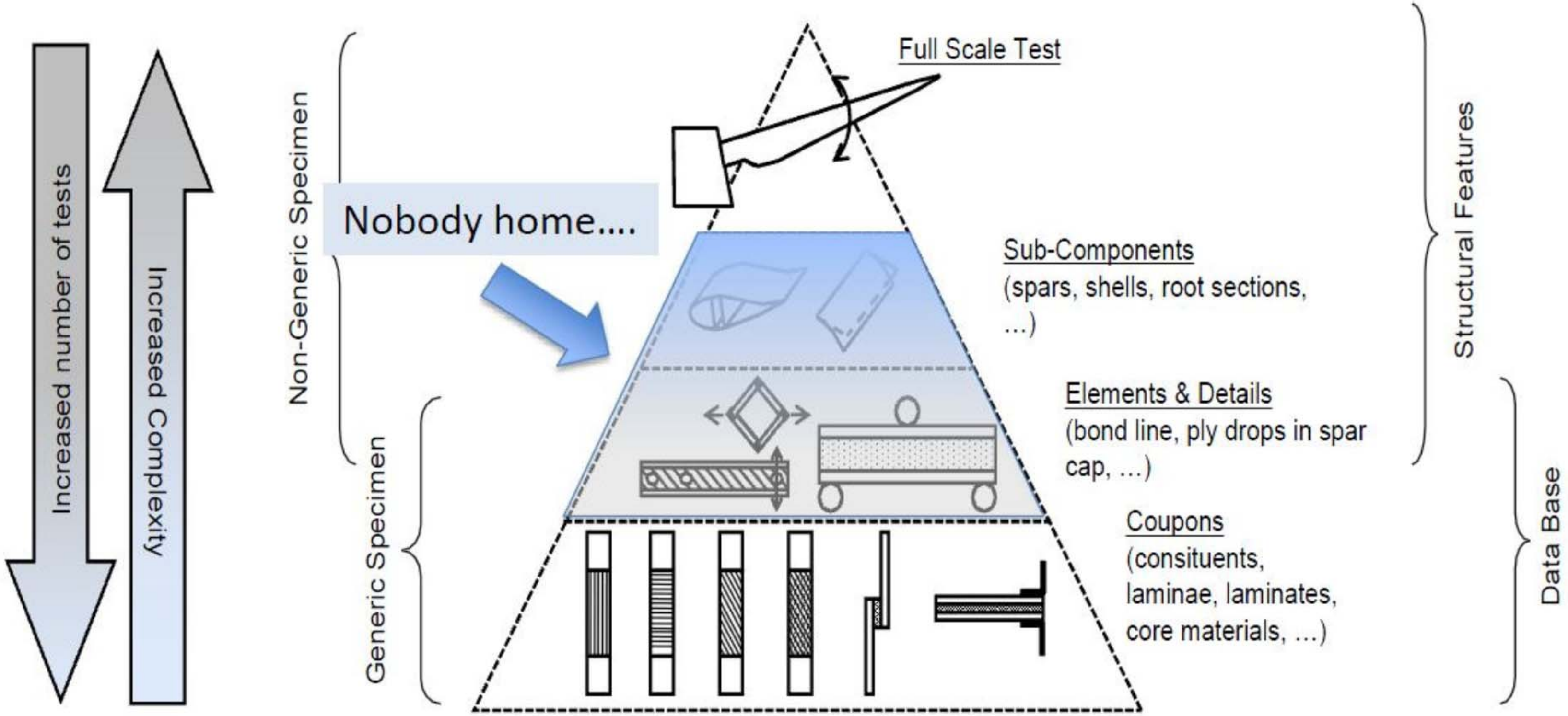
The Wind Turbine Industry cannot afford the Complete Aerospace Building Block

- Composite Wind Turbine Blades are **COST Driven**

- Aircraft reliability is a SAFETY issue, wherein almost any price is acceptable; wind turbines are primarily an ECONOMIC issue.
- Note: Public perception of safety is important, but not the industry technical driver

- Nonetheless, the aircraft industry has a well established track record for quantifiable reliability. It is the “Gold Standard.”

Rotor Blade Testing…….
Something is missing



Increased number of tests

Increased Complexity

Non-Generic Specimen

Generic Specimen

Nobody home….

Full Scale Test

Sub-Components
(spars, shells, root sections, …)

Elements & Details
(bond line, ply drops in spar cap, …)

Coupons
(consituents, laminae, laminates, core materials, …)

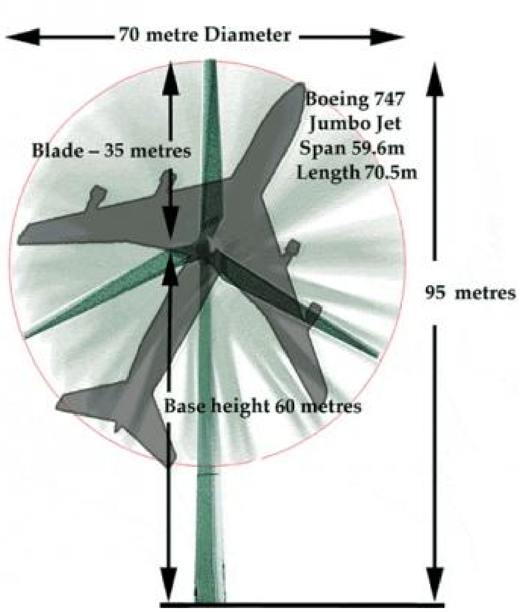
Structural Features

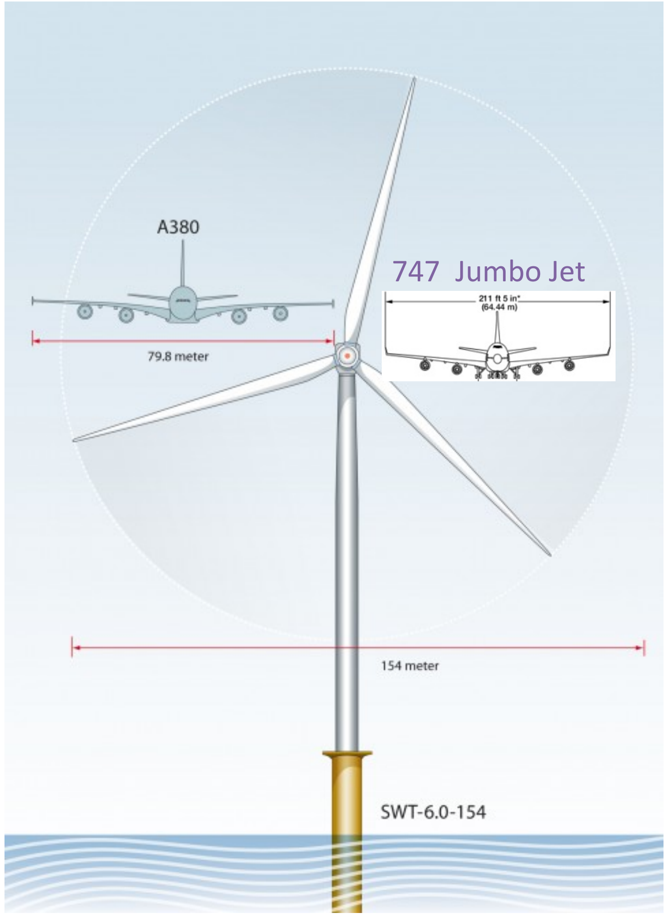
Data Base

Source: IEC 61400-5 (draft version)

Composite Wind Turbine Blades

- Turbines are getting larger
- Low cost manufacturing means higher probability for manufacturing defects
- Increased length means increased weight
- Can’t afford the typical over design of the blade





A Unique Opportunity for the wind turbine industry to embrace a different paradigm for composite structures

- These structures are BIG > 100 m diameter
- “Near aerospace” design requirements
- They have high structural demands, many hours/day for 20 years
- Extreme environments, Alaska, Hawaii, Antarctica
- Less than $10/lb costs
- The only mechanical fasteners are between the root and the metal turbine hub

From a July 2013 email from John Tracy to Steve Tsai and Doug Cairns, re-iterated at the AIAA SciTech Conference, January 2014

“For us, it's about focusing our efforts where the payoff will be the greatest. Introducing a new material for the fuselage with so little lead time (several years is little lead time for us considering how long it takes to qualify the materials, make sure it can be scaled up, do all the sub element testing, etc) is very hard. What we really need is to have the composites community help figure out how we can qualify a material and get it production ready much faster than it is possible to do today.”

Same holds true for wind turbine blades and other primary structure

The Box Aerospace has Created for Itself

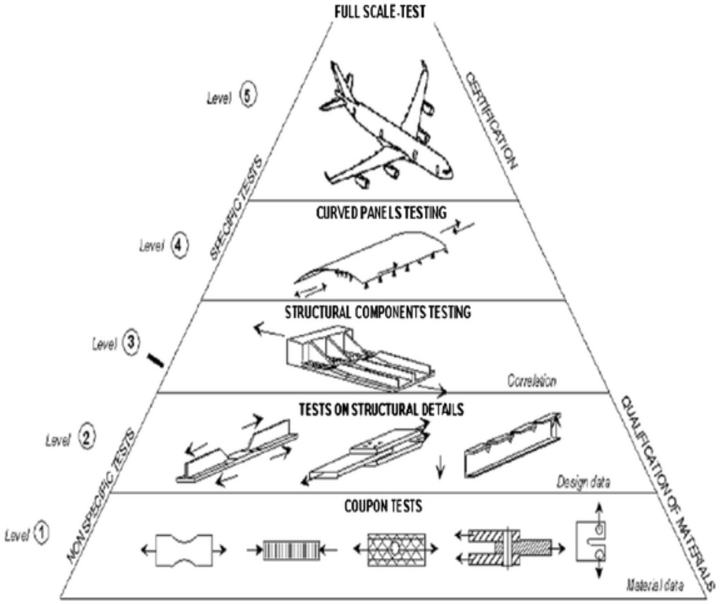
- The range of materials is limited, evolutionary for the past 20 years, not revolutionary
- The range of manufacturing is limited
- The tooling for structural configurations are limited to a specific airframe
- The test configurations are specific
- The “Building Block” is not agile for other configurations or industries

The Future for Commercial Aerospace Composite Structures

- The building block approach may not be sustainable as the airframe transitions to be mostly composite materials
- Boeing almost “broke the bank” on the 787 Dreamliner, much of it due to composites and integration
- Certifying agencies such as the FAA are reluctant to change
- The motivation for change may not be great. The cost for 787 Dreamliner is between $150-200 Million (depending on configuration)

Personal note: *Cairns decided to shift from aerospace emphasis to wind and other commercial applications of composite over 20 years ago; opportunities for innovation greater without constrained legacy*

Let’s Revisit the Building Block

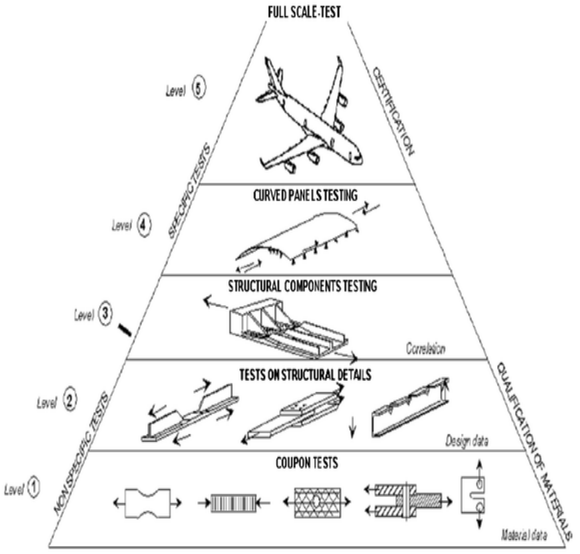


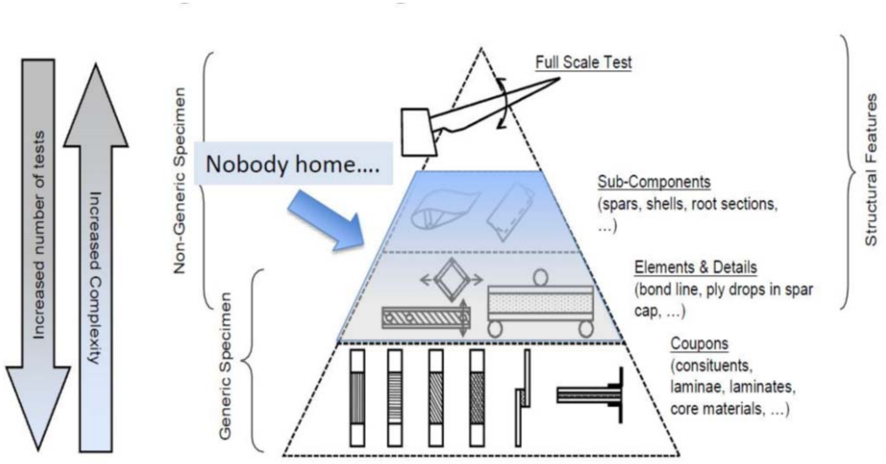
- Assuming that the same materials and manufacturing are used in each step, what is different?
    - The only difference is GEOMETRY
    - If one assumes that the material and manufacturing is the same, there is substantial information at the lower levels which should make higher levels predictable
- Then why do we use the Building Block approach? We don’t have supreme confidence that we can predict three-dimensional failure response leading to failure

How the DTU VILLUM CENTER FOR ADVANCED STRUCTURAL AND MATERIAL TESTING is Different and Relevant

- The Bottom – Up approach
  - Micro Scale Testing
  - Material (coupon) Testing
  - Substructure and Component Testing
  - Full and Large Scale Testing
  - Key Measuring Equipment to understand scale-up
- Building Block hierarchy, without narrow constraints compared to aerospace
  - Inspired by certain configurations (e.g. wind turbine structures), but not limited to them
  - Coalesces a “Community of Scholars” within Denmark

Where the Twain Shall Meet




Nobody home....

The DTU VILLUM CENTER FOR ADVANCED STRUCTURAL AND MATERIAL TESTING has the potential for bringing an affordable building block hierarchy to industrial and commercial applications of composite materials and structures

Shifting Gears

Montana State University Composites Group Mission

To understand the Materials – Manufacturing – Structural Performance Hierarchy for Composite Materials and Structures.

Some Basic Philosophy

- There is tremendous information to be gained at lower levels
- Levels in the building block do not need to be exact component, but should contain the geometric features relevant to full scale
- Upper levels in the Building Block should be used for validation, not for statistical database building or primary certification (Certification is a consequence of demonstrating scale-up, with limited testing at larger scales)

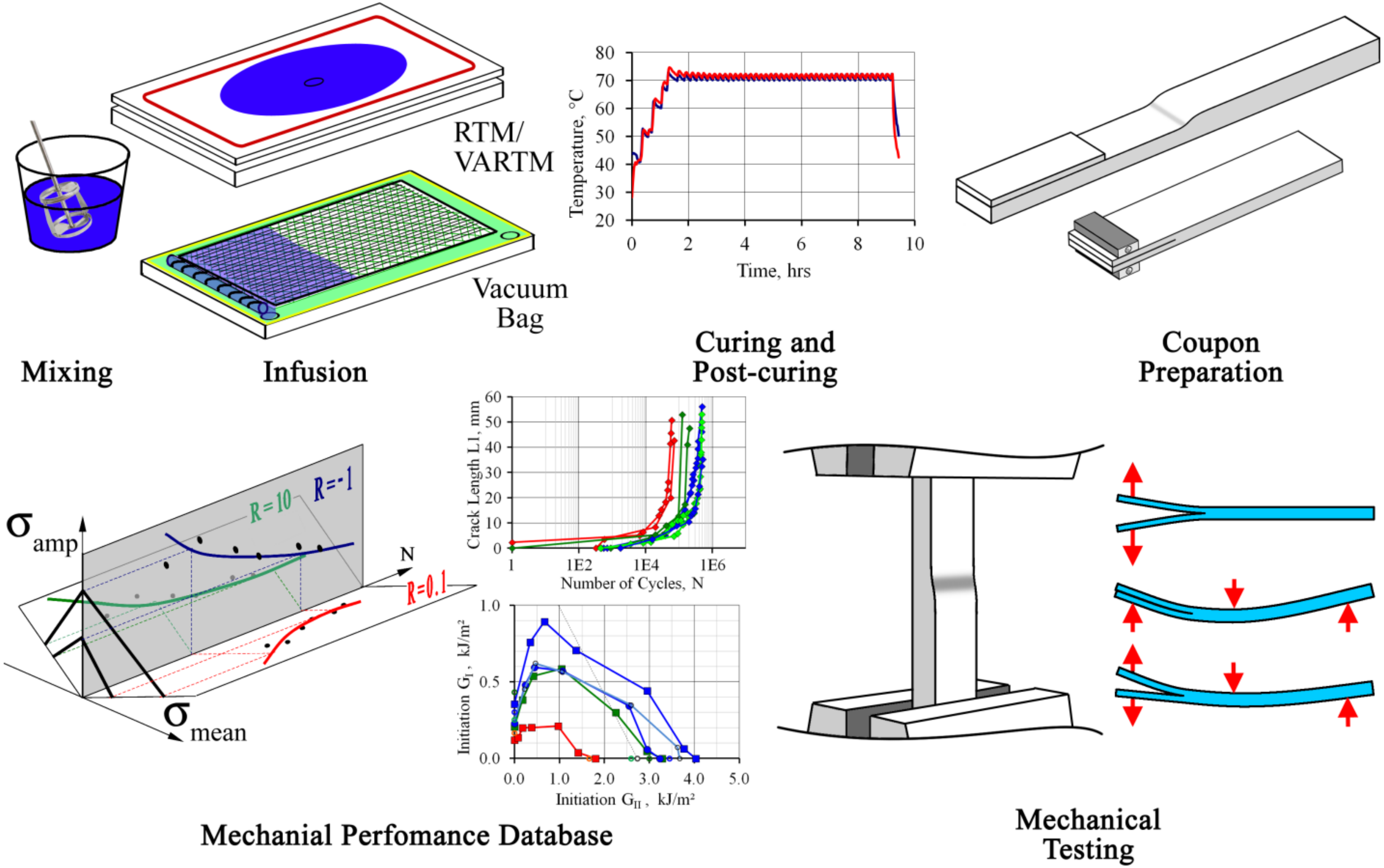
Montana State University Expertise and Capabilities to Meet That Challenge

- Multi-Axial Testing
  - In the Building Block Approach, the materials have not changed, only the geometry has changed
  - This geometry change introduces multi-axial loads
  - Multi-Axial Testing and Failure Criteria can substantially streamline the Building Block Approach to qualify materials and validate scaleup (time and cost)
  - Low cost field repairs of composites

- Progressive Damage Modeling
  - Continuum Damage Modeling (nonlinear constitutive response)
  - Discrete Damage Modeling (actual damage is modeled)
  - Unique combinations for best results
  - Probabilistic Modeling for Structural Reliability

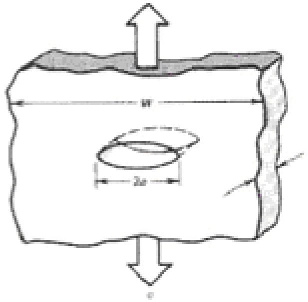
- Adhesive Joints in Composites
  - Durability and Damage Tolerance for a wide variety of adhesives (including high cycle fatigue)
  - Thick adhesive joints (huge implications for reducing manufacturing and assembly costs)
  - Advance fracture mechanics (failure modes and complicated fracture paths)

MSU-Bozeman Composite Group Manufacturing and Material Characterization



Damage Initiation and Growth Relatively Well Known for Metals

- Fracture Mechanics allow the post damage characteristics of a metallic structure to be known

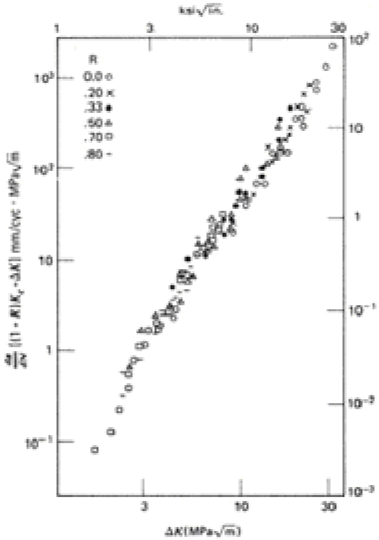


For limit loading:

$$K_{1C} = \sigma(\pi a)^{1/2}$$

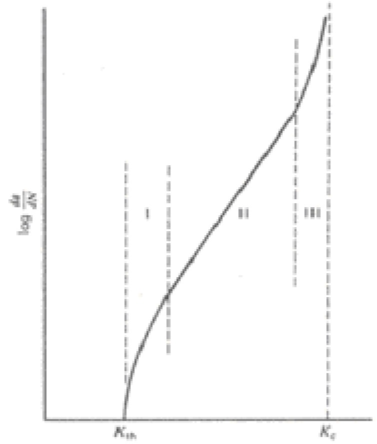
or critical strain energy release rate:

$$G_{1C} = K_{1C}^2 / E(1 - \upsilon^2)$$



For durability:

Paris' law for crack growth:
da/dn vs. ΔK

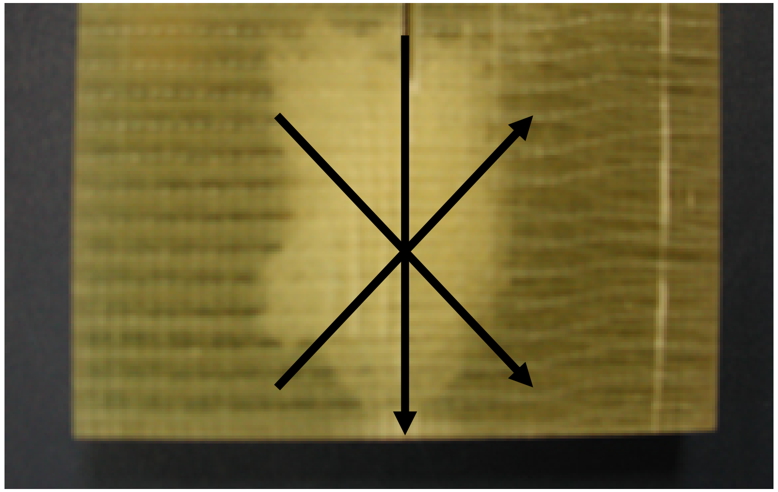


Challenges in Scale Up of Failure Criteria for Composite Materials

- Composites are not isotropic
- Unlike isotropic materials uniaxial testing cannot be used for a reduction of parameters for multiaxial failure initiation and propagation
- Testing and validating material response lower levels will benefit for streamlining certification and scale up (ala John Tracy’s challenge)

Composites

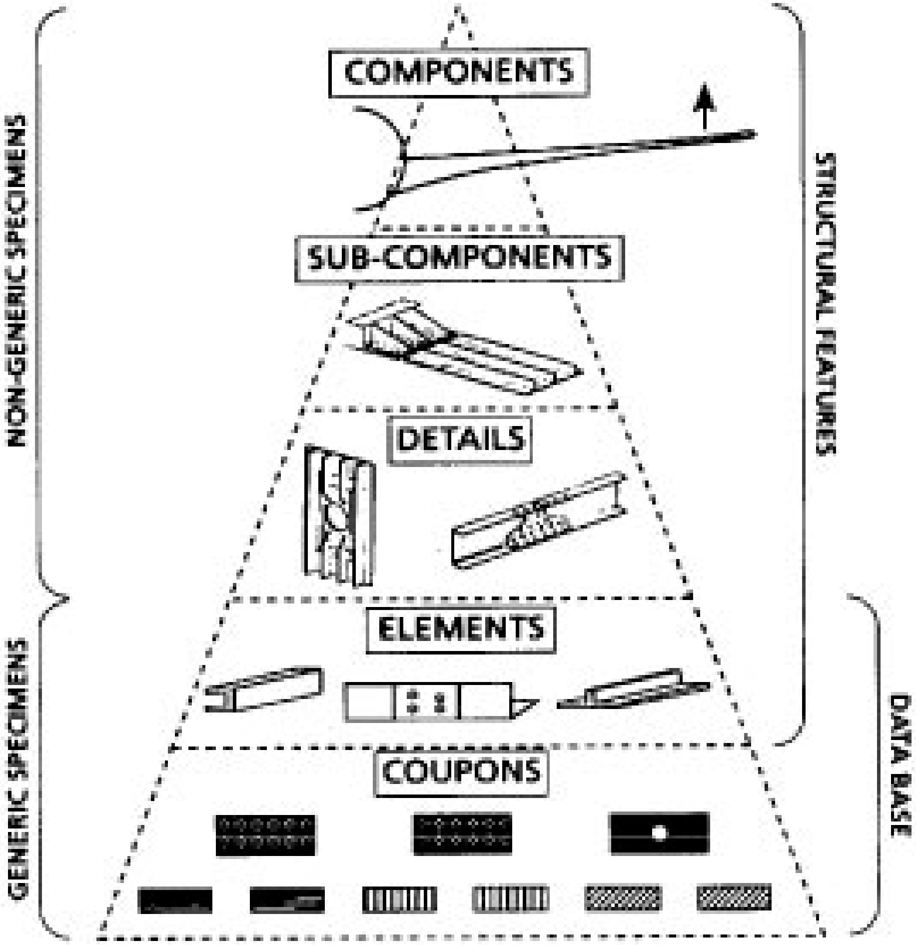
- No full analog of fracture mechanics exists for composite materials
- Damage may occur from:
  matrix cracking
  fiber breakage
  fiber debonding
  delamination



- This makes failure criteria for composites difficult

Streamlining the Building Block Approach

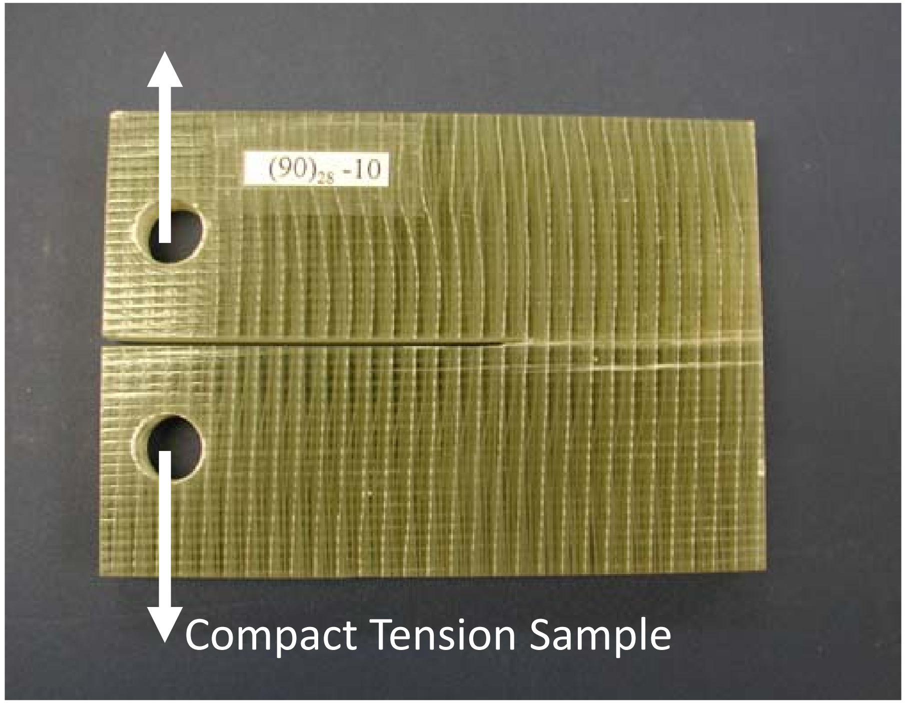
- The prir s to
  develop allow a
  designe e
  characte cture
- This too fort and
  cost of t gn
  method



$80 – $350 Million for such a database

Dissipated Energy

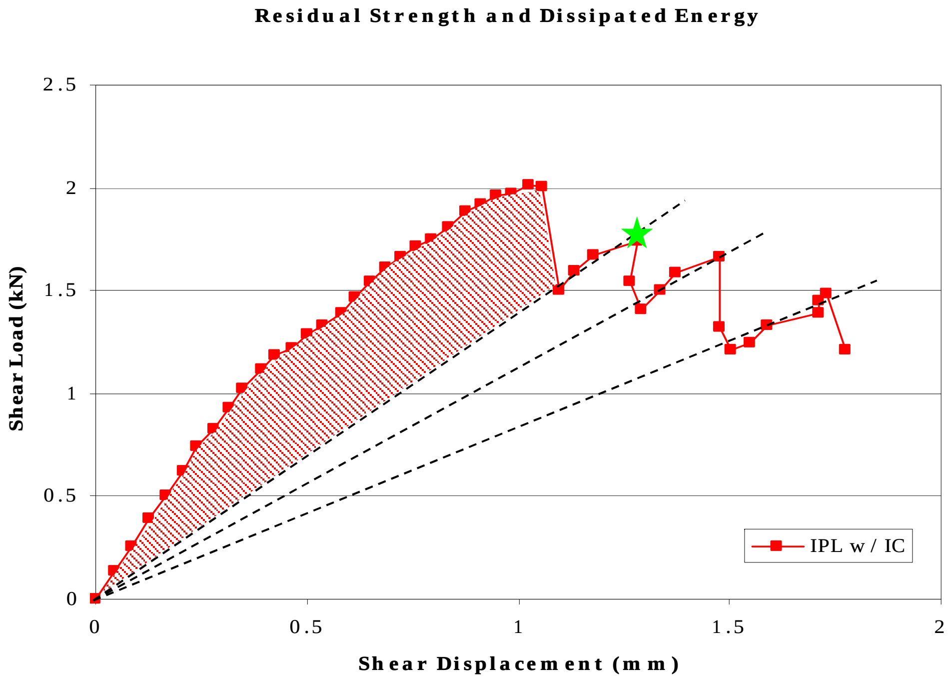
- Energy is dissipated when a system accrues damage



Compact Tension Sample

Residual Strength

- Fiber reinforced plastics are essentially brittle so they typically unload to their undeformed configuration



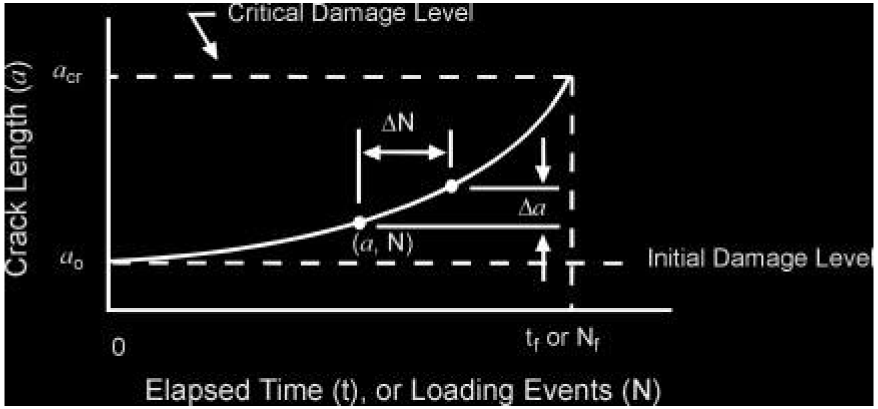
------- Secant Stiffness

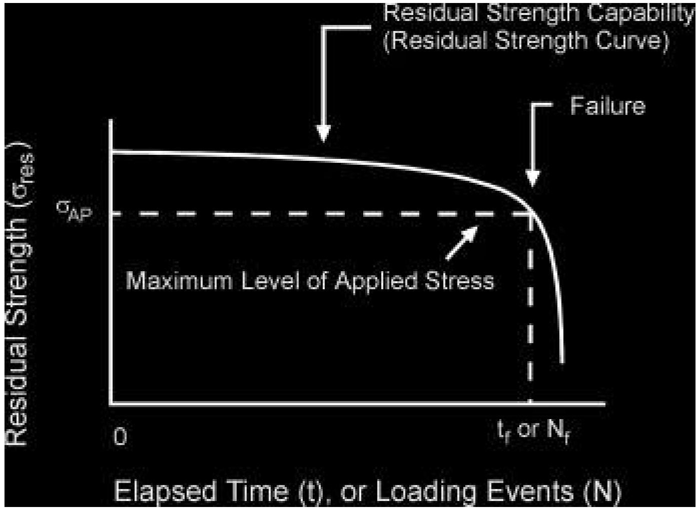
★ Residual Strength

▨ Dissipated Energy

Damage Tolerant Design

- Predictable cyclic loading causes stable crack growth
  - Over the life of a component, periodic inspection illuminates the residual strength





Images from DTD Handbook
http://www.siresearch.info/projects/dtdh/sections/index.php?page=2_1_1

Damage Initiation

- Existing failure surfaces (maximum stress/strain, Tsai-Hill/Wu, Hashin, etc.) all assume a specific shape
  - Instead use interpolation functions with local stress or strain data and a damage metric
  - Total dissipated energy is a scalar quantity and is directly analogous to damage
  - Least squares regression provides best fit to empirical data

Damage Initiation

- Constraints
  - Dissipated energy is nonnegative
  - Dissipated energy can never exceed total strain energy
    - Since the actual strain energy density is also unknown, theoretical strain energy is used based on elastic properties

Dissipated Energy Density Function

Φ = Total Dissipated Energy in a Structure

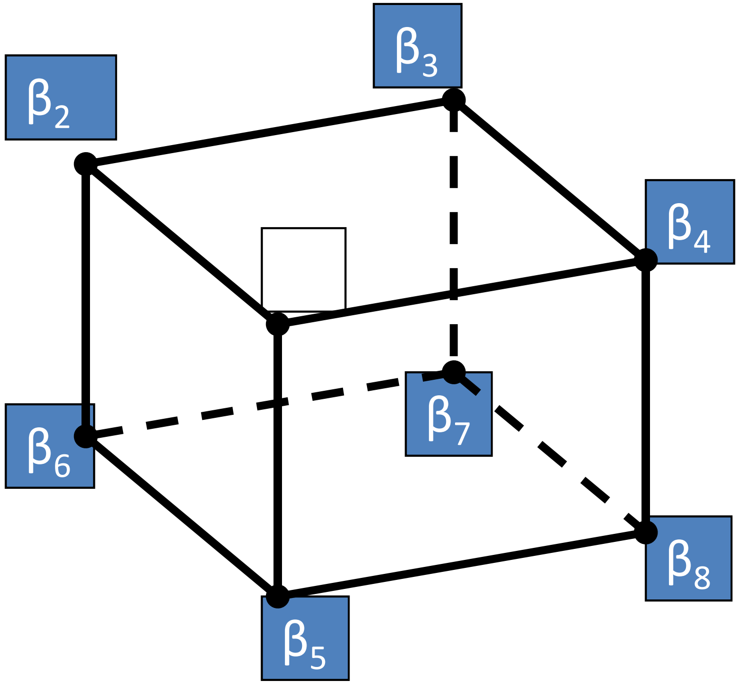
$\varphi(\varepsilon)$ = Dissipated Energy / unit volume

ε = material strains

$$\Phi = \int \varphi(\varepsilon)\, dv$$

Damage Initiation

- Linear interpolation element represents dissipated energy density based on strain



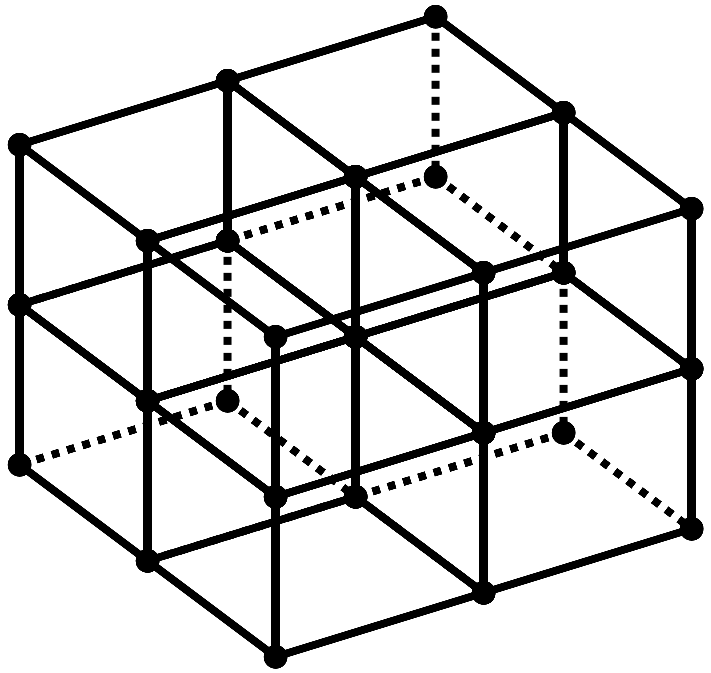
$$\phi(\vec{\varepsilon}) = \sum_i \beta_i N_i(\vec{\varepsilon})$$

$$N_i(\vec{\varepsilon}) = \frac{(1 \pm u)(1 \pm v)(1 \pm w)}{8}$$

u, *v*, and *w* map the strains inside the element from -1 to 1

Damage Initiation

- Several elements are combined to delineate any arbitrary strain space



Damage Initiation

- Experimental dissipated energy is equated to the sum of the of DE from the model on a per-ply-per-element basis

$$\Phi = \sum_{e} A_e \sum_{p} t_p \sum_{i} \beta_i N_i\left(\vec{\varepsilon}_{e,p}\right)$$

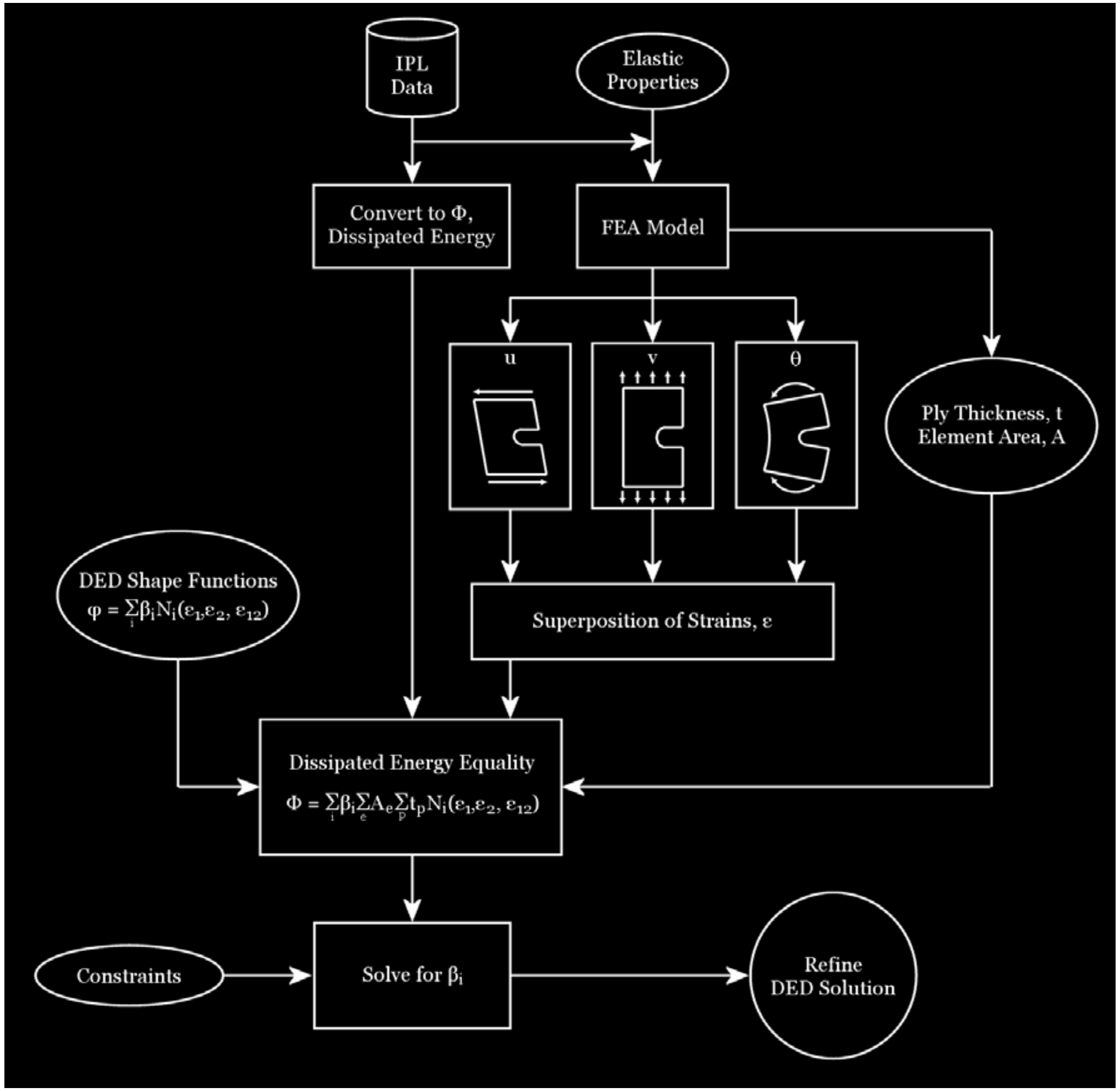
or

$$\Phi = \sum_{i} \beta_i X_i \quad \text{where} \quad X_i = \sum_{e} \sum_{p} A_e t_p N_i\left(\vec{\varepsilon}_{e,p}\right)$$

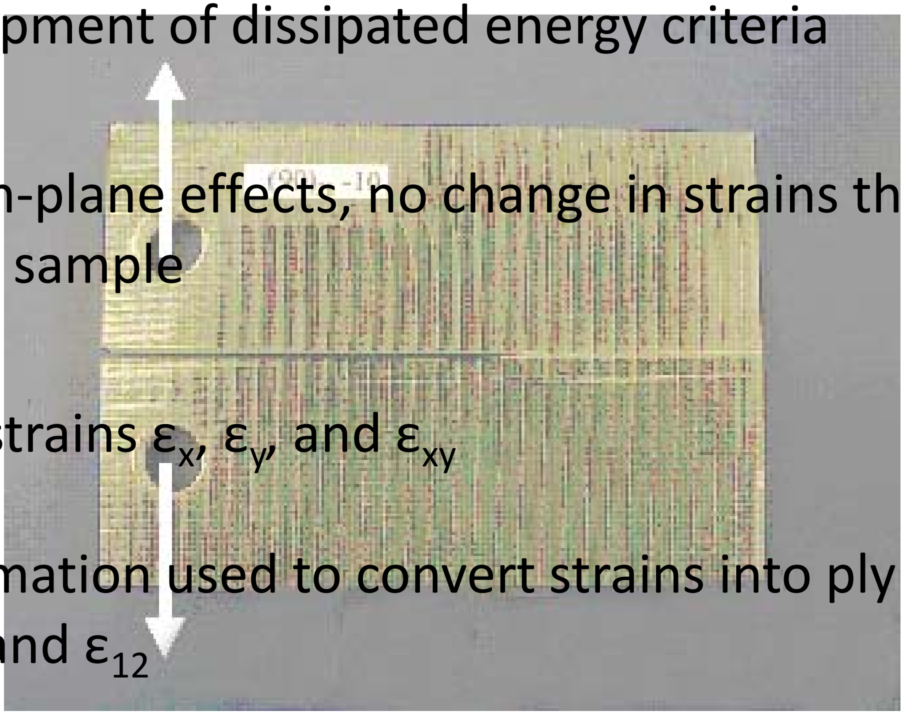
Damage Initiation and Progression

- By including considerably more experimental data points Φ than nodes β, the unknown nodal values can be found by linear least squares
  - First, however, the nodal value must be constrained so that the dissipated energy density solution is physically realistic

DED Function Process



Compact Tension Sample

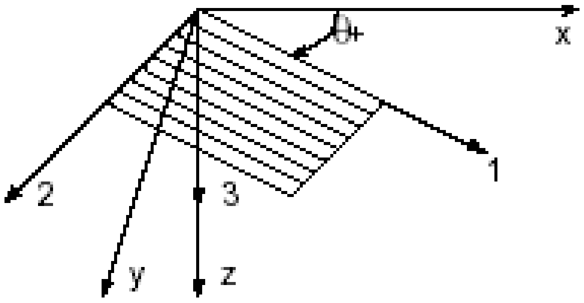


Used for development of dissipated energy criteria

Dominated by in-plane effects, no change in strains through the thickness of the sample

Three in-plane strains ε_x, ε_y, and ε_{xy}

Tensor transformation used to convert strains into ply coordinate strains ε_{11}, ε_{22}, and ε_{12}



Material Information

Laminates created from D155 e-glass fibers and isopolyester resin

Manufactured by resin transfer molding process

Laminates contain 28 plies, 12.7 mm thick

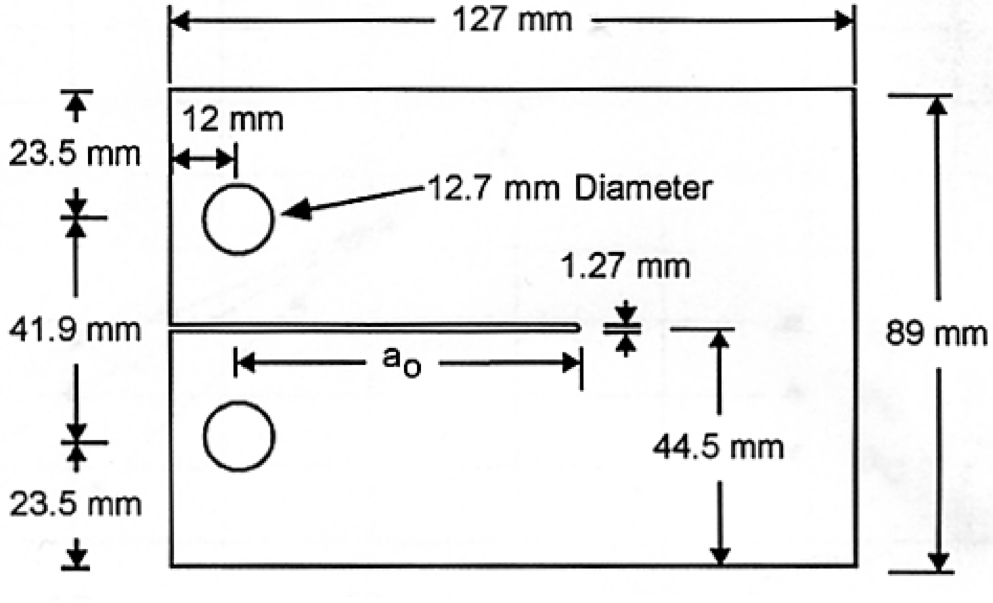
Four possible ply angles: 0, 90, +45 and –45

Analysis performed on six different laminates

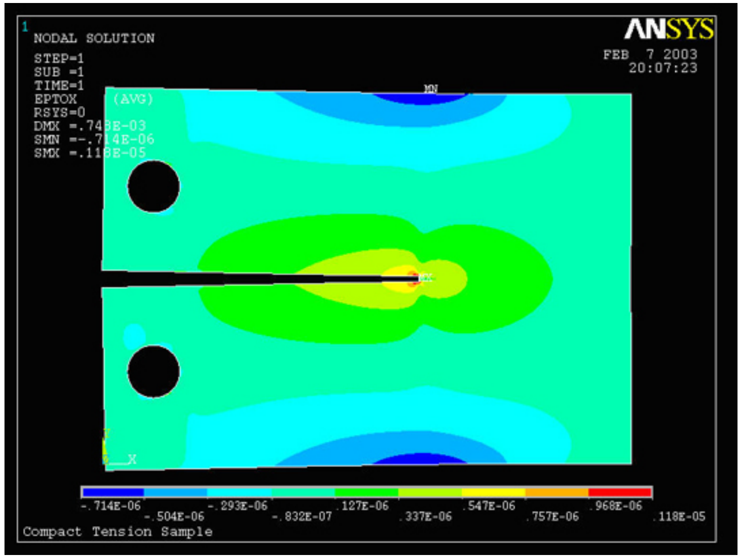
Testing performed on an Instron 8562 screw machine

Laminates:

1: 90_{28}
2: $(90_2/0)_{4s}$
3: $(90_{13}/45)_s$
4: $(90_7/\pm45/90_5)s$
5: $((90_4/\pm45)_2/90_2)s$
6: $((90_2/\pm45)_3/90/45)s$



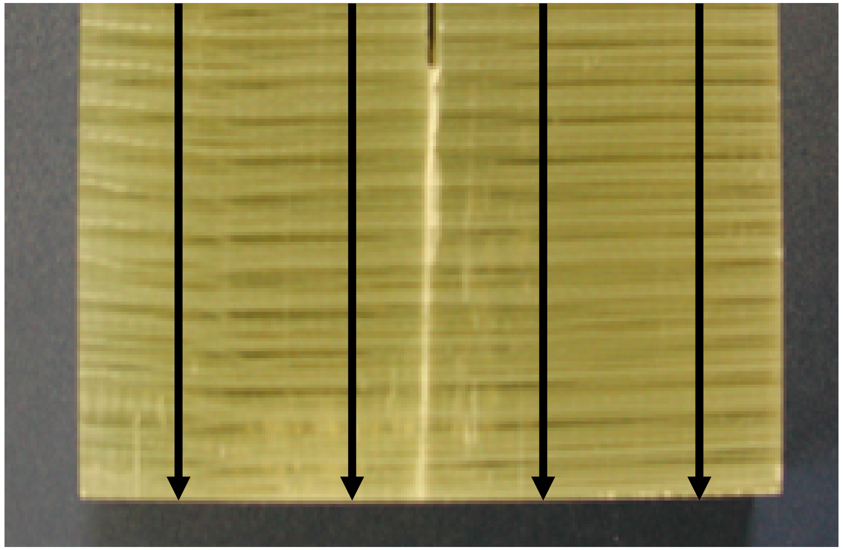
Finite Element Modeling



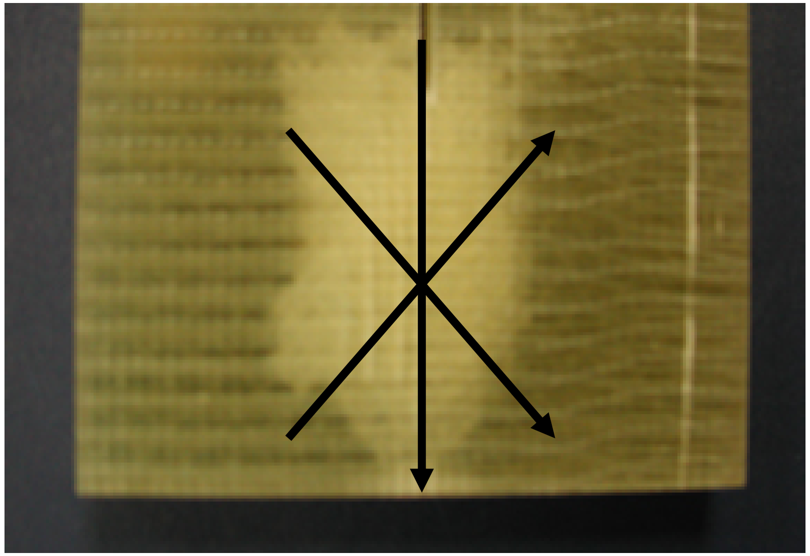
- Finite element model created in Ansys
- Two dimensional model, uses shell91 composite elements
- Quadratic shape functions

Results with CTS samples

- Compiled Fit: Six Experiments Used



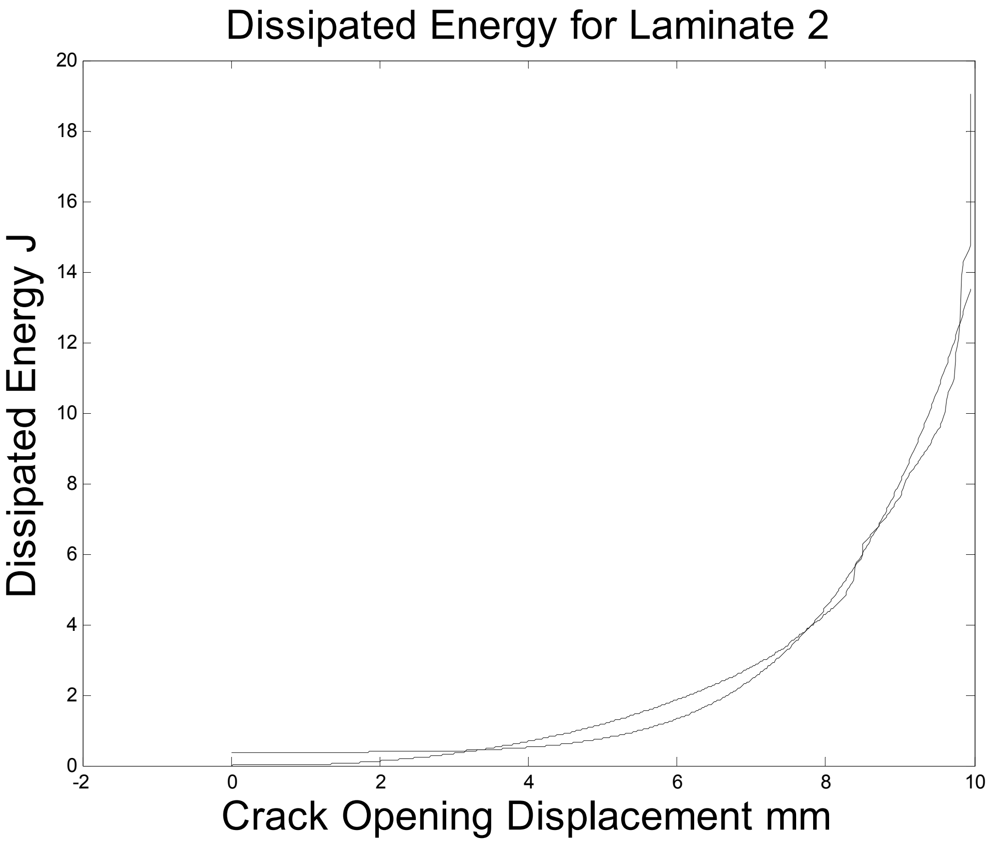
Fits are less accurate due to lack of 45 degree plies



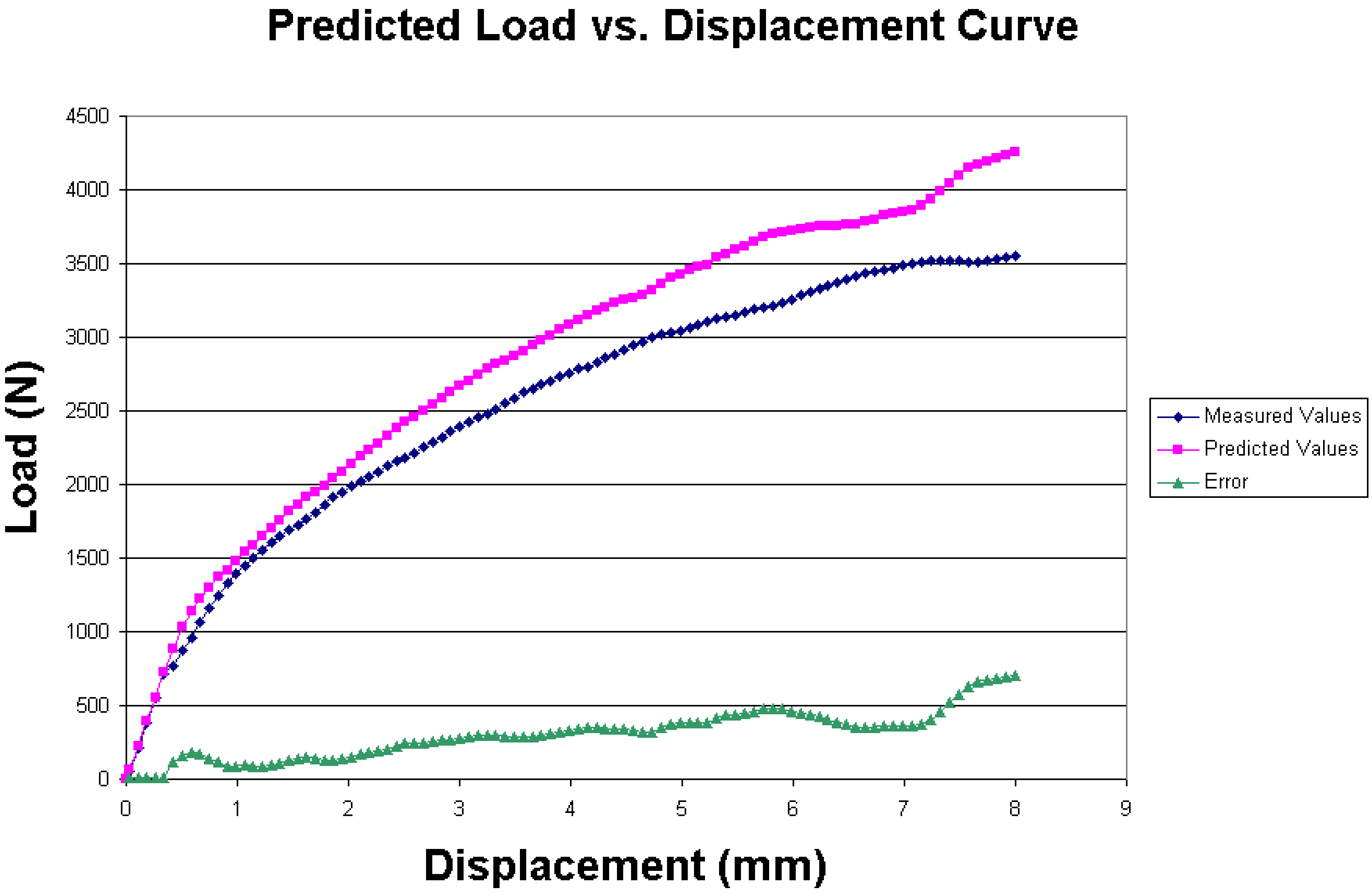
Fits are accurate for these four laminates.

Predicted Behavior

Use five laminates to derive C vector, predict behavior of the sixth.



Load-Displacement Behavior



Results

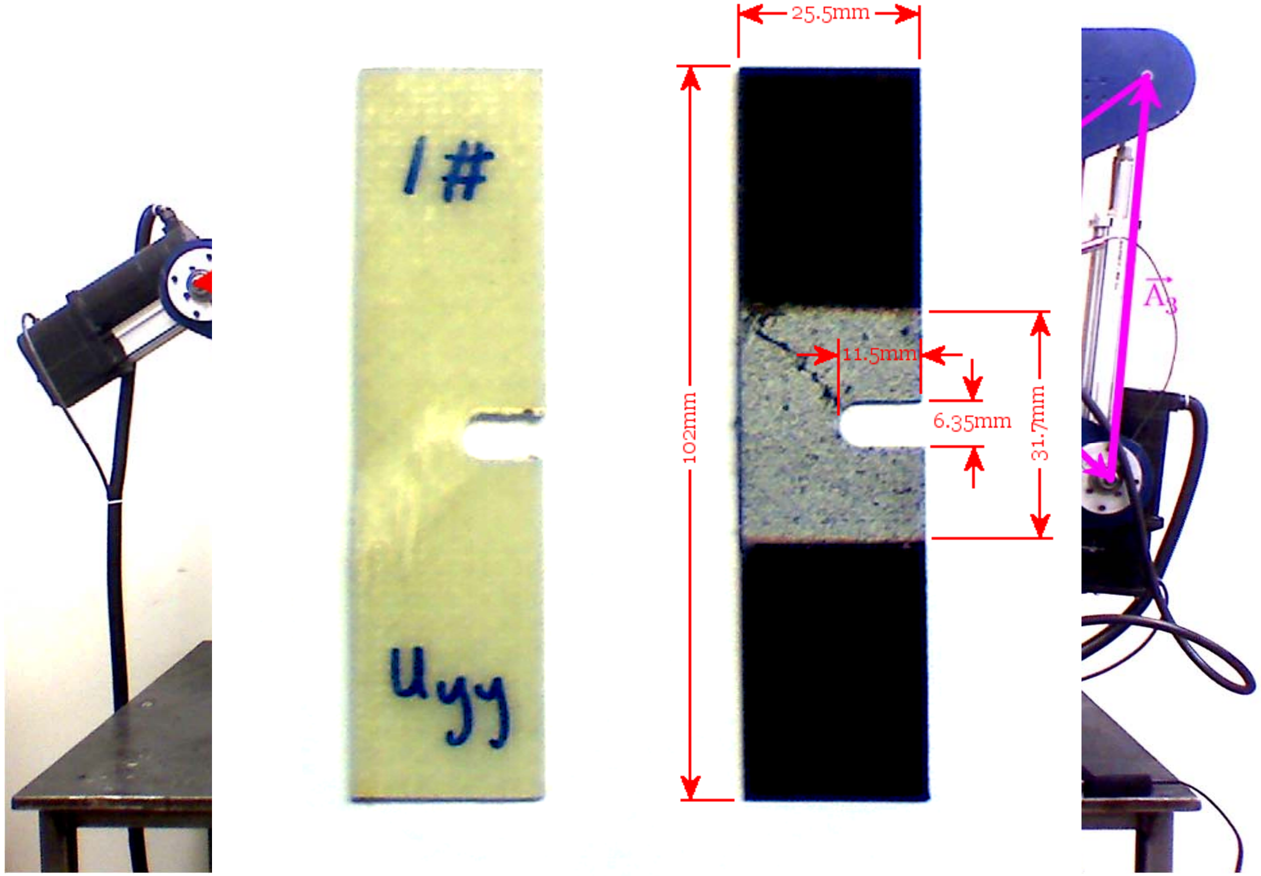
- The dissipated energy of a CT sample can be satisfactorily approximated with a least squares approximation for laminates with less than 90 percent 90 degree plies
- This allows for prediction of the load vs. displacement relationship for a structure
- Allows one to analyze a given strain state on a structure and determine if there has been any energy dissipated
- Locations in the structure where damage is occuring can also be determined from the dissipated energy density function

Limitations of this method

- To find the best C vector more data are needed.
- If CT samples are used a large number of different laminates will be required. This will be highly labor intensive.
- A machine that can provide many different displacements will require only one laminate to be made. This will allow for much cheaper material characterization.

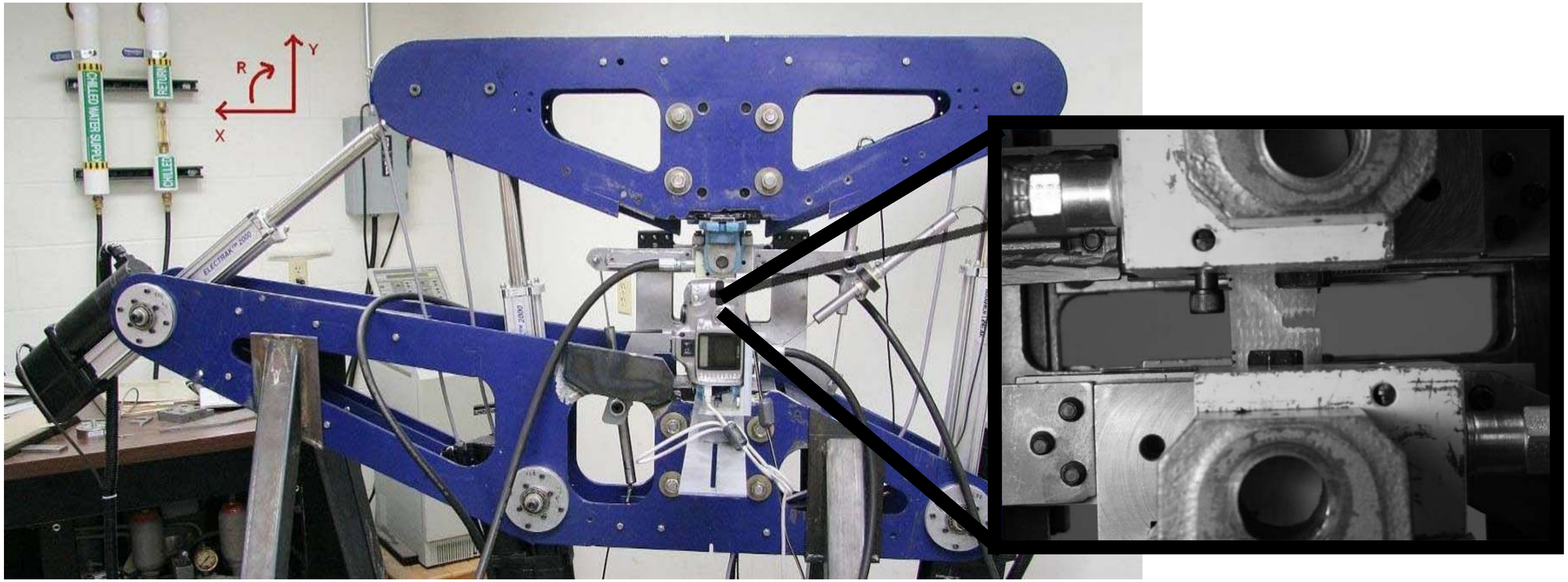
Multiaxial Testing

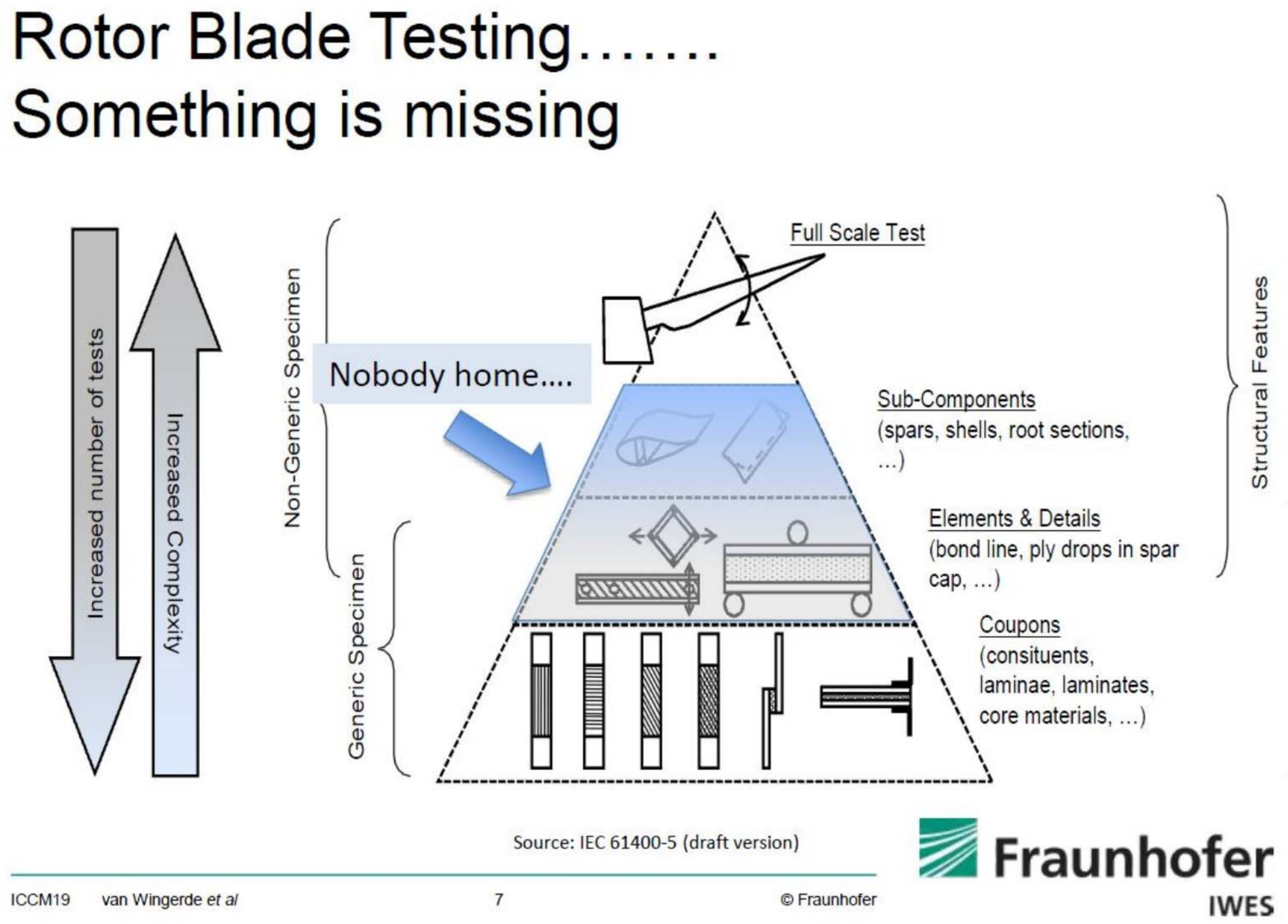
- MSU In-Plane Loader



MSU In Plane Loader (IPL)

- Can load specimens in tension (Y), shear (x) and rotation (R) axes
- Gathers load and displacement data for all axes at the grips using load cells and linear-variable differential transducers (LVDTs)
- Funded for several years by ONR and AFOSR





Rotor Blade Testing…….
Something is missing

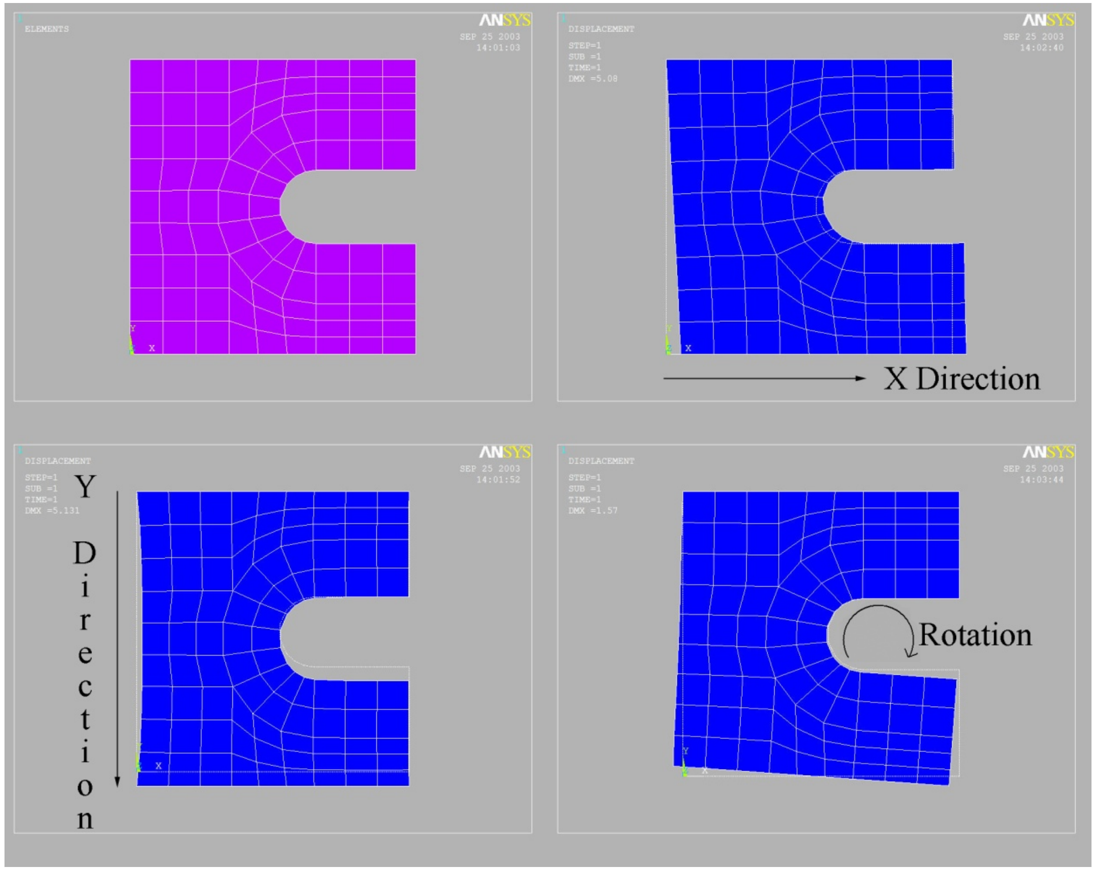
Source: IEC 61400-5 (draft version)

ICCM19 van Wingerde *et al* 7 © Fraunhofer

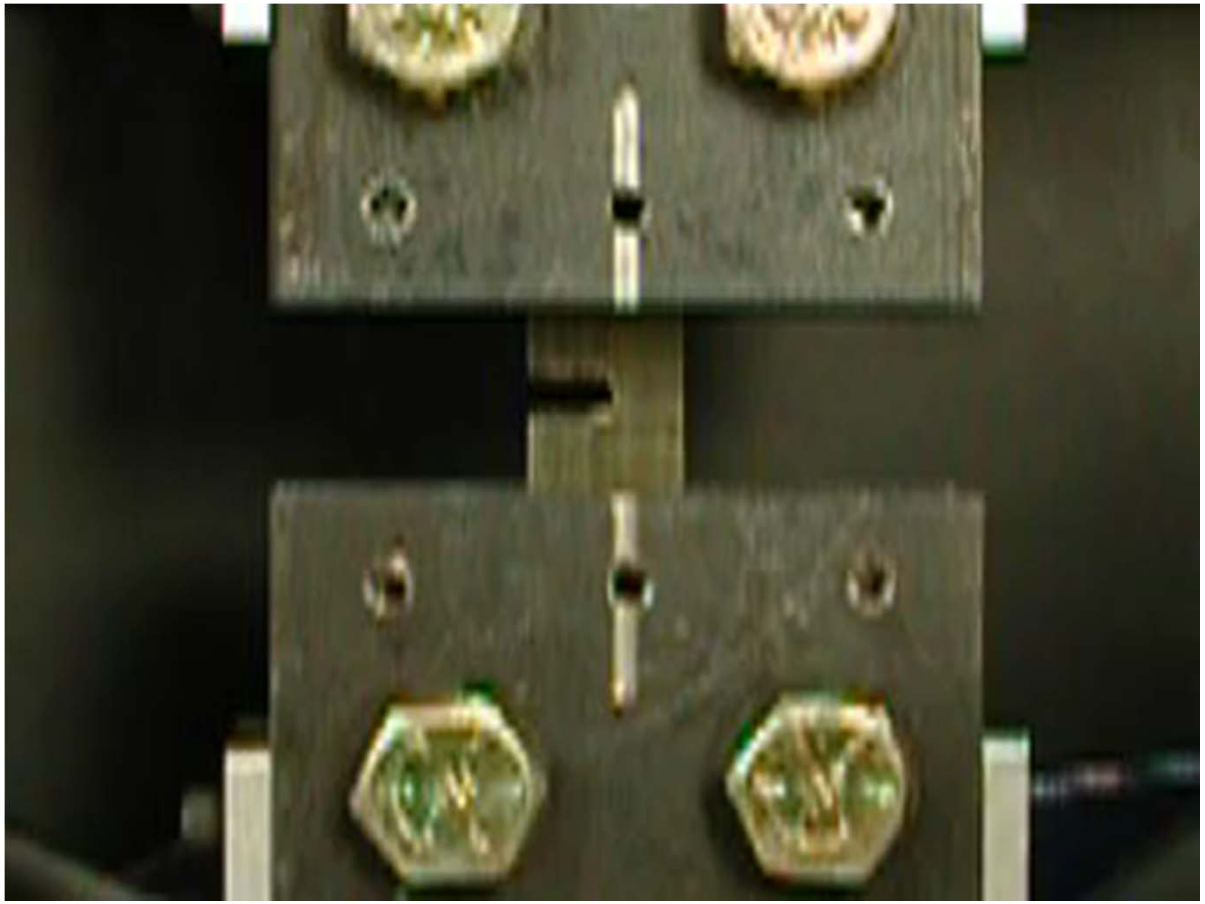
Fraunhofer IWES

Learn as much as you can at the lower levels, use the upper levels for **validation**, **not** basic **database building**

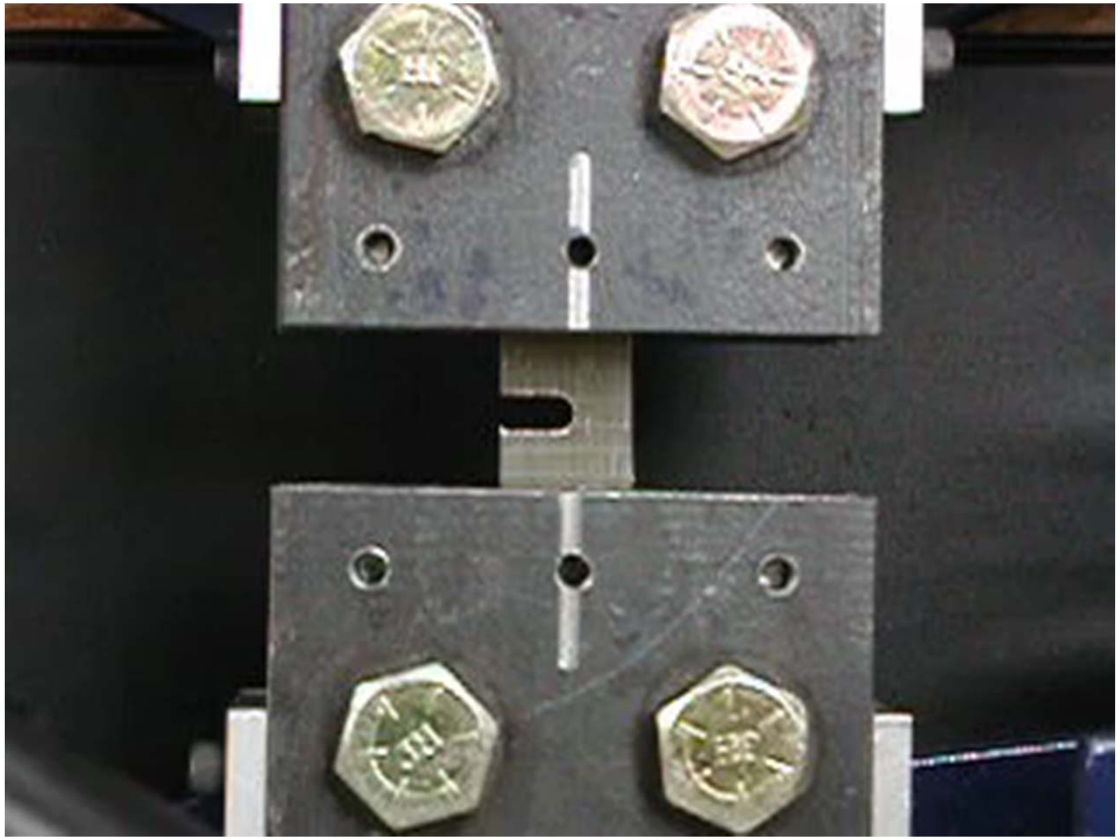
In Plane Loader Motion



In Plane Loader Rotation Plus Shear

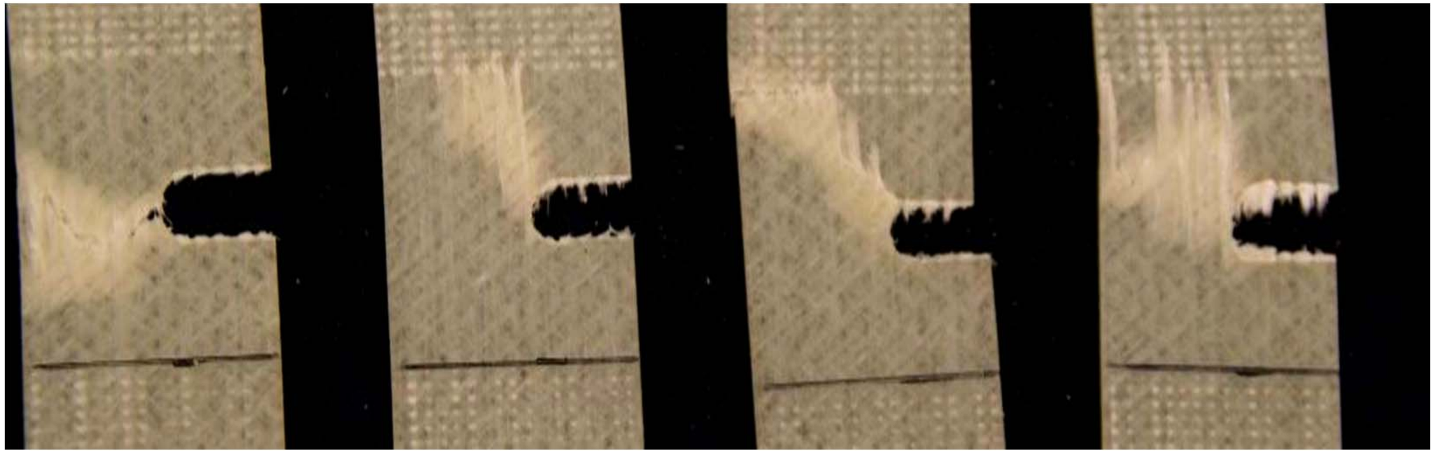


In Plane Loader Rotation Plus Shear



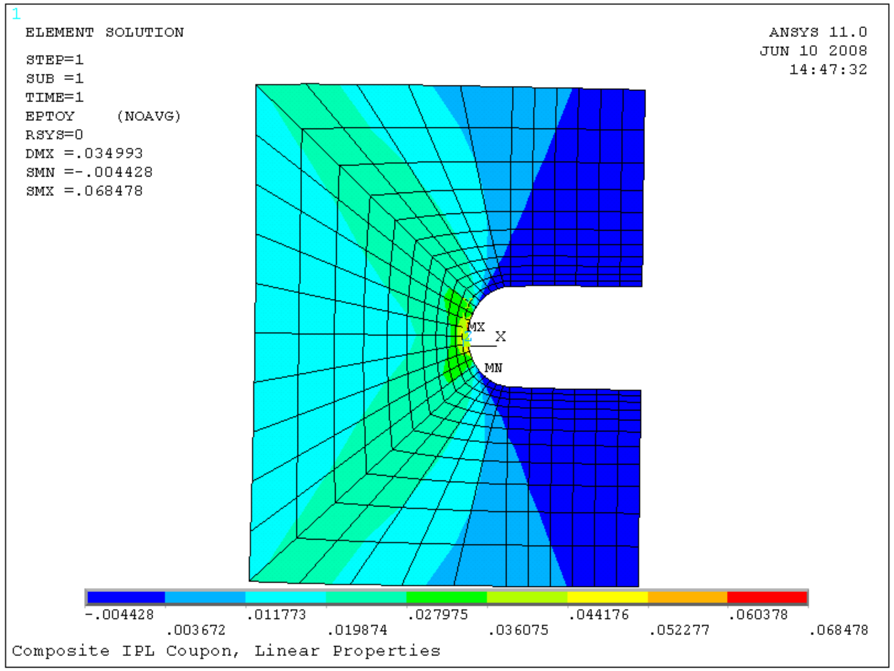
Composite Material Failure

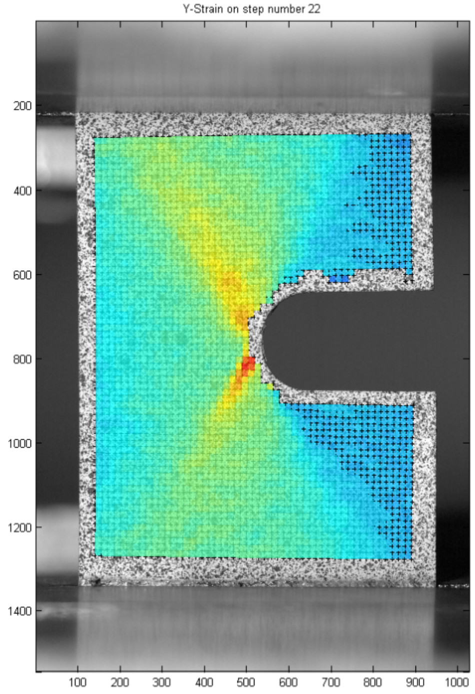
- Gradual accumulation of damage; damage includes fiber breakage and debonding, matrix crazing and cracking and delamination
- Multiple forms of damage lead to multiple forms of failure
- Failure typically predicted with empirical formulas such as Maximum Stress, Maximum Strain and Tsai-Wu
- Ability to measure multi-axial constitutive response DIRECTLY, no assumptions about interactions necessary



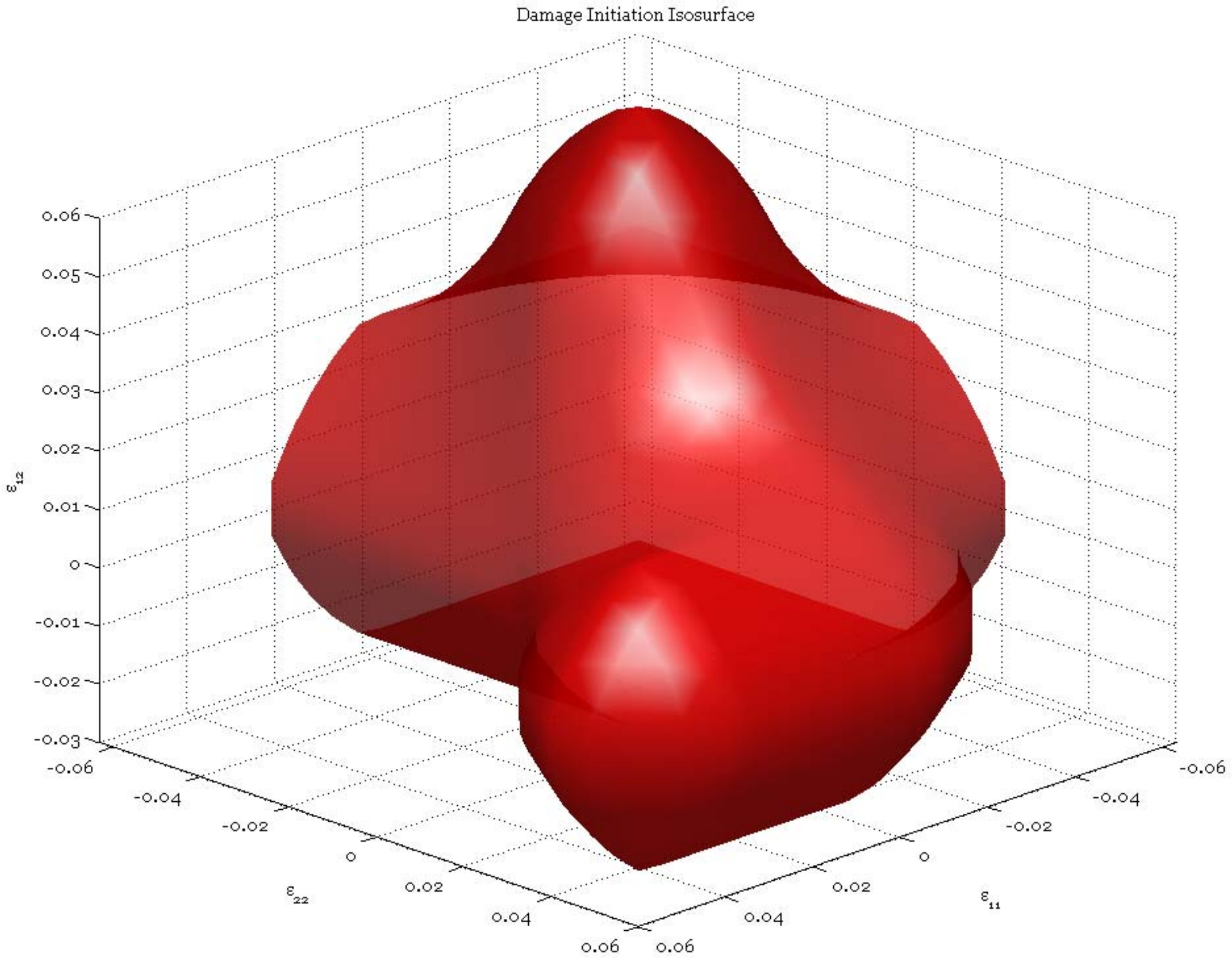
Damage Initiation

- In-plane strains in ply principal axes can be approximated through linear FEA or measured via digital image correlation

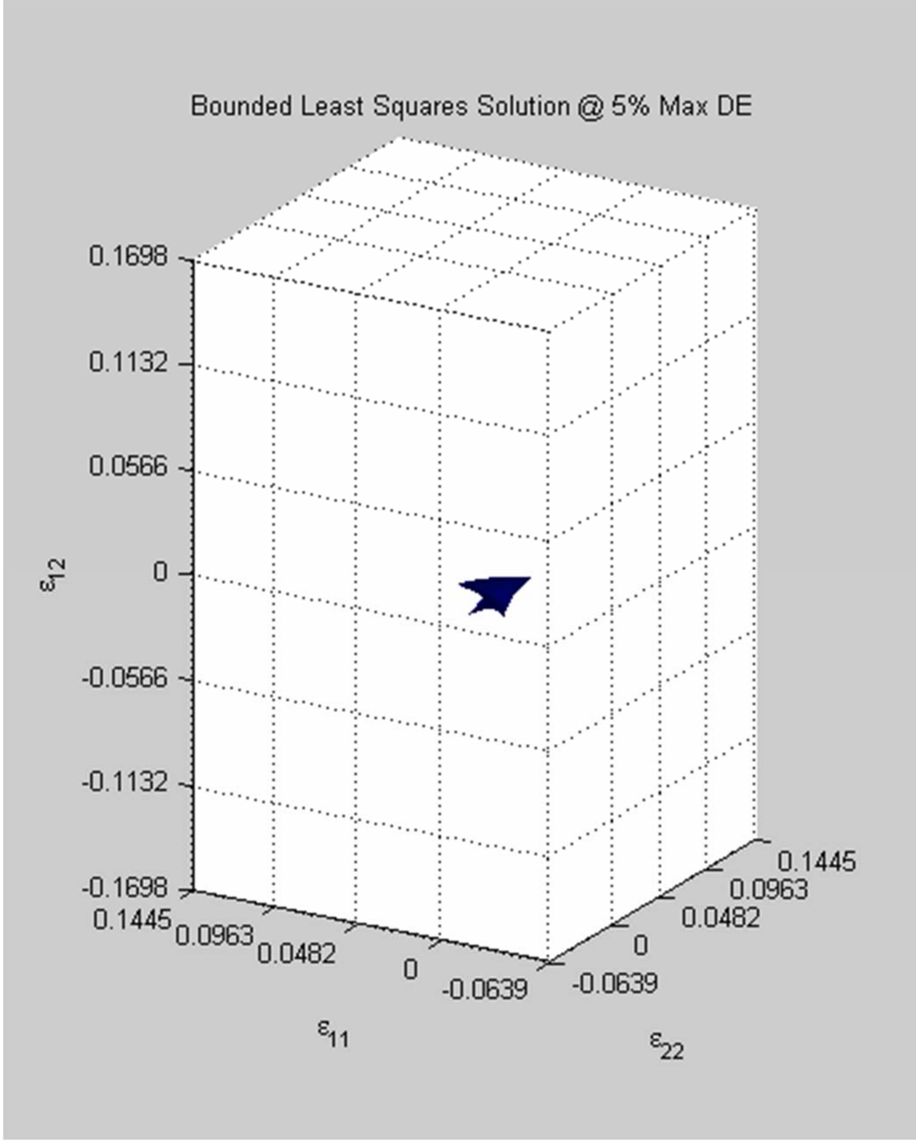




Damage Initiation Isosurface



Damage Progression



Progressive Damage Modeling

- Importance
  - For example, damage models help to determine
    - Ability to sustain design loads without incurring damage
    - Critical modes of failure

  - Identify material/structural designs that limit growth of damage
    - Good design is an iterative process
    - Good models save time, money, lead to optimized solutions

  - Help understand residual strength in the presence of damage or flaws
    - Damage tolerance may extend service lifetime
    - Determine ability to continue service
    - Especially important for fatigue loading (high cycles, growth of damage over time)

Continuum Damage Modeling

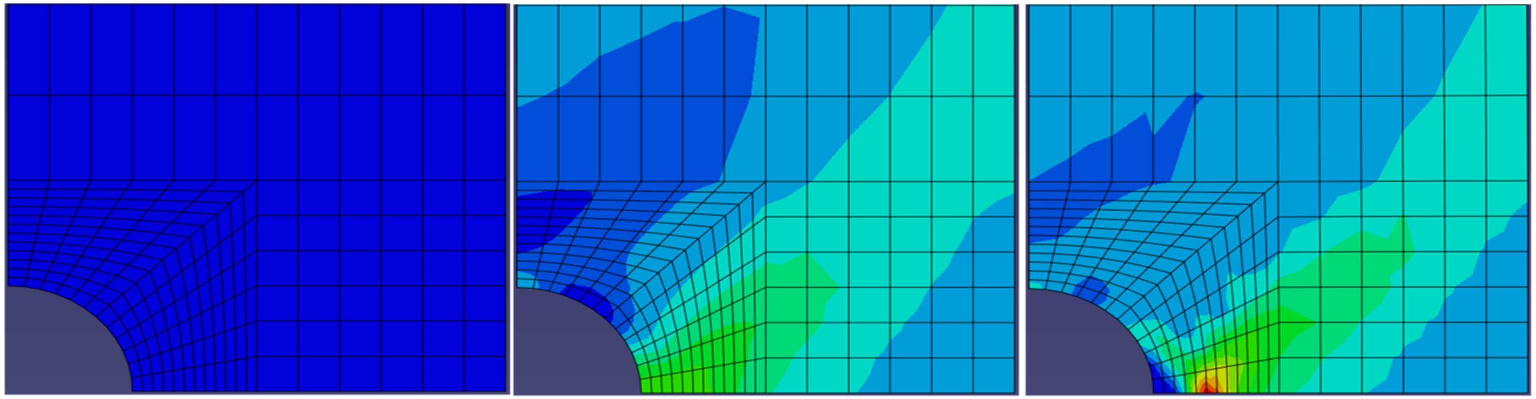
- **Continuum Damage Modeling (CDM)**
  - A "pseudo-representation"
  - Does not model the exact damage
  - Updates constitutive properties as damage occurs
  - As the model iterates, the constitutive matrix, *C* or *S*, is updated to reflect equilibrium damage
  - *C* or *S* may simplify; based on material and lay-up

Compliance Matrix for Orthotropic Material:

$$\begin{Bmatrix}\varepsilon_{xx}\\ \varepsilon_{yy}\\ \varepsilon_{zz}\\ \varepsilon_{yz}\\ \varepsilon_{zx}\\ \varepsilon_{xy}\end{Bmatrix}=\begin{bmatrix}\frac{1}{E_x} & \frac{-\upsilon_{yx}}{E_y} & \frac{-\upsilon_{zx}}{E_z} & 0 & 0 & 0\\ \frac{-\upsilon_{xy}}{E_x} & \frac{1}{E_y} & \frac{-\upsilon_{zy}}{E_z} & 0 & 0 & 0\\ \frac{-\upsilon_{xz}}{E_x} & \frac{-\upsilon_{yz}}{E_y} & \frac{1}{E_z} & 0 & 0 & 0\\ 0 & 0 & 0 & \frac{1}{2G_{yz}} & 0 & 0\\ 0 & 0 & 0 & 0 & \frac{1}{2G_{zx}} & 0\\ 0 & 0 & 0 & 0 & 0 & \frac{1}{2G_{xy}}\end{bmatrix}\begin{Bmatrix}\sigma_{xx}\\ \sigma_{yy}\\ \sigma_{zz}\\ \sigma_{yz}\\ \sigma_{zx}\\ \sigma_{xy}\end{Bmatrix}$$

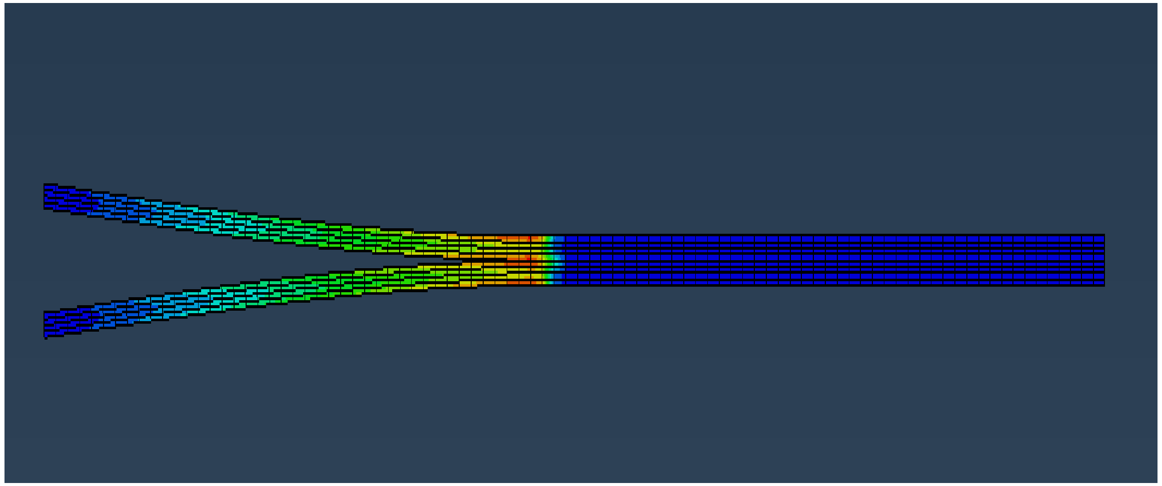
As damage occurs, the material properties (*E*, *v* & *G*) may be adjusted to account for a different response in the damaged specimen.

As such, C may be adjusted depending on failure criteria.



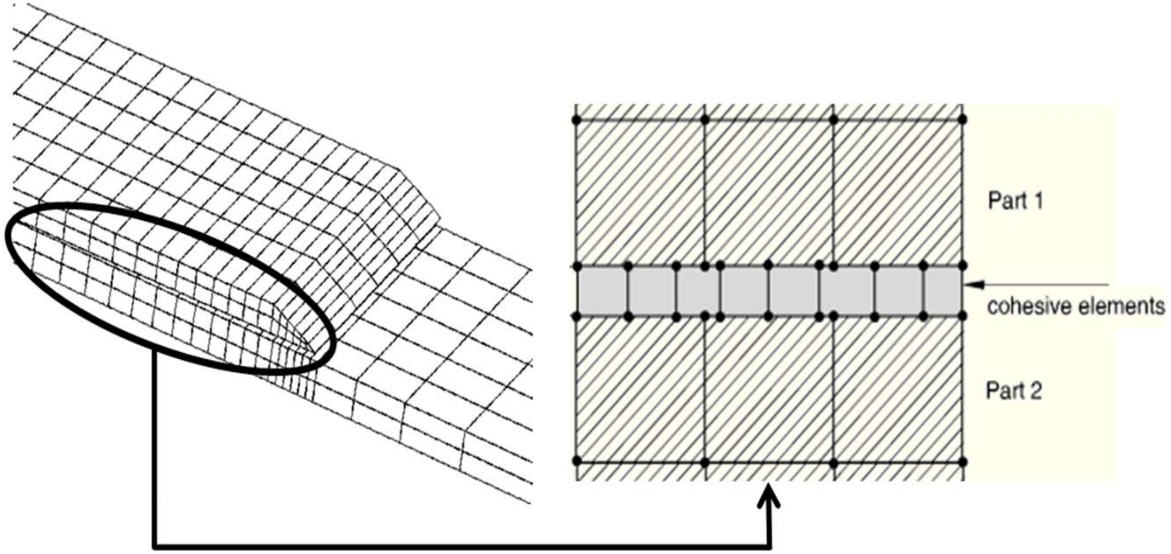
Discrete Damage Modeling

- **Discrete Damage Modeling (DDM)**
  - Models the damage as it occurs (prior knowledge is helpful)
  - Generally, computationally more expensive
  - Utilizing Cohesive Elements; improvement on VCCT/LEFM because crack path not necessary

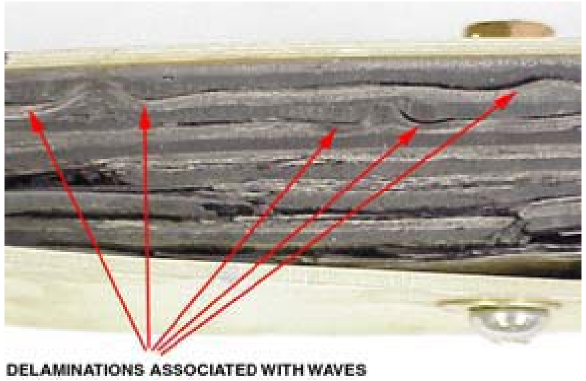


DDM: Cohesive Elements

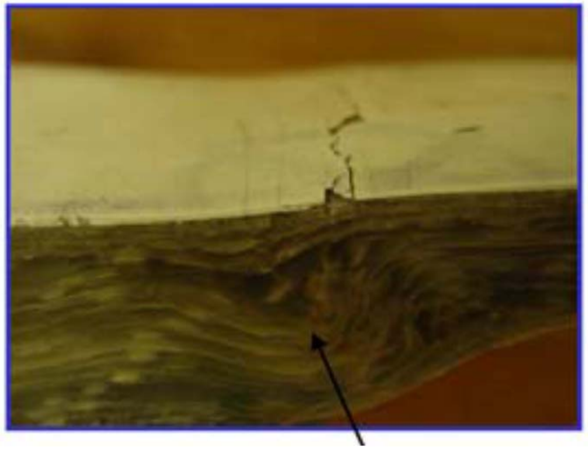
- Cohesive Elements
  - Traction-separation based modeling for bonded interfaces (composites)
  - Layer of essentially zero thickness elements added between layers where crack is expected
  - Models the initial loading, the initiation of damage, and the propagation of damage leading to eventual failure



Wind Turbine Blade Reliability – Not Just an Academic Problem



Delaminations in a Low-Cost Composite Structure

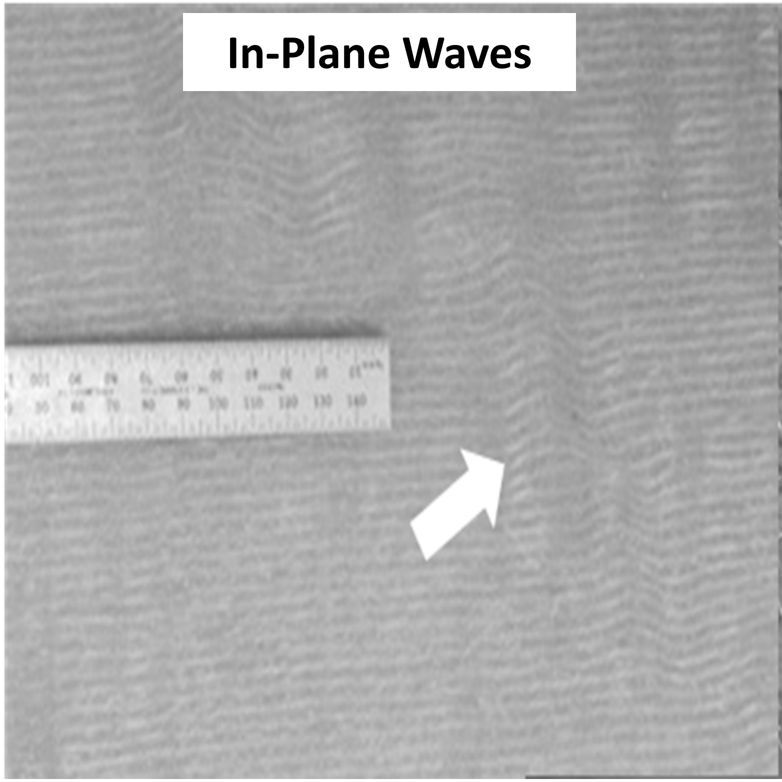


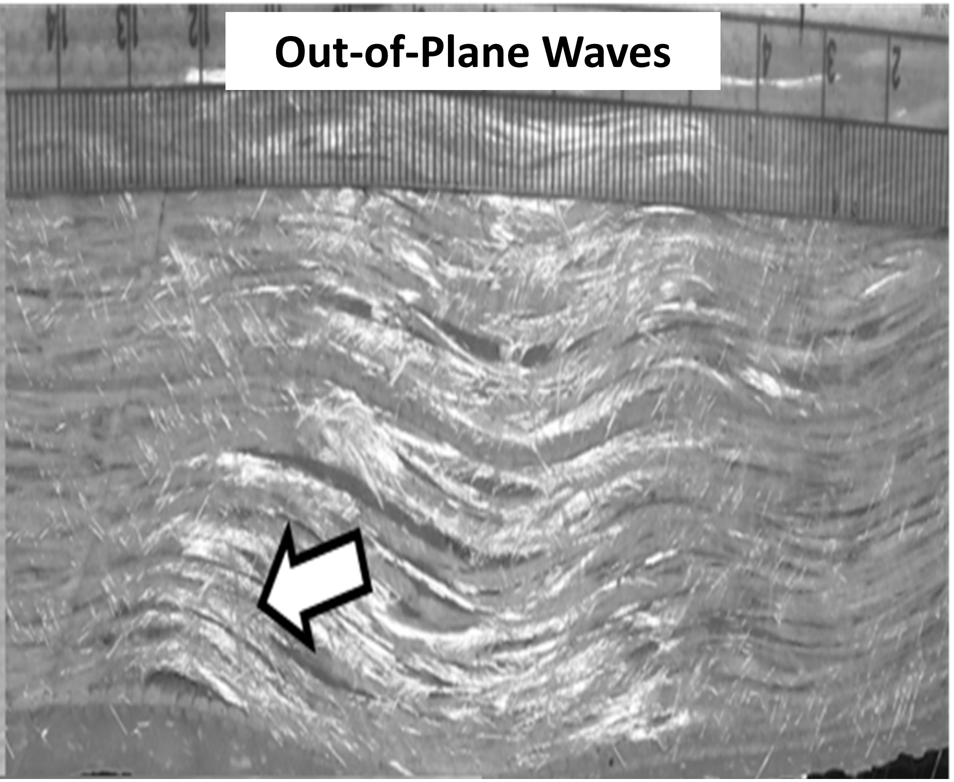
Glass Fiber Reinforced Wind Turbine Blade Local Failure at a Manufacturing Flaw

Field Failure of a Wind Turbine Blade (Judith Gap Montana 2009)

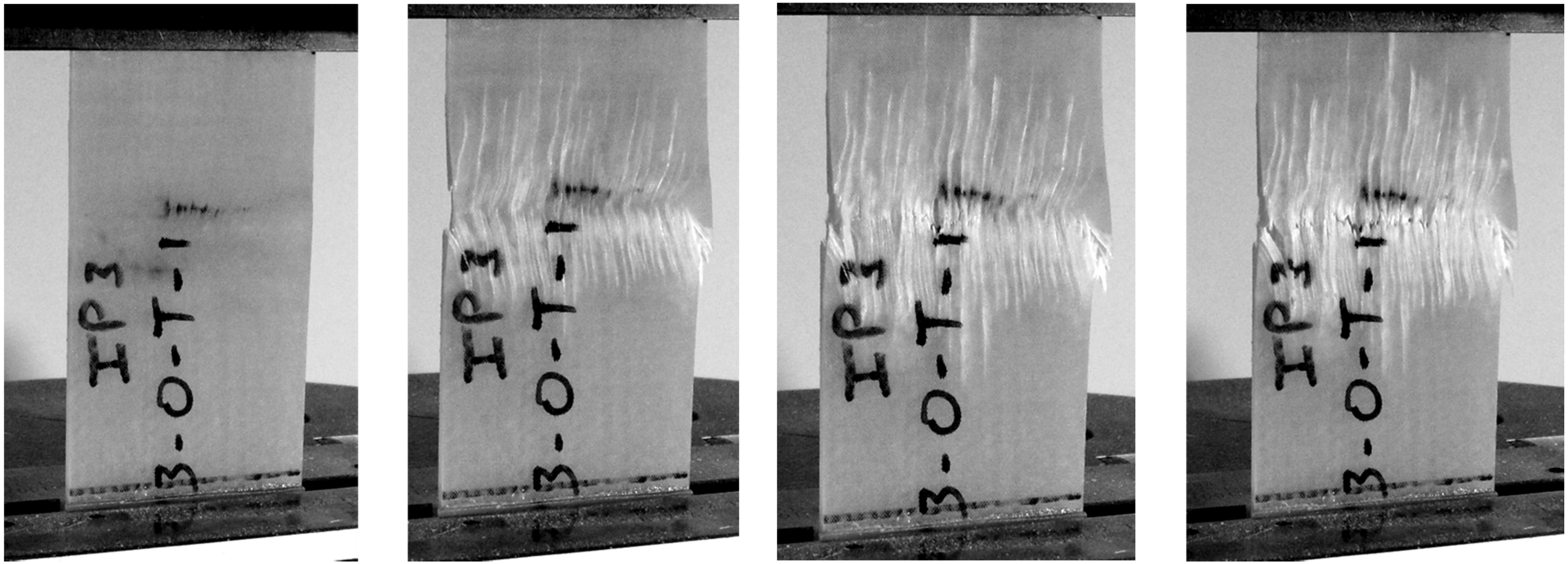
Defect Types

- Waves: bending or waviness along fiber length
  - In-plane (IP): fiber waves on surface (left)
  - Out-of-plane (OP): fiber waves through thickness (right)
  - Characterized by misalignment angle (θ) or amplitude (A) & wavelength (λ)





0° Tension In-Plane Wave Progressive Damage



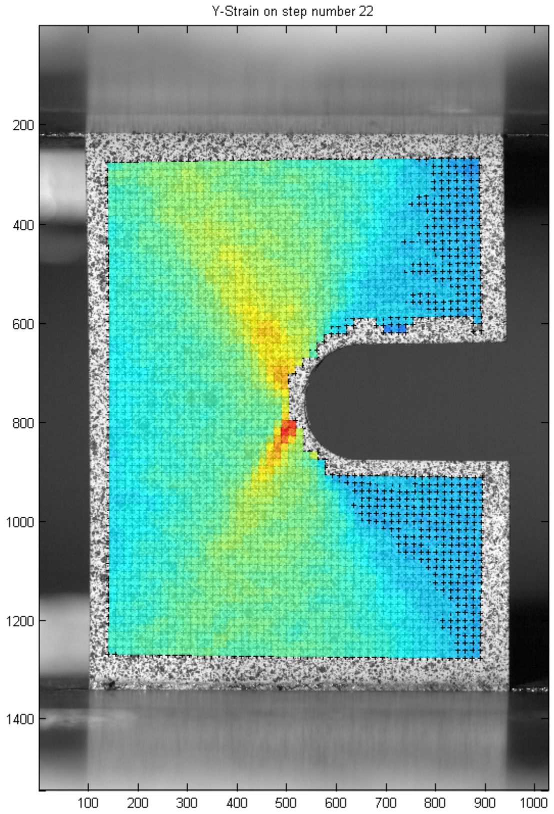
Matrix Cracking

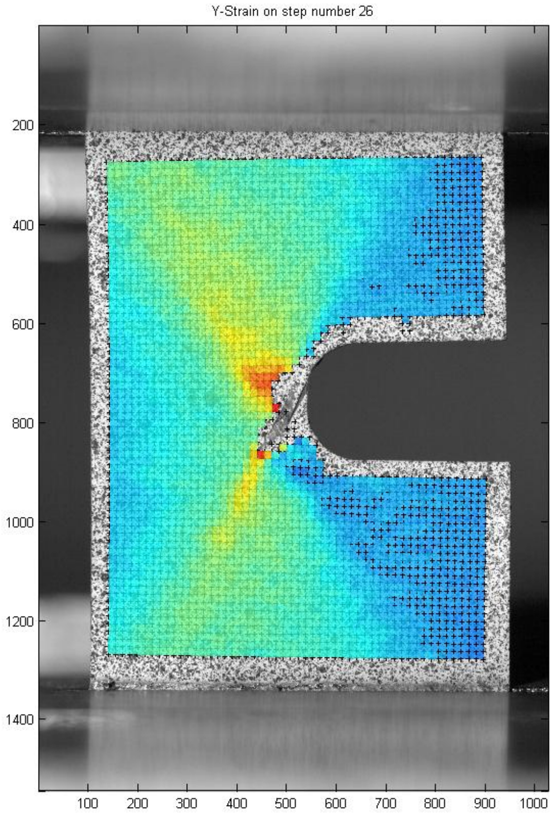
Ultimate Ply Failure

Damage visualized with images and Aramis digital image correlation (DIC) system.

Improved Testing Methodologies for Advanced Composites : Full Field Strain Validation

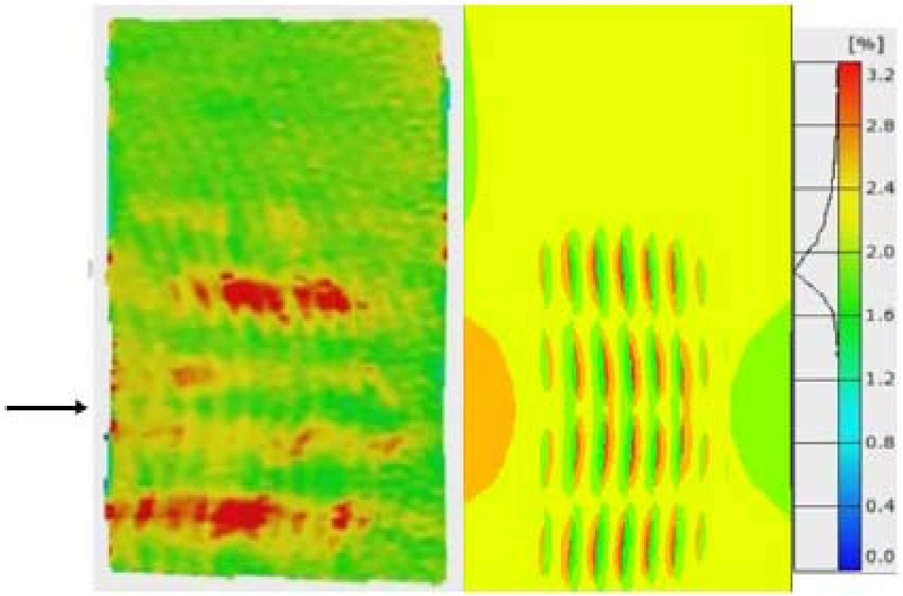
- Full field strain data for progressive damage is generated via Digital Image Correlation – closing the loop for experimental/analytical correlations





This work was done at MSU for Goodrich Aerospace - project with AFOSR for fiber-reinforced ceramic matrix gas turbine blades

Good Experimental/Analytical Correlations of Partial Width Waves

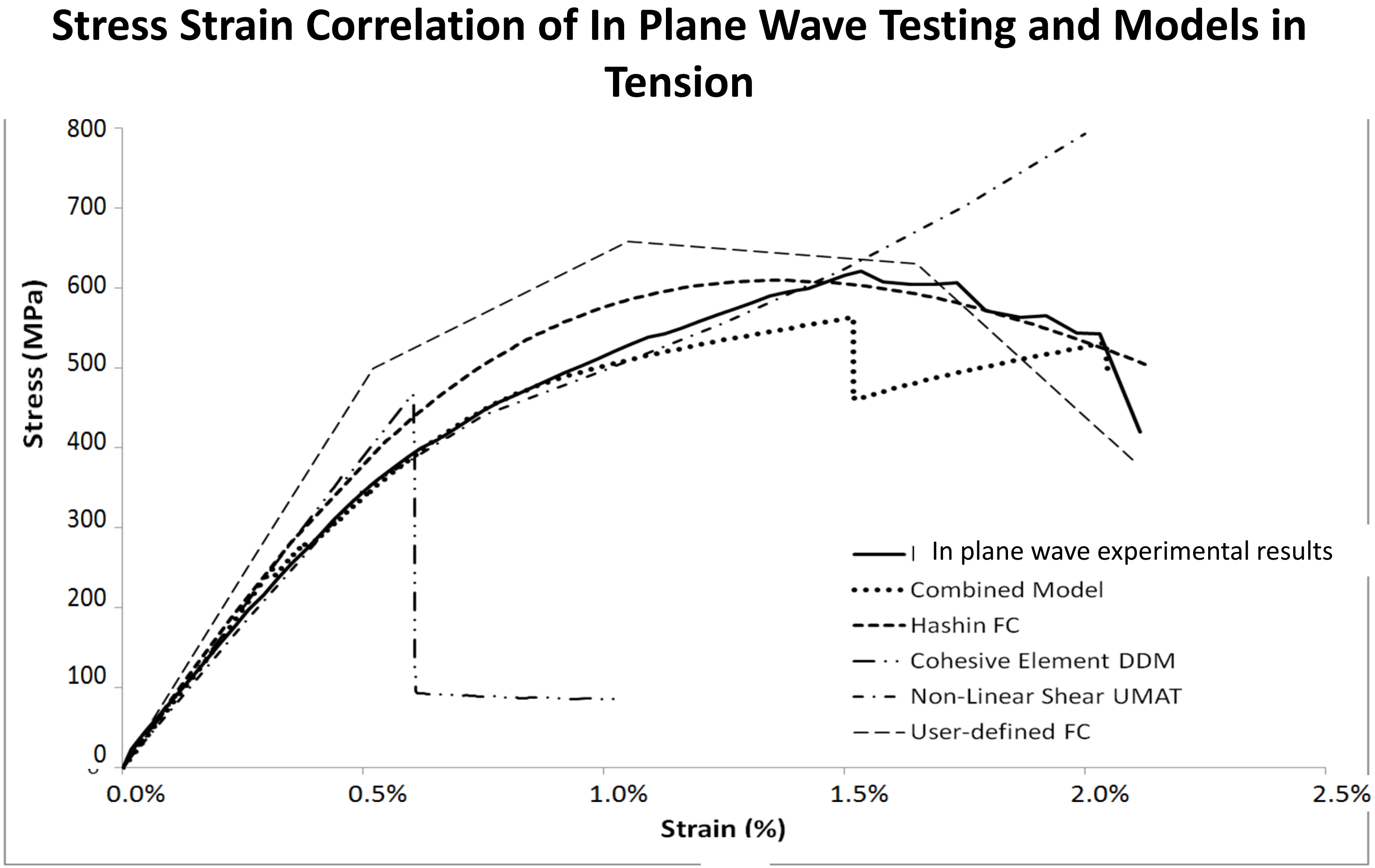


DIC from Experiment:
(longitudinal strain)

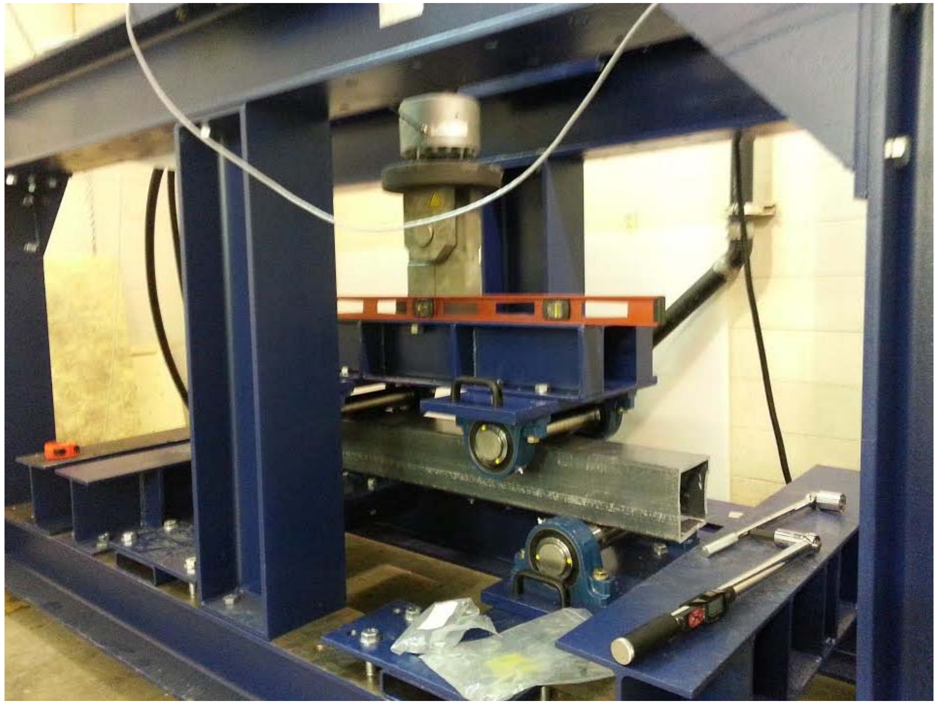
Finite Element Model
(“soft inclusion” local
strain

concentration)

Review of Analytical/Experimental Correlations, various Progressive Damage Models developed at MSU

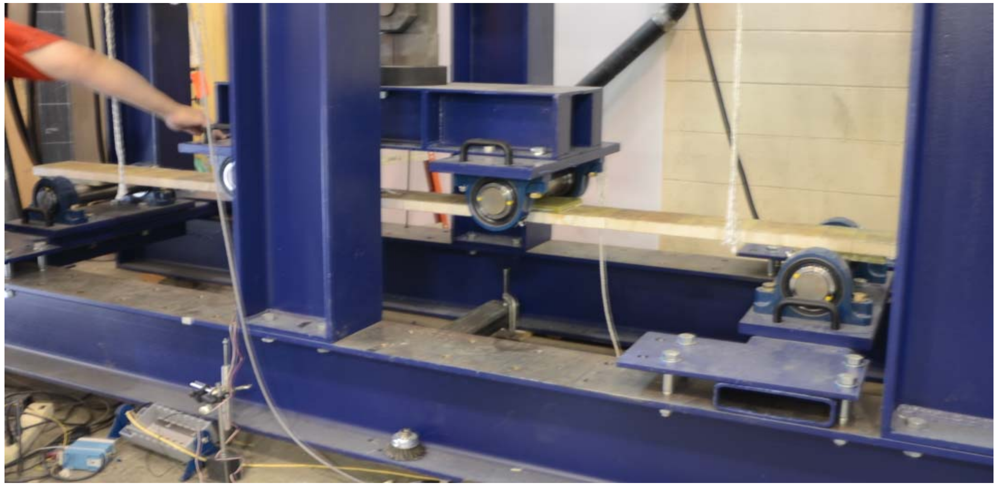


Scale Up to Substructures



Montana State University, Multi-Scale, Multi-Axial Testing Machine, structures up to 2m, bending and torsion

Substructures (Sandwich Beams)

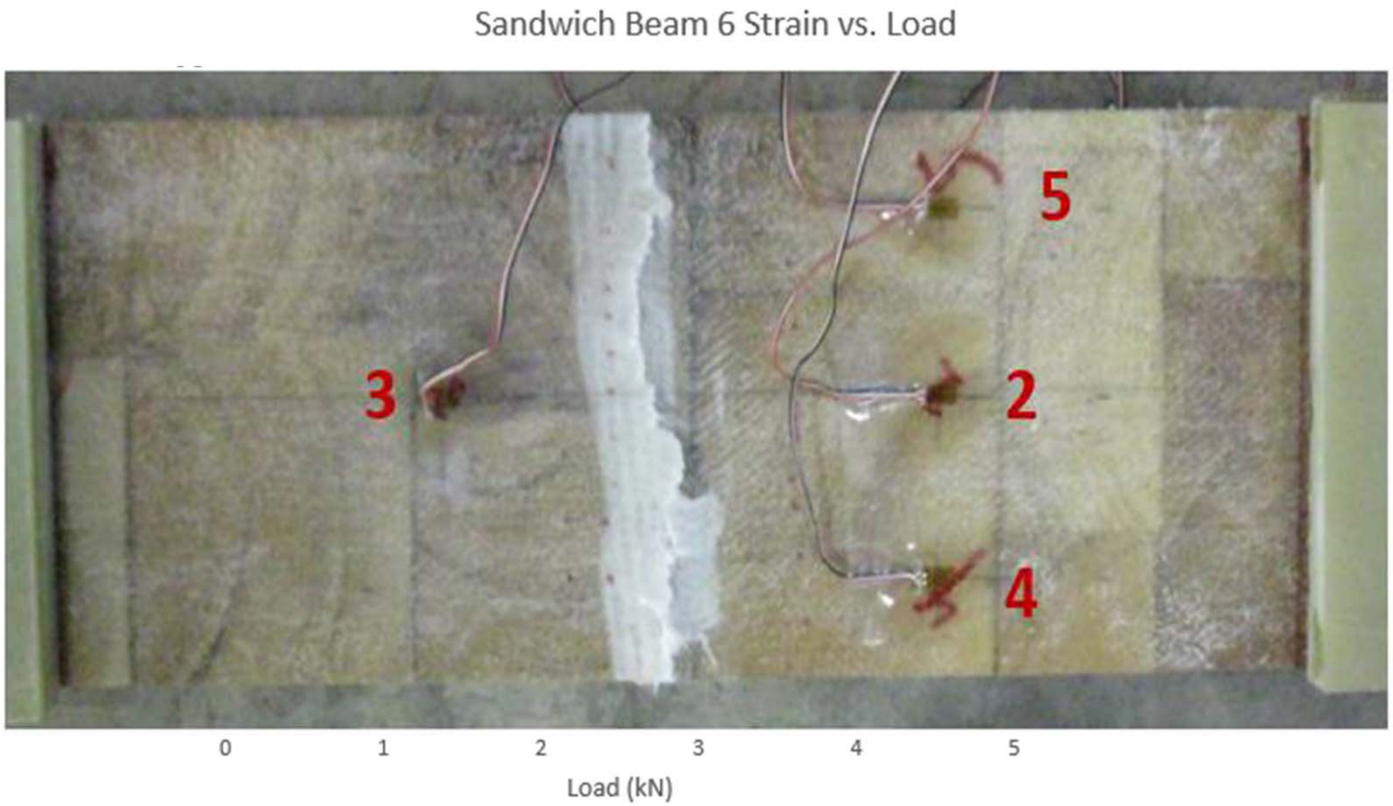


Montana State University's Multi-Scale, Multi-Axial Test Facility, beams of approximately 2m

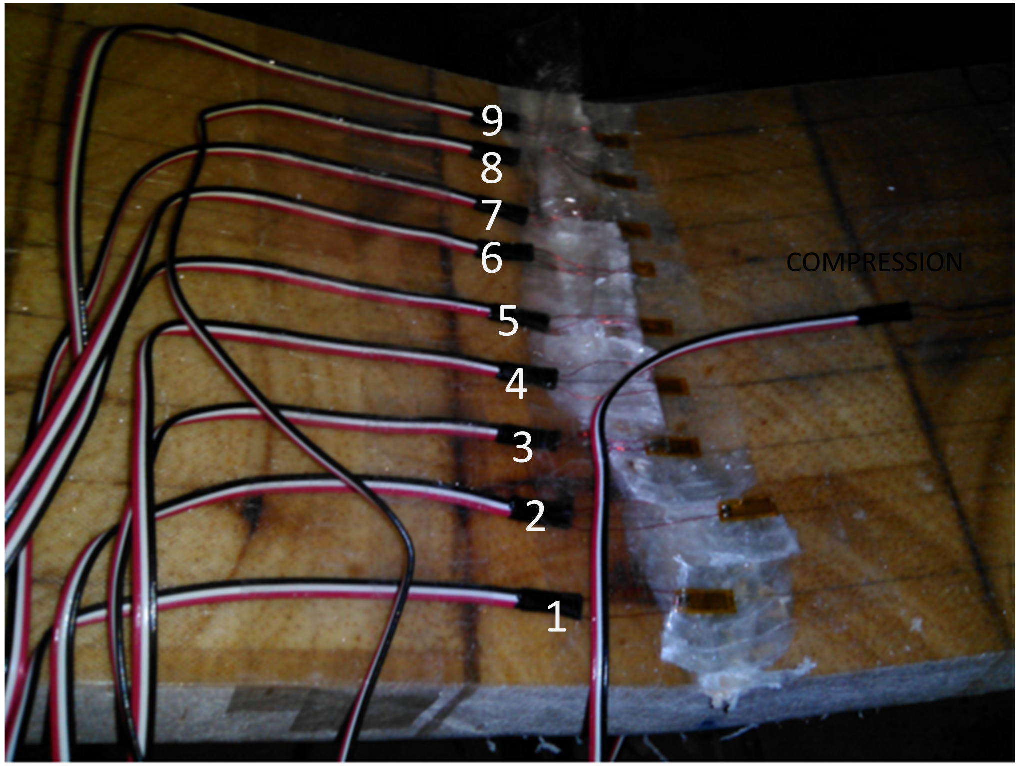
- Capable of Multi-Axes (bending and torsion)
- Intermediate step between coupons and full scale blades
- Much faster and lower cost than full blade

4 Pt Bending of Sandwich Beam

Beam with Full Width Flaw



Beam with Full Width Flaw (10/24/15)



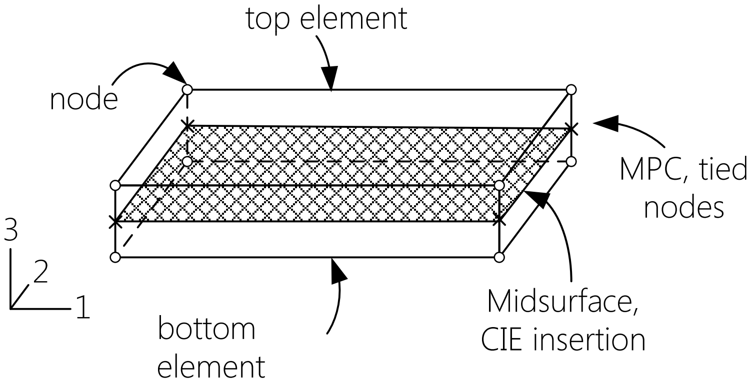
Unflawed Beams vs. Flawed Beams

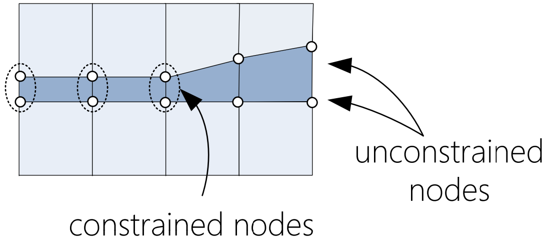
- Load to Failure
  - No Flaw – 6.2kN
  - Full Width Flaw 3.8-4.4 kN, depending on severity
  - Partial Width Flaw, wavy fibers in middle, straight fibers on edges, 5.8 kN, substantial capacity for load redistribution

- Results are consistent with coupons, takeaway – coupons representative of flaws in structures

Multipoint Constraint Cohesive Zone (MCZM) Model for Fracture & Debonding of Composites

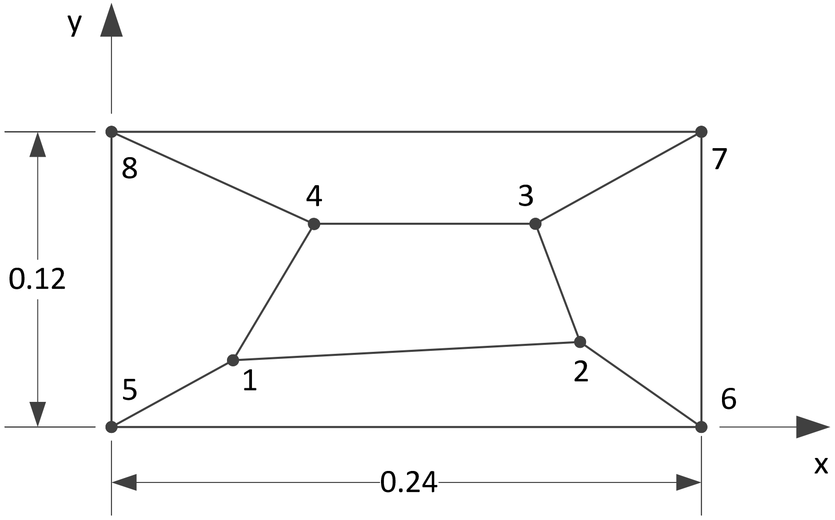
- Eliminate DOF from Intrinsic Cohesive Elements
  - Insertion of CIEs
    - CIEs are inserted prior to running solver (Intrinsic Scheme)
    - Increases number of elements, nodes & corresponding DOF
  - Definition of Master-Slave Multipoint Constraints (MPCs)
    - Eliminates slave node DOF
    - Returns system to original size
    - CIEs become “dormant”
  - Deactivate MPCs where damage criterion satisfied
    - CIEs are “activated” only as needed during solution (Extrinsic Scheme)





Patch Test

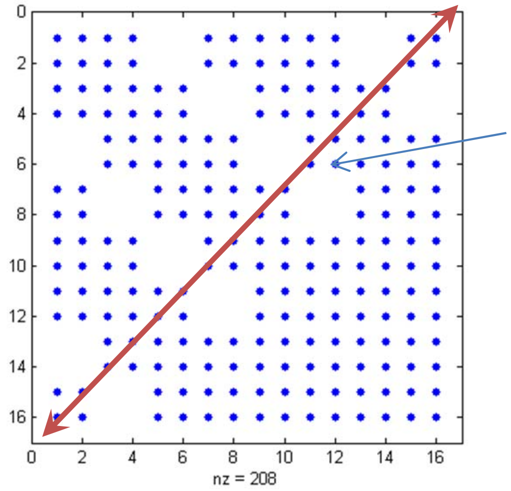
- Test:
  - Correct representation of exact solution?
- Repurposed here to gage the quality of:
  - interfacial conditions
  - MPC enforcement
- Comparison of models:
  - Conventional mesh
  - Intrinsic cohesive mesh
  - MCZM



- Linear plane strain (CPE4) elements
- Modulus
  $E = 1.0$ MPa
- Poisson's Ratio
  $\nu = 0.25$
- Prescribed Displacement Field:
  $U_x = 0.001(x + 0.5y)$
  $U_y = 0.001(0.5x + y)$

Stiffness Matrix Visualization

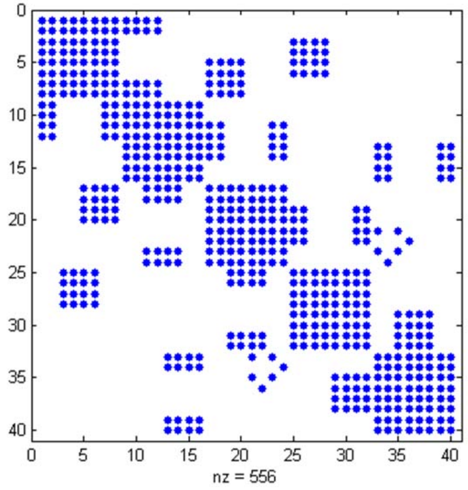
1



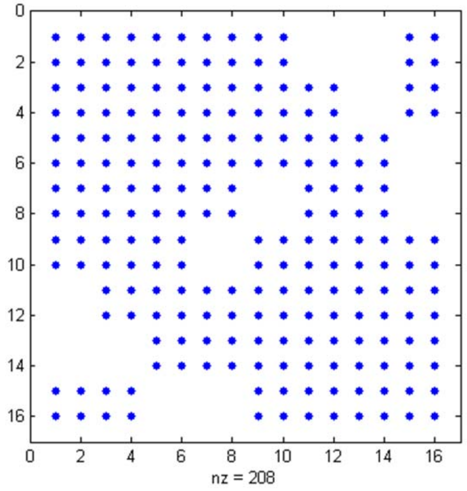
Related to Bandwidth for solution cost

1. Original Conventional Mesh → 16x16
2. Intrinsic Cohesive Mesh → 40x40
3. MCZM: Elimination of DOF → 16x16

2



3



Patch Test Results: Displacement
MCZM Patch Test

Fig 9. *Ux Conventional Mesh*

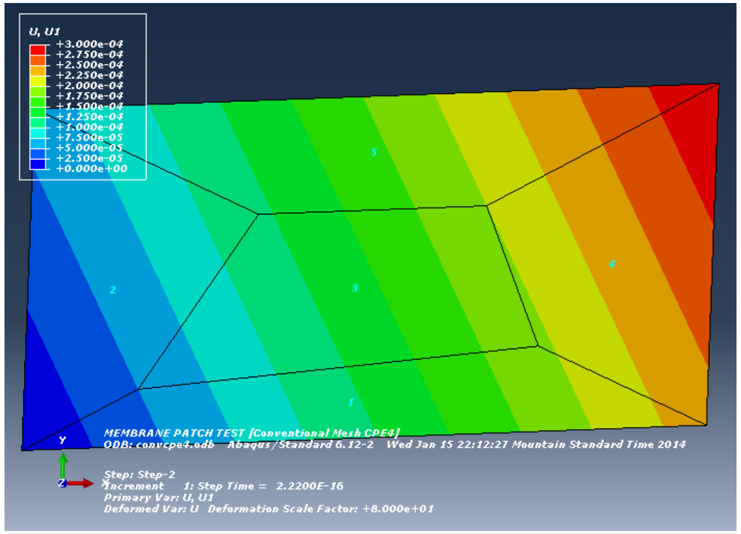


Fig 10. *Uy Conventional Mesh*

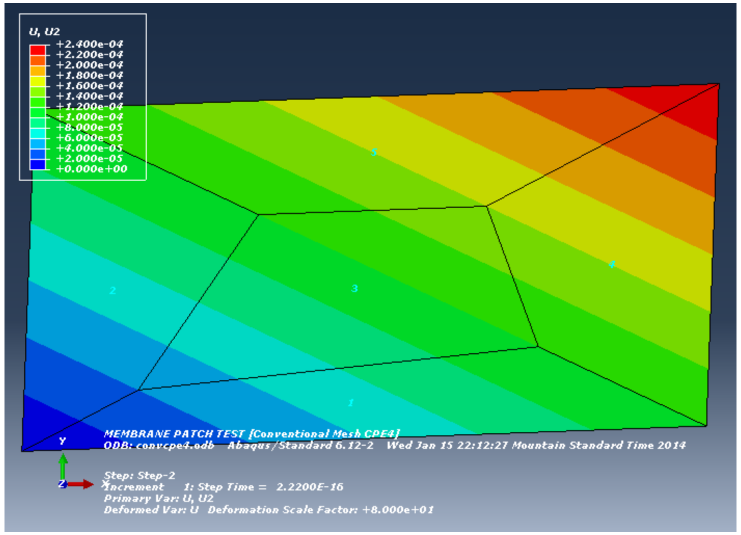


Fig 11. *Ux MCZM Mesh*

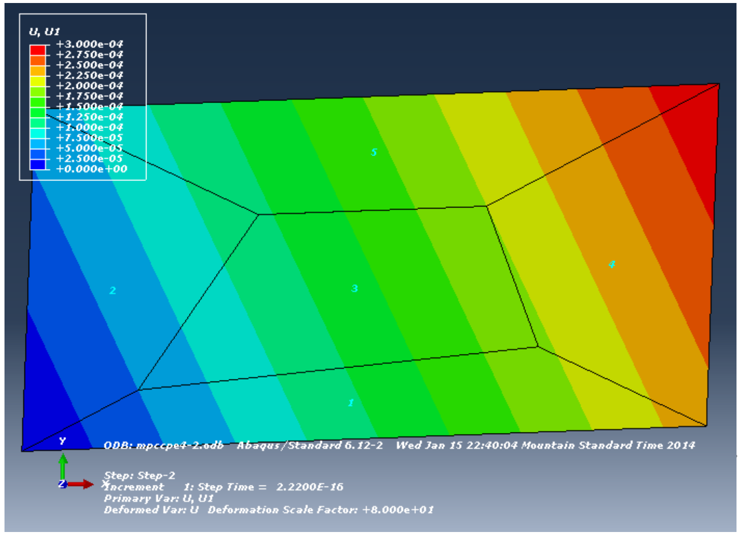
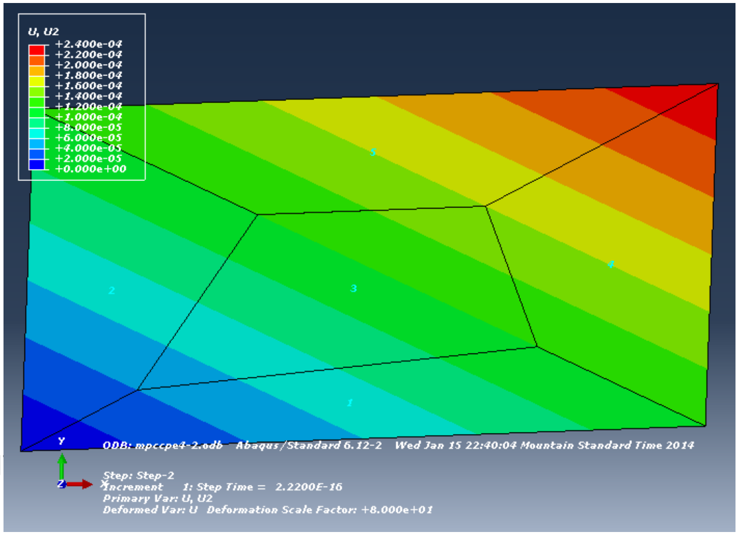


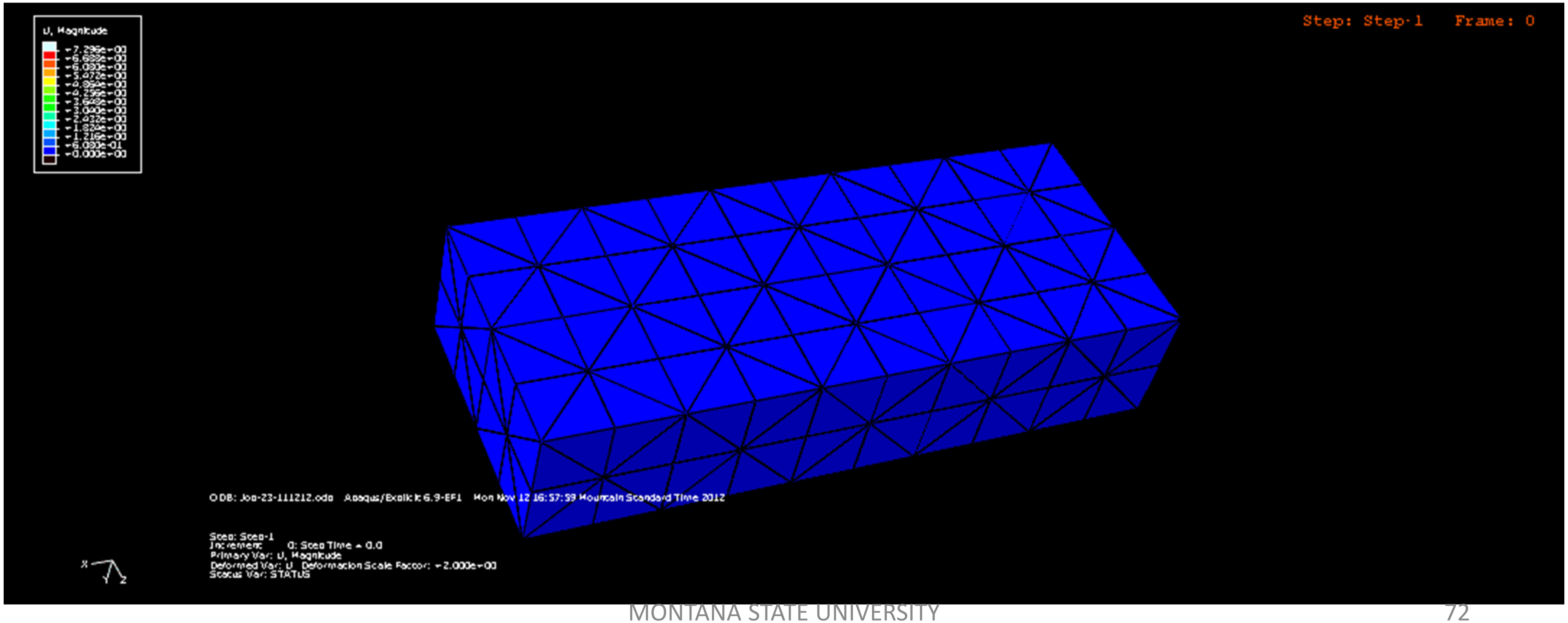
Fig 12. *Uy MCZM Mesh*



Example: 3D Intrinsic MCZM
Tetrahedral elements with cohesive zones invoked at interfaces

CLICK on Image to Play Progressive Damage video

Example: 3D MCZM crush demonstration



Implications of the MCZM

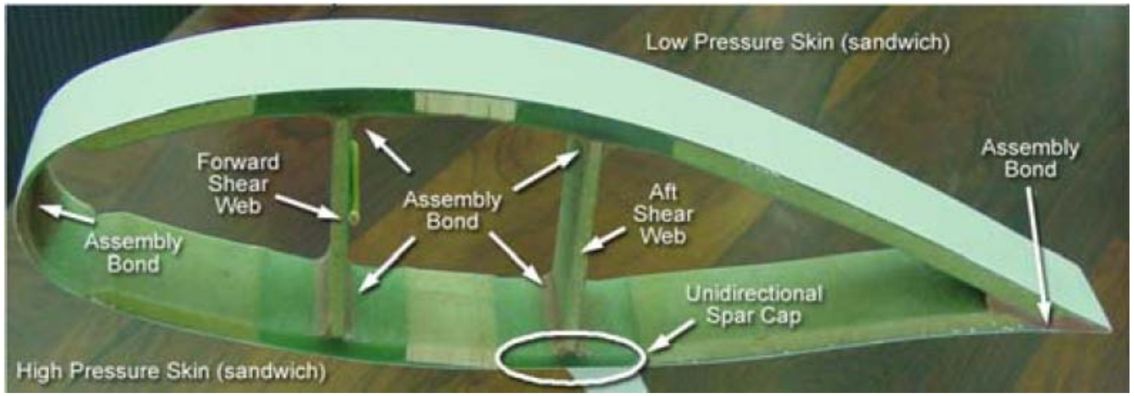
- Initially same bandwidth as model without damage
- Cohesive zone is only invoked when damage occurs
- No a priori assumptions about fracture path are required
- 3D formulation offers unique possibilities for progressive damage modeling of composite structures
- To our knowledge, NO ONE ELSE IN THE WORLD other than MSU has done this.

Adhesive Joints

- Adhesive joints in composites offer excellent joining and excellent opportunities for reducing labor and part count
- **Caveat:** Mechanical Fasteners are typically not as good as a good adhesive joint, **but** a bad adhesive joint can be disastrous
- Having a clear understanding of these joints is important to exploit the advantages
- The experience from MSU comes from the wind turbine blade industry; 50m+ long blades without a single fastener except at the root fitting, 20 year lifetime in extreme enviornments, up to 10^9 cycle fatigue loading

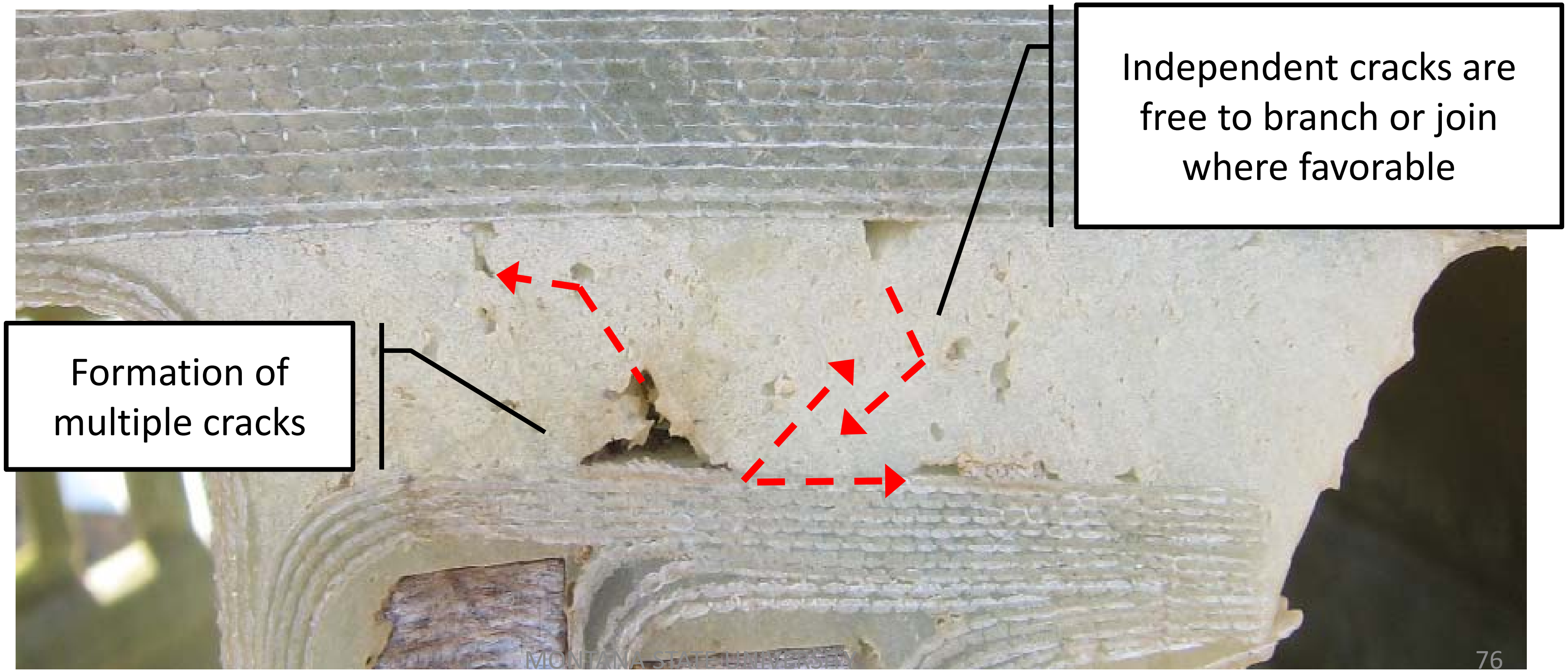
Composite Wind Turbine Blades

These root studs are the ONLY mechanical fasteners in the entire blade structure



Challenges in modeling damage growth

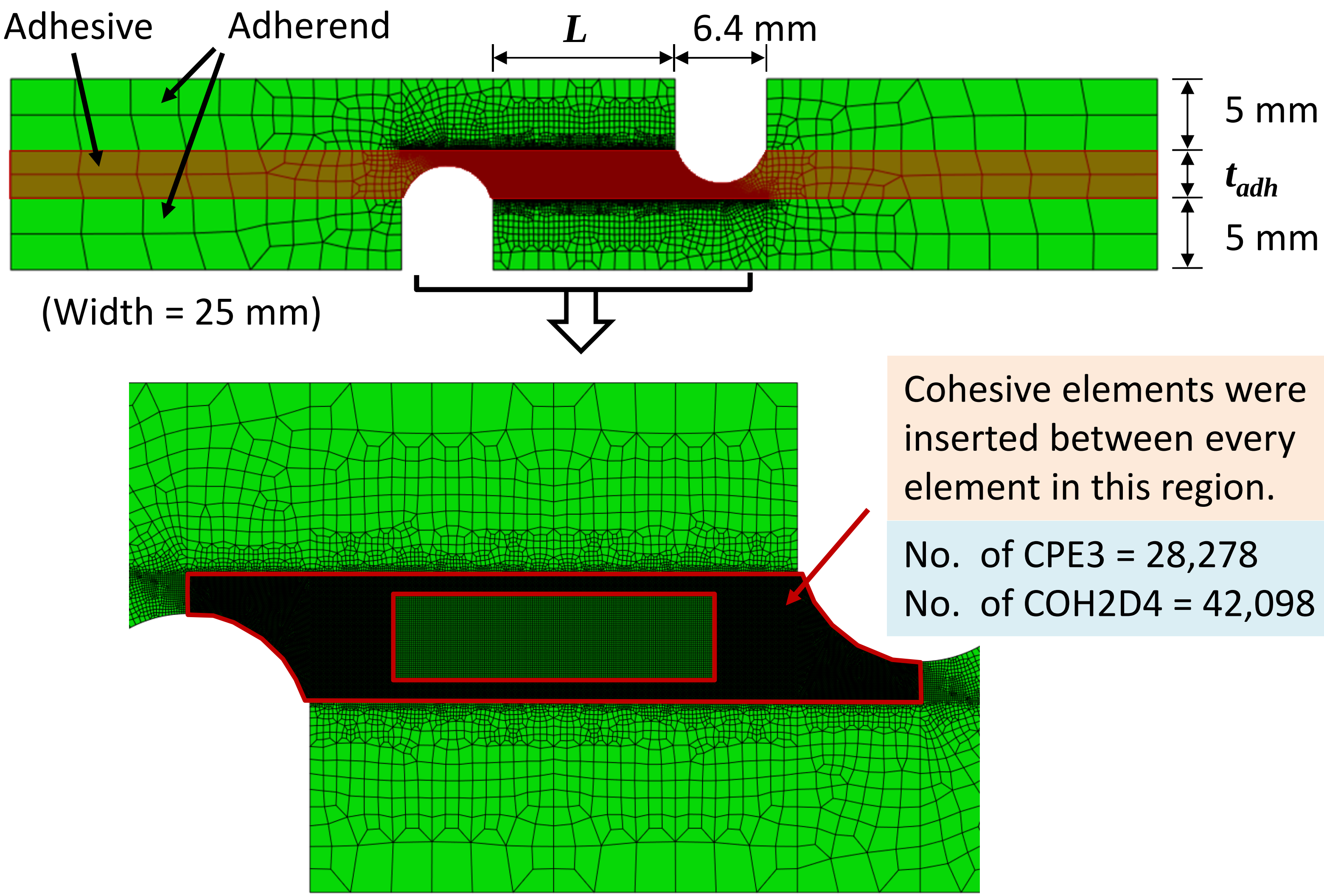
- Geometrically complex crack growth, without *a priori* knowledge of where it might occur



Formation of multiple cracks

Independent cracks are free to branch or join where favorable

FE Modeling

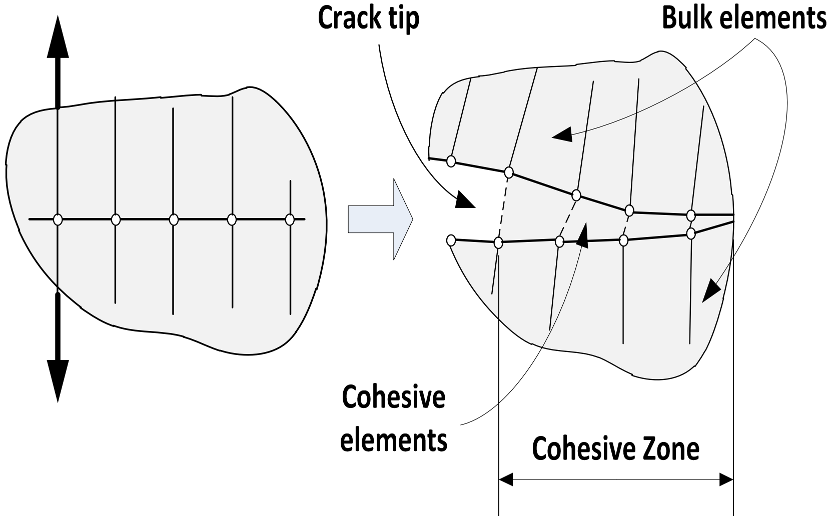


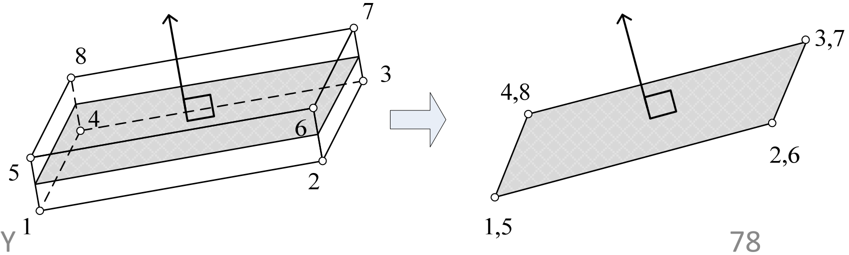
Cohesive elements were inserted between every element in this region.

No. of CPE3 = 28,278
No. of COH2D4 = 42,098

Phase I: Cohesive Zone Model (CZM)

- Represents a major advancement over conventional fracture mechanics (LEFM)
  - Crack growth without remeshing or crack tip elements
  - Crack-tip singularity functions do not need to be calculated, represents cohesive forces over an extended crack tip
  - Brittle, quasi-brittle, and ductile fracture
  - No initial crack required
- Cohesive Interface Elements (CIEs) are placed within a mesh along continuum element boundaries
- CIEs are generally collapsed to form a zero-thickness "interface" between bulk elems
- Damaged CIEs represent all damage and the cohesive forces in fracture zone
- Therefore, the CIE size must be small enough to resolve the fracture process zone





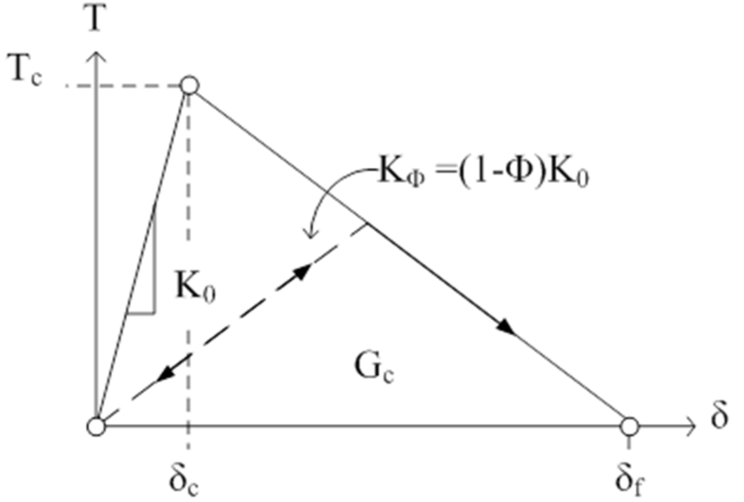
General Form of the T-δ Relation

$$t_i = \begin{cases} K_0\delta_i & \text{for } \delta_i^{max} \le \delta_i^c \\ (1-\Phi)K_0\delta_i & \text{for } \delta_i^c \le \delta_i^{max} \le \delta_i^f \\ 0 & \text{for } \delta_i^{max} \ge \delta_i^f \end{cases}$$

$$\Phi = \frac{\delta_m^f(\delta_m^{max} - \delta_m^c)}{\delta_m^{max}\left(\delta_m{}^f - \delta_m^c\right)}$$

$$\delta_m = \sqrt{\langle\delta_n\rangle^2 + \delta_s^2 + \delta_t^2}$$

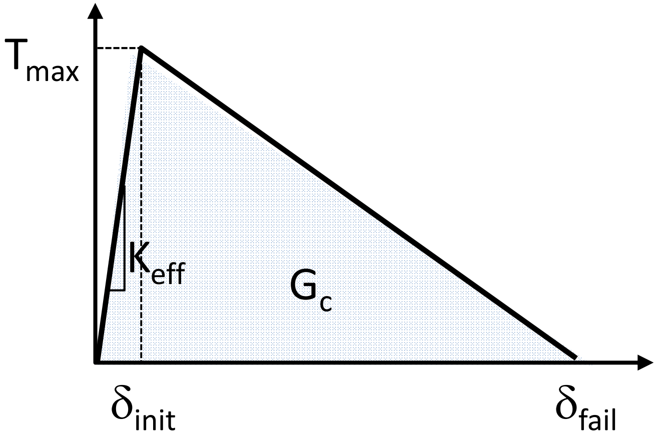
$$\delta_m^f = 2\ G_c/T_c$$



K_0 = initial elastic stiffness (penalty stiffness)
T_c = cohesive strength (stress criterion)
G_c = cohesive fracture energy
Φ = damage parameter
δ_m = effective displacement across the element surfaces
δ_m^c = critical effective displacement at damage initiation
δ_m^f = critical effective displacement at complete material degradation
δ_m^{max} = maximum effective displacement achieved during loading

Traction-separation relation of Adhesive

- Triangular shape Traction-separation relation

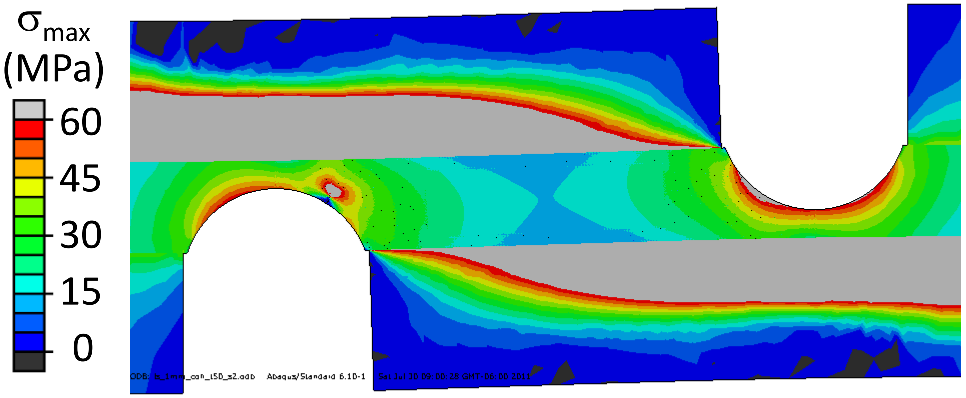


T_{1max} (MPa)	G_{Ic} (N/mm)	K_{1eff} (MPa/m)
62.5	0.7	50×10^5
T_{2max} (MPa)	**G_{IIc} (N/mm)**	**K_{2eff} (MPa/m)**
50.	1.0	50×10^5

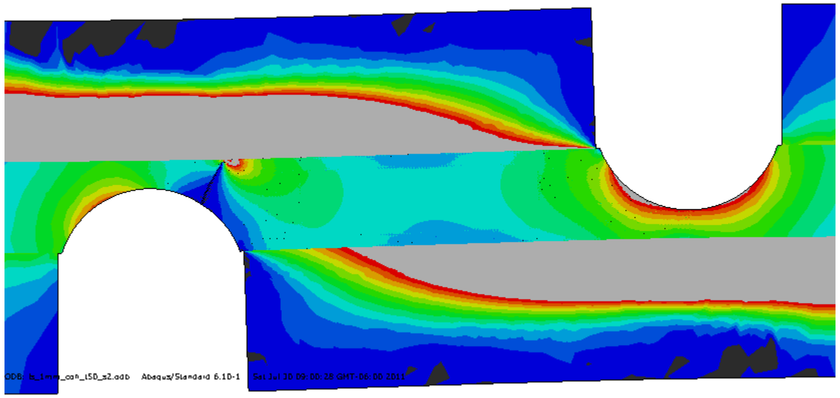
- Damage initiation criteria = MAXS
- Damage evolution type = Energy
- Mixed mode behavior = Power law, Power = 1

Crack Propagation History

(BC1, L = 12.7 mm, t_{adh} = 3.25 mm)

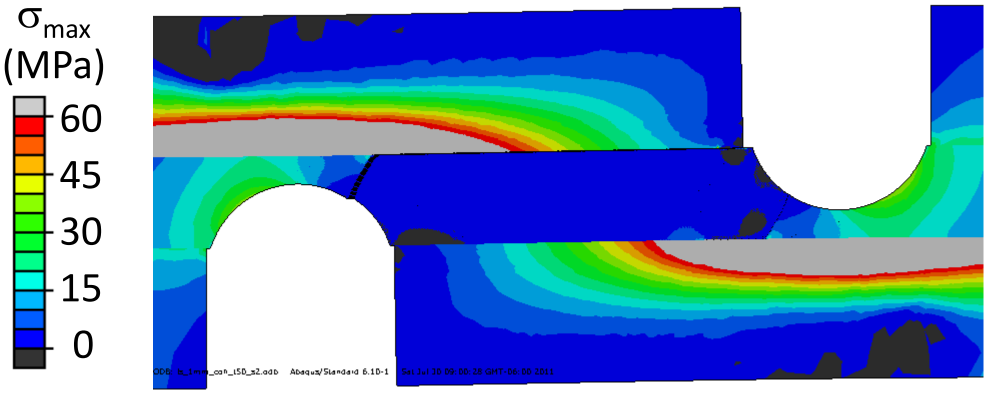


1. Crack is initiated. The initial propagation is mode I dominated.

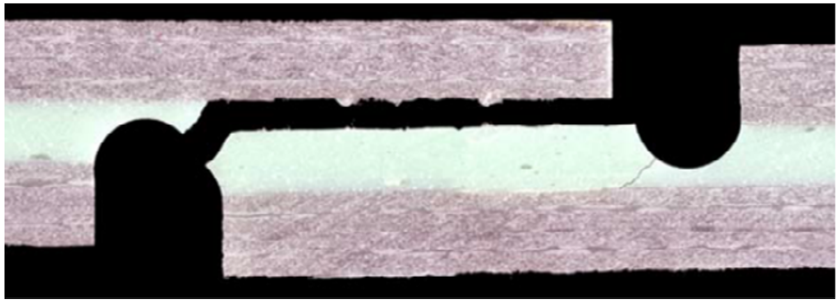


2. The crack front hits the adhesive-adherend interface, becomes a mixed mode problem.

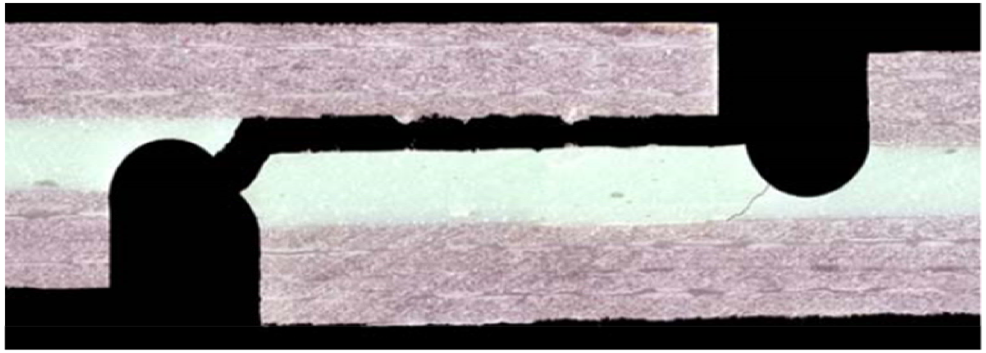
Crack Propagation History (cont.)

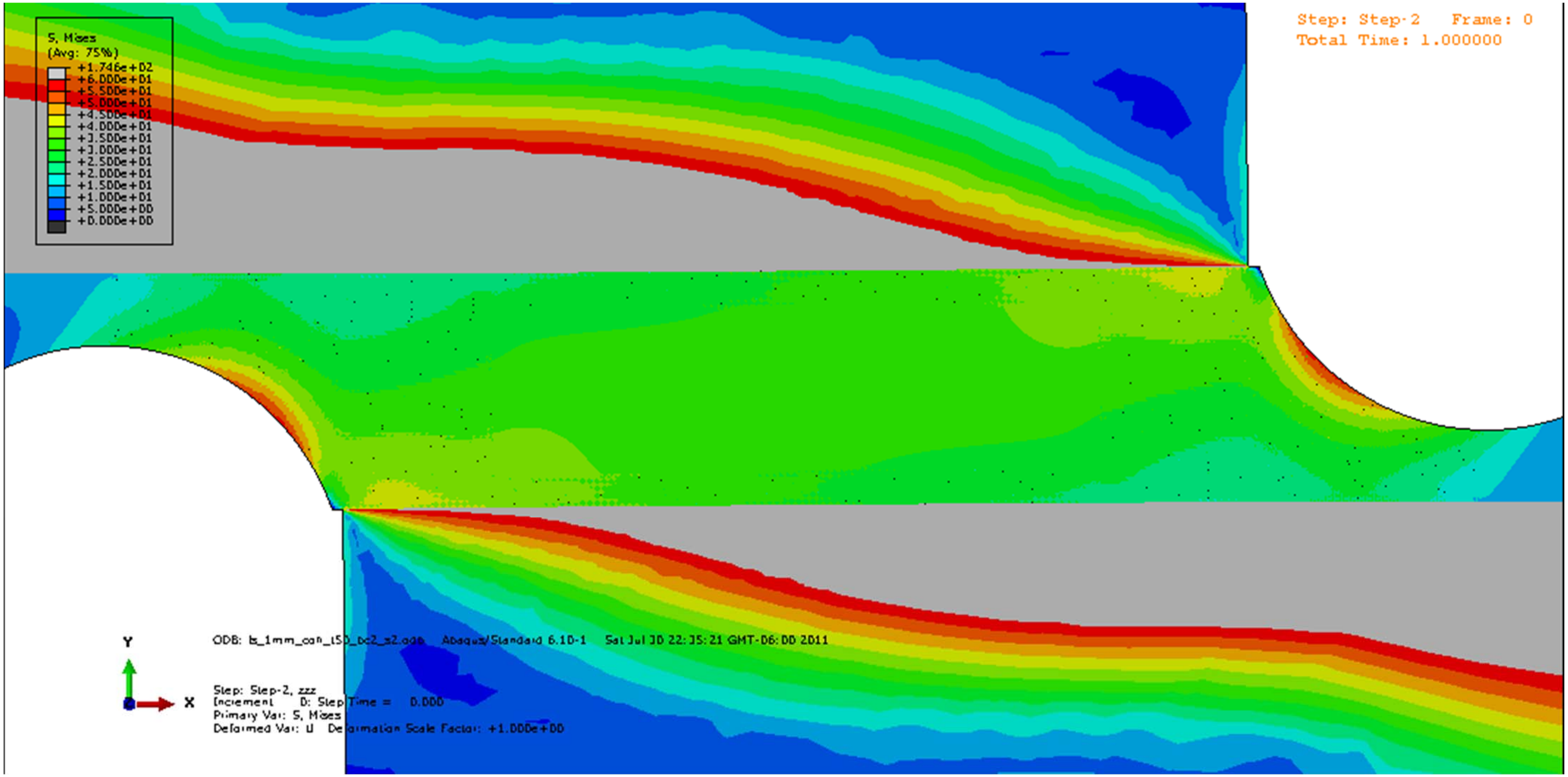


5. The upper crack propagated completely though the bondline; non-self similar crack propagation correlating with experiment



Example: Numerical-Experimental Correlation with Notched Lap Shear Test





Other MSU Research Topics of Potential Interest to the **DTU VILLUM CENTER FOR ADVANCED STRUCTURAL AND MATERIAL TESTING**

- **Low cost carbon fibers** – collaborative work with Sandia National Laboratories and Oak Ridge National Laboratories (Besides Cairns' experience at Hercules for carbon fiber processing (Hexcel), we have a new PhD student at MSU who was a Process Engineer at Zoltek, now Toray.)

- **Subscale Testing** – Unique multi-axial load frame to fill in gaps in the building block hierarchy

- **Acoustic Emission** monitoring – correlations with progressive damage and damage tolerance

Other MSU Research Topics of Potential Interest to the **DTU VILLUM CENTER FOR ADVANCED STRUCTURAL AND MATERIAL TESTING**

- **Process Modeling with Validation**

- **Experimental Design for Manufacturing**
  - ANOVA
  - DOE and Taguchi Methods
  - Heuristic Process Model (multivariate process modeling)

- **NDI** – ultrasonic and DIC; completing the loop for Damage Tolerance

Opportunities for the DTU VILLUM CENTER FOR ADVANCED STRUCTURAL AND MATERIAL TESTING

- “If you build it, they will come”; maybe, but better to be proactive and show the world the benefit for multi-scale testing and analyses (Famous Abraham Lincoln quote: *“Good things come to those who wait, but only the things left over by others who hustle.”*)
- Lots of implicit opportunities for a large constituency (within and outside of DTU) during the application of the center, e.g.
  - Electrical and Computer Engineering, understanding the controls and data acquisition
  - Statisticians, understanding how statistical data at lower levels translate to higher levels
  - Business School – Business model, sustainability plans
  - Industry partners, a new paradigm for their product development and certification
- By doing analysis and developing predictive capabilities at each step, the Center can show the utility of its combined capabilities

Cairns' Evaluation of the DTU VILLUM CENTER FOR ADVANCED STRUCTURAL AND MATERIAL TESTING

- Based on site review June 2-3, 2016
- Bigger and more comprehensive Centers in the world at each level, but none with the holistic approach of DTU/Villum Center
  - Testing at lower levels, but no capabilities/understanding of scale-up
- More intimate connection between testing and analysis for predictive scale-up. Specific recommendation:

  If the lower level contains the same materials, manufacturing, and sufficient length scales to capture multiple units of the governing microstructure scales, there is no reason to believe that testing at those scales cannot be applied analytically to expensive and more time consuming higher level testing.
- Needs a demonstration project to coalesce and provide a common goal for constituents at each level
  - That demonstration project could be Wind Energy, plus other projects from the Mechanical Engineering Civil Engineering
- Integrate more of the Key Measuring Equipment, combined with analysis and testing
- Develop a compelling "case study" and market the approach to other industries

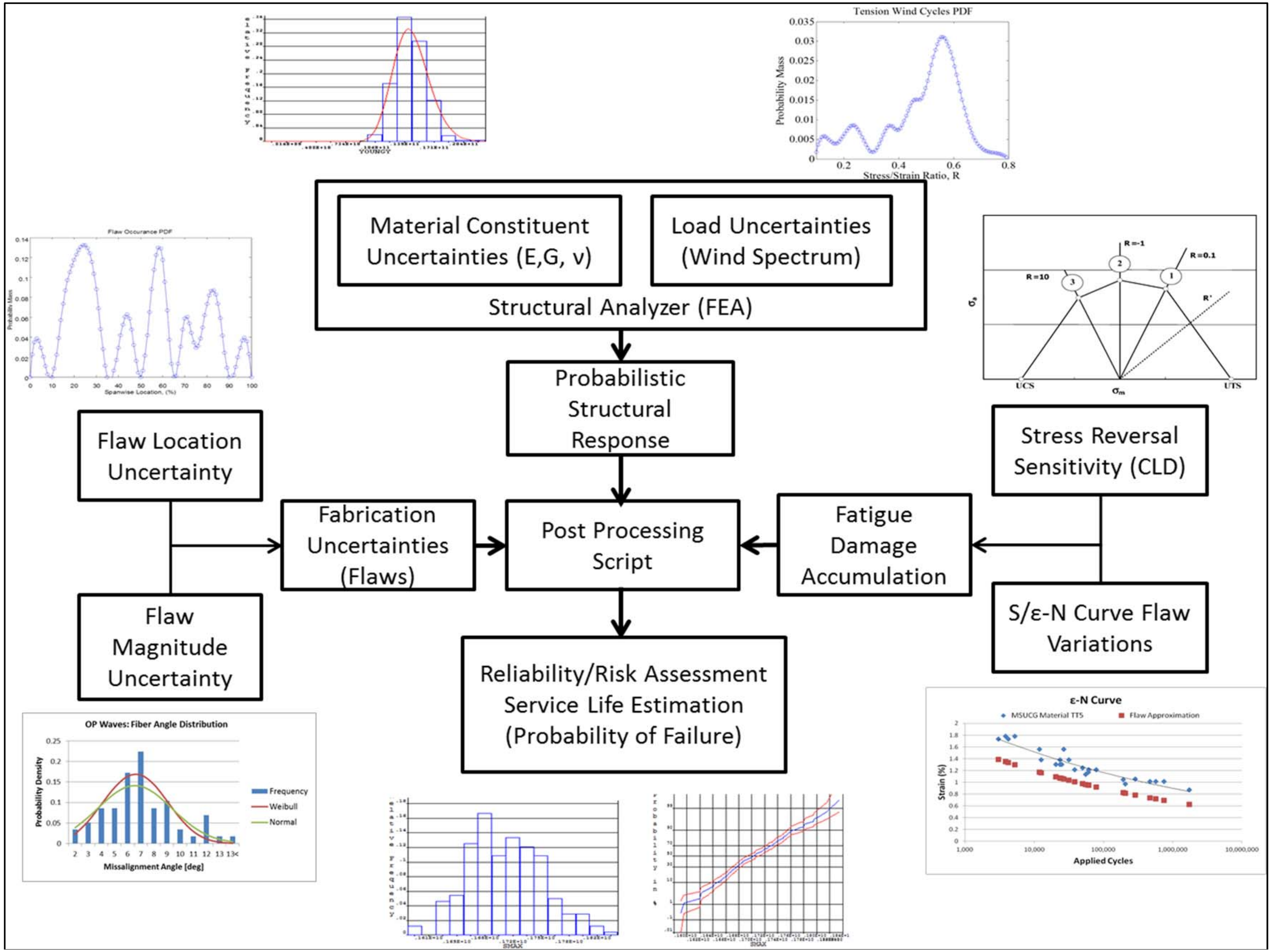
Value-Added by the Center

- For Industrial/Commercial Applications (first obvious customers)
  - A new paradigm for bringing new materials into production
  - Quantifiable reliability
  - Applications to many industries
    - Wind turbine blades
    - Automotive
    - Other transportation
    - High end recreational products

- For the Aerospace Industry
  - A more universal application of the Building Block approach
  - Demonstration of predictive capabilities at each level
  - Show that the actual component (geometry) at each level is needed if sufficient information is gained by previous level
  - May be able to get aerospace to break its addiction to this development approach for new materials and structures

Thank You!

Comprehensive Approach with Probabilistic Reliability Can Streamline the Certification and Scaleup for the Tracy Challenge; Approach Validated by MSU with Composite Wind Turbine Blades



Material Constituent Uncertainties (E,G, ν)

Load Uncertainties (Wind Spectrum)

Structural Analyzer (FEA)

Probabilistic Structural Response

Flaw Location Uncertainty

Flaw Magnitude Uncertainty

Fabrication Uncertainties (Flaws)

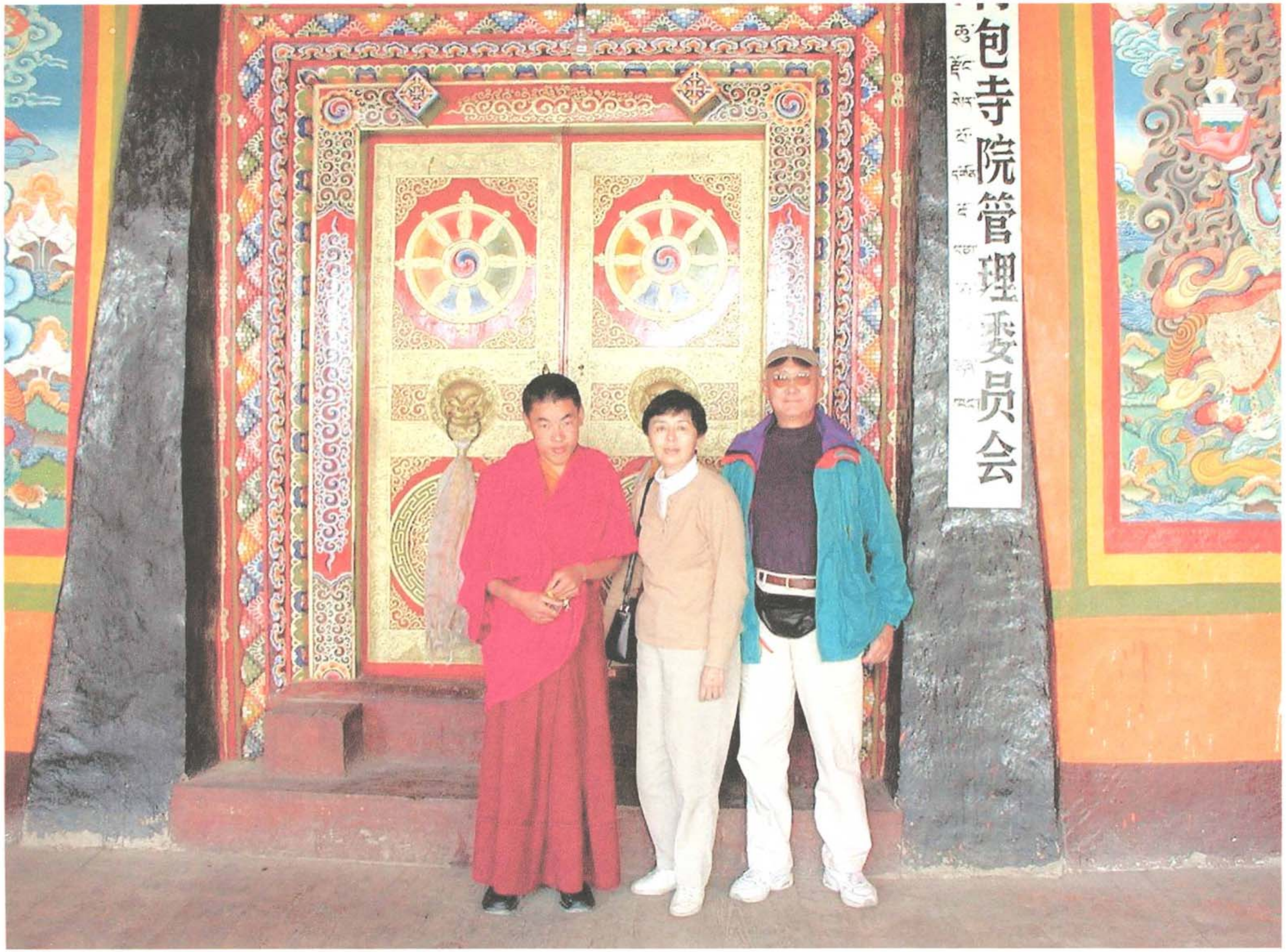
Post Processing Script

Stress Reversal Sensitivity (CLD)

S/ε-N Curve Flaw Variations

Fatigue Damage Accumulation

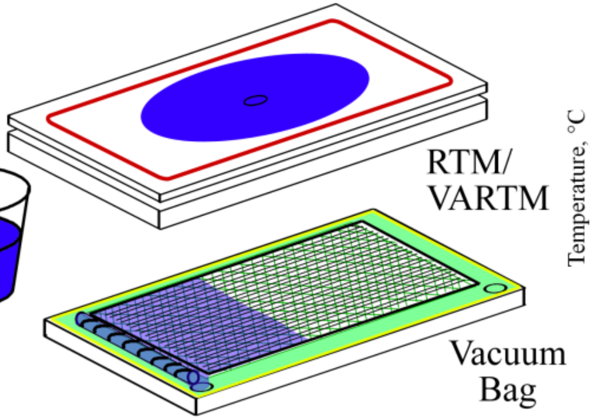
Reliability/Risk Assessment Service Life Estimation (Probability of Failure)



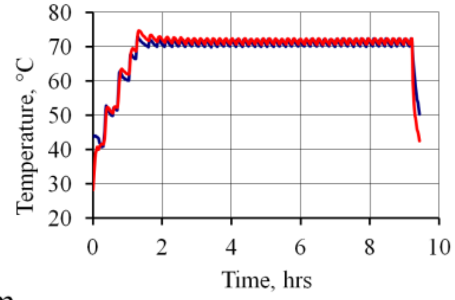
Email from Ed to Doug Cairns, November 1, 2001:
We went to the Potala Palace in Tibet seeking enlightenment. The Dalai Lama was not around and I was received by the Lieutenant Lama who suggested that enlightenment is through probability and most likely via the causal relation paradigm/conjecture (the basis for re-incarnation, etc.). So, we are on the right track.
Cairns' comment on picture: The expression on the Lieutenant Lama's face speaks volumes regarding his interaction with Ed.

MSU-Bozeman Composite Group Manufacturing and Material Characterization

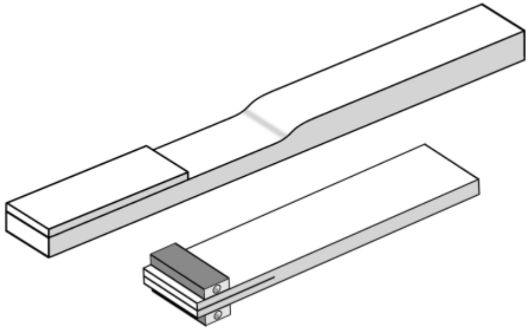
Mixing



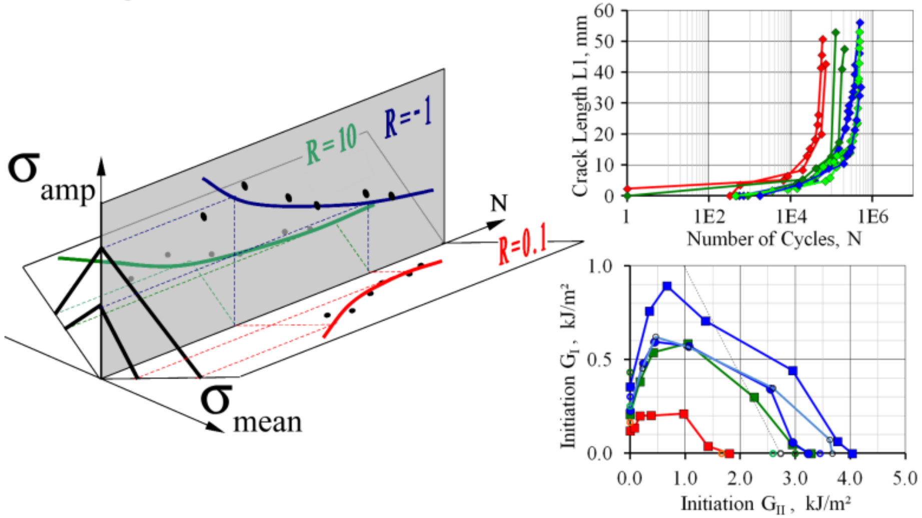
Infusion



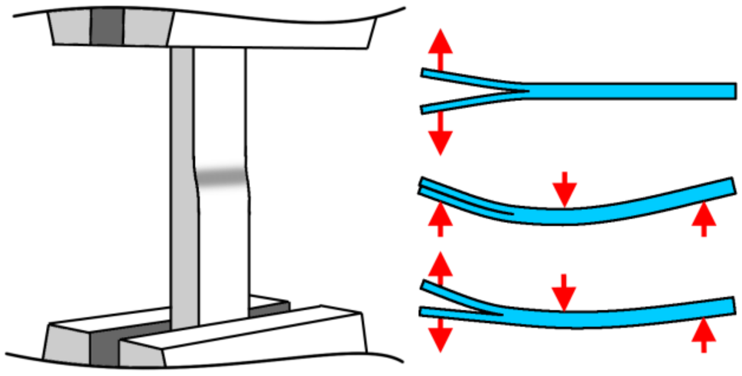
Curing and Post-curing



Coupon Preparation



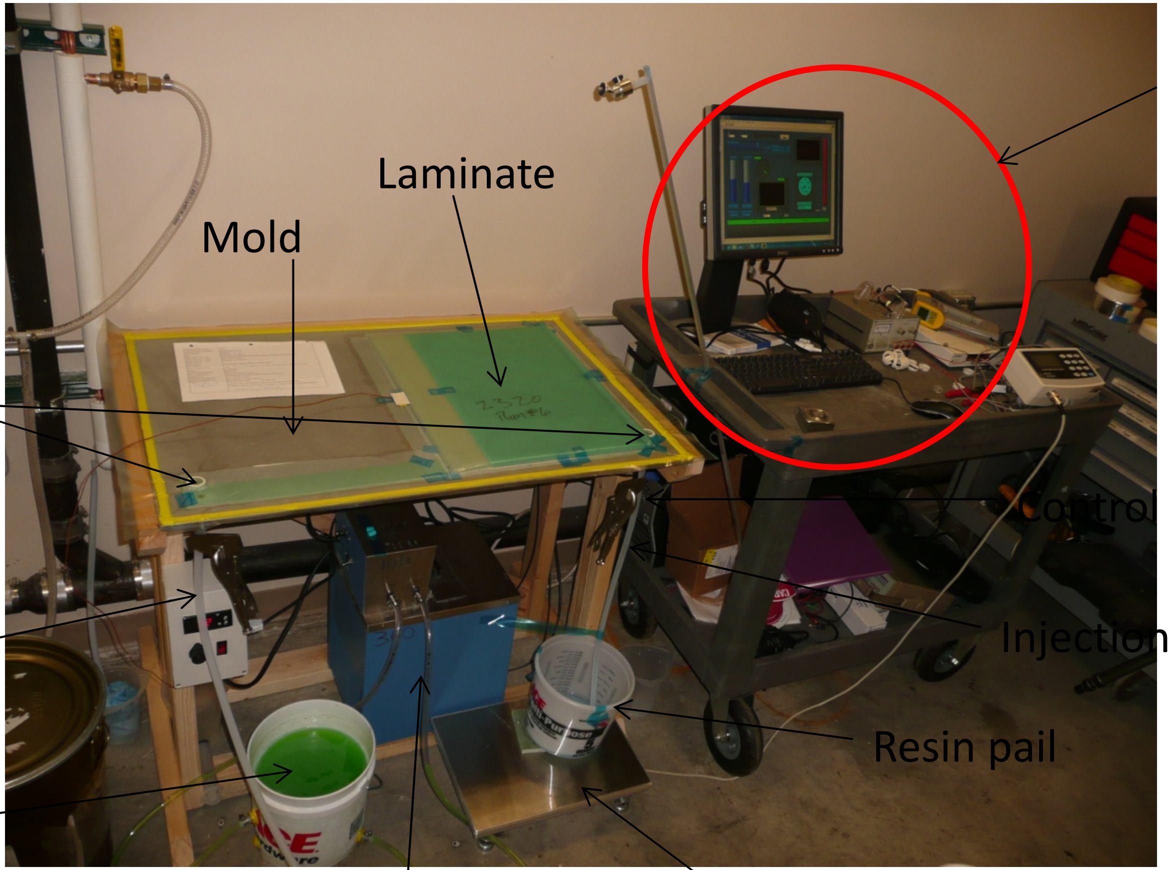
Mechanial Perfomance Database



Mechanical Testing

Experimental Setup & Equipment

Laminate Setup



Data acquisition center

Laminate

Mold

Pressure Transducers

Control Valve

Vacuum port

Injection port

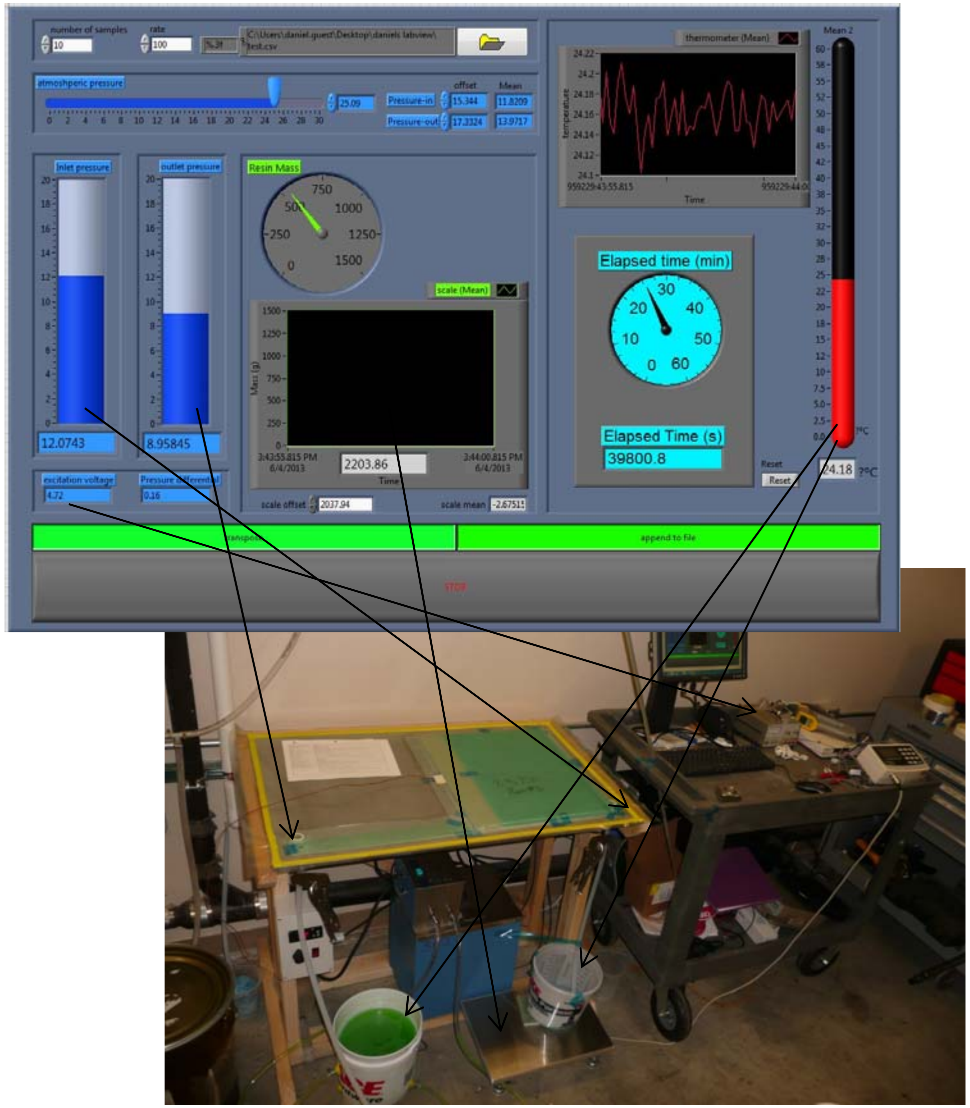
Resin pail

Recirculation bath

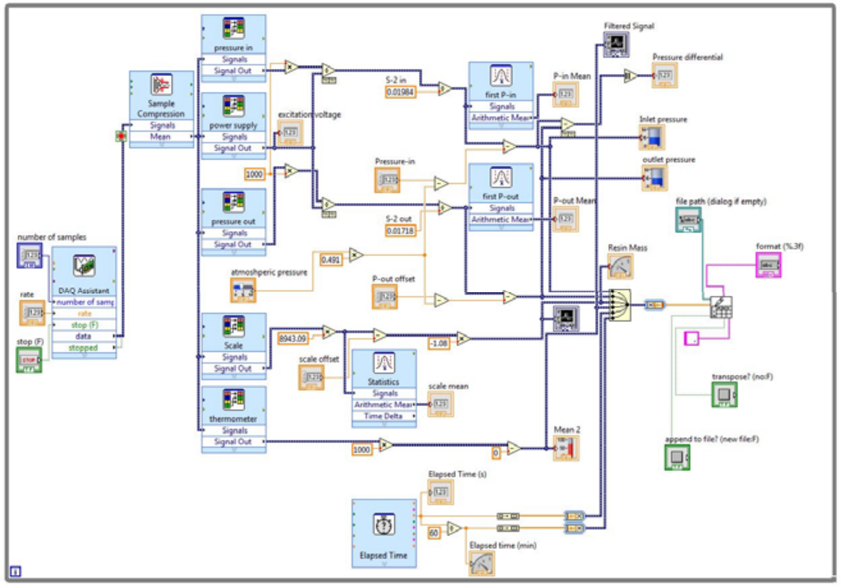
Glycol temperature control unit

Scale

Data Collection Software

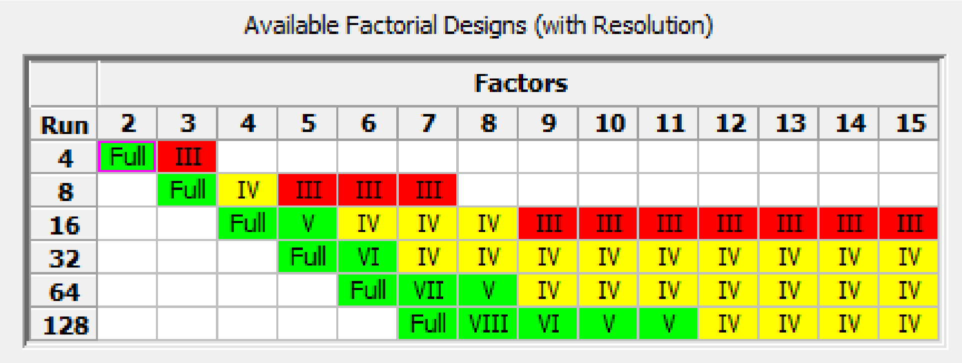


- •Labview was used to collect data
- •Can acquire multiple signals
- •Over 700 math functions
- •Graphical programming



Manufacturing and Testing Research Extended to More Complicated Structures

Infusion of Subscale Beams



Available Factorial Designs (with Resolution)

	Factors													
Run	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
4	Full	III												
8		Full	IV	III	III	III								
16			Full	V	IV	IV	IV	III	III	III	III	III	III	III
32				Full	VI	IV	IV	IV	IV	IV	IV	IV	IV	IV
64					Full	VII	V	IV	IV	IV	IV	IV	IV	IV
128						Full	VIII	VI	V	V	IV	IV	IV	IV

Parameters were identify that are most likely to produce porosity:

- NFL – number of layers of flow media
- FAA – laminate architecture
- NFA – number of layers of fabric
- IFR – injection flow rate
- ITS – injection temperature
- VPS – vacuum pressure
- DGR – degassed resin

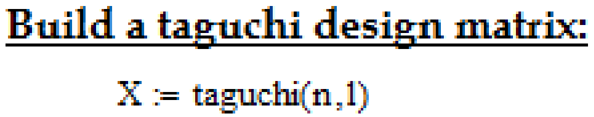
Taguchi Design of Experiments

- Experiment design based on statistical methods which employ orthogonal arrays
- Primarily used to improve product quality by minimizing variation
- Reduce cost by reducing the loss function

$$l\left(y\right) = k_c\left(y - \tau\right)^2$$

Taguchi Design Matrix

- Mathcad's design matrix utility was used
- Input parameters are process parameters
- High /low values assigned based on parameter extremes



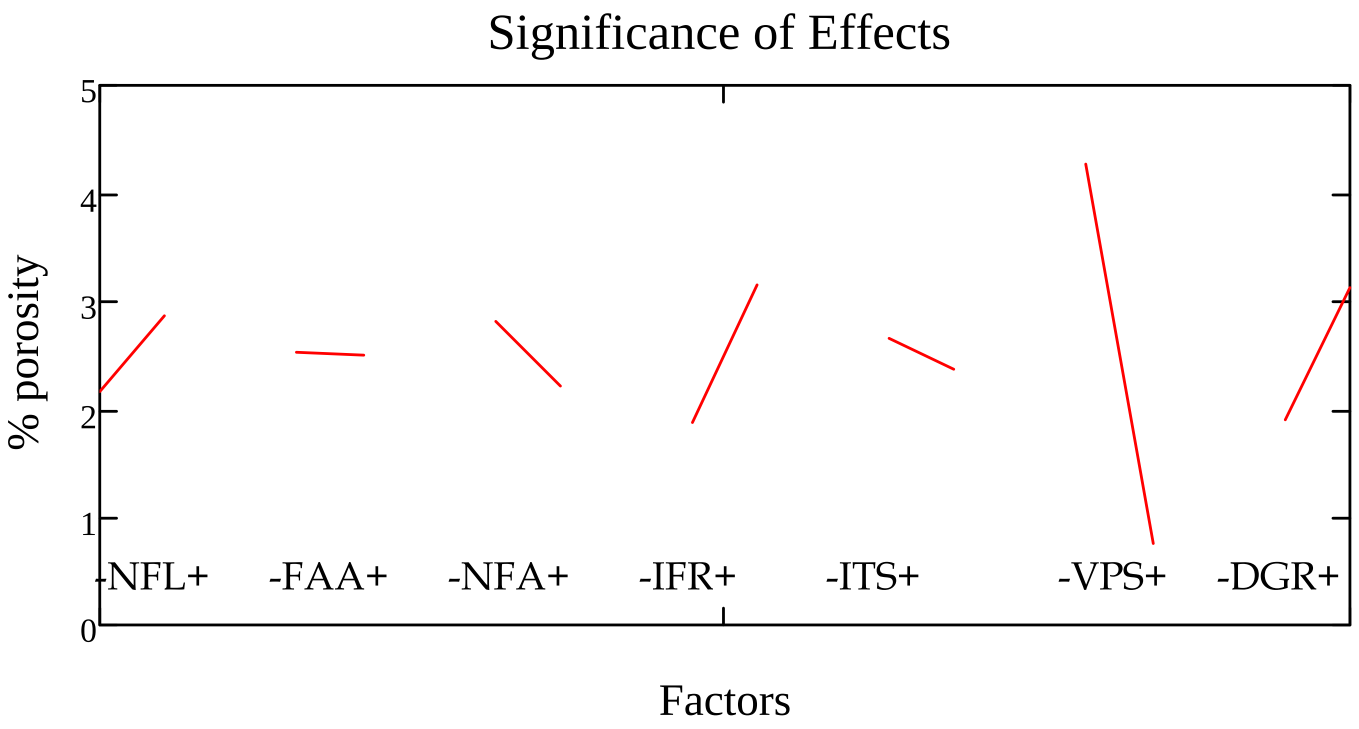
Build a taguchi design matrix:

X := taguchi(n,1)

Output Parameters

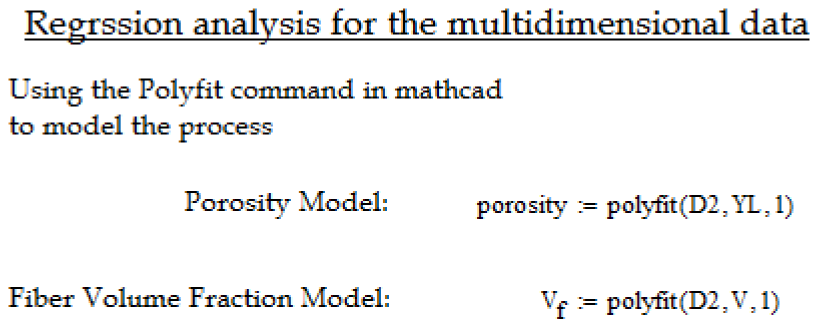
- Porosity content
- Fiber volume fraction
- Ultimate strength
- Monitored input parameters
  - Pressure
  - Temperature
  - Flow rate

ANOVA Plot for Porosity



Analysis of the data using ANOVA techniques shows which factors contribute the most to porosity

Modeling The Process



Regrssion analysis for the multidimensional data

Using the Polyfit command in mathcad
to model the process

Porosity Model: porosity := polyfit(D2, YL, 1)

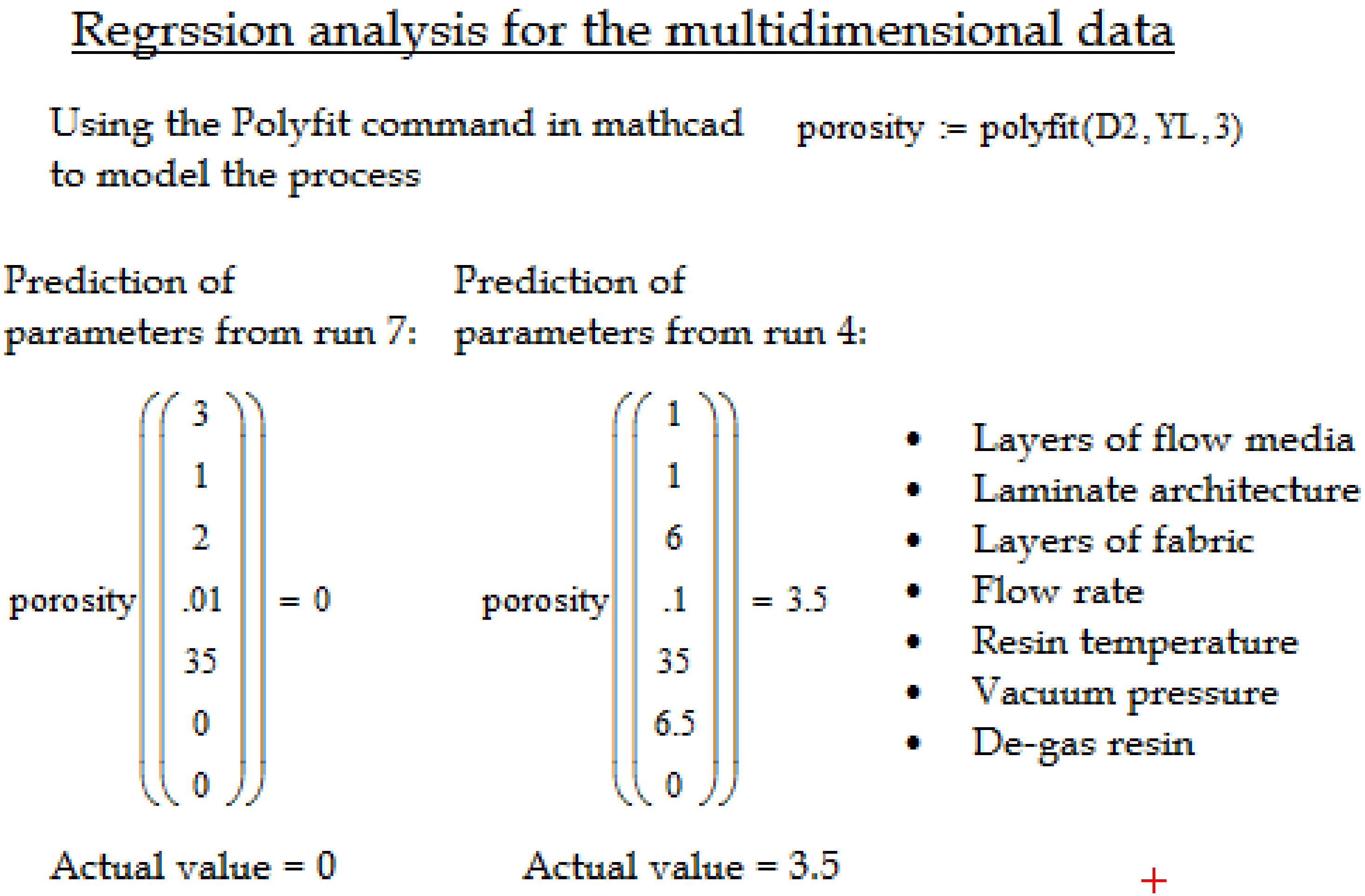
Fiber Volume Fraction Model: V_f := polyfit(D2, V, 1)

Multivariate Polynomial Regression

$$Y = c_0 + c_1 A + c_2 B + c_3 AB$$

- Provides a means of modeling multiple input parameter values
- Polynomial is a function of parameter values and fitting coefficients

Validation



Regrssion analysis for the multidimensional data

Using the Polyfit command in mathcad
to model the process

$\text{porosity} := \text{polyfit}(D2, YL, 3)$

Prediction of
parameters from run 7:

$$\text{porosity}\left(\begin{pmatrix}3\\1\\2\\.01\\35\\0\\0\end{pmatrix}\right) = 0$$

Actual value = 0

Prediction of
parameters from run 4:

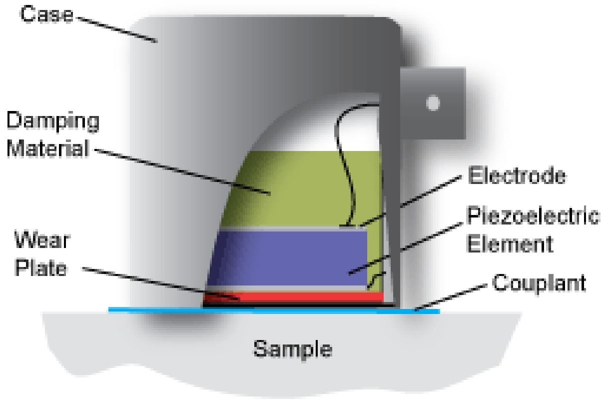
$$\text{porosity}\left(\begin{pmatrix}1\\1\\6\\.1\\35\\6.5\\0\end{pmatrix}\right) = 3.5$$

Actual value = 3.5

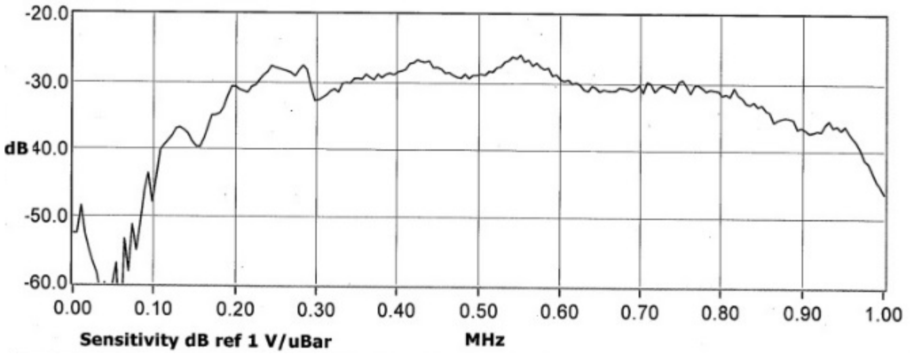
- Layers of flow media
- Laminate architecture
- Layers of fabric
- Flow rate
- Resin temperature
- Vacuum pressure
- De-gas resin

Acoustic Emission Technology

- Based on piezoelectric technology
- Elastic waves traveling through a material deform the piezo
- Produces a voltage waveform
- High-rate recording equipment captures voltage waveforms

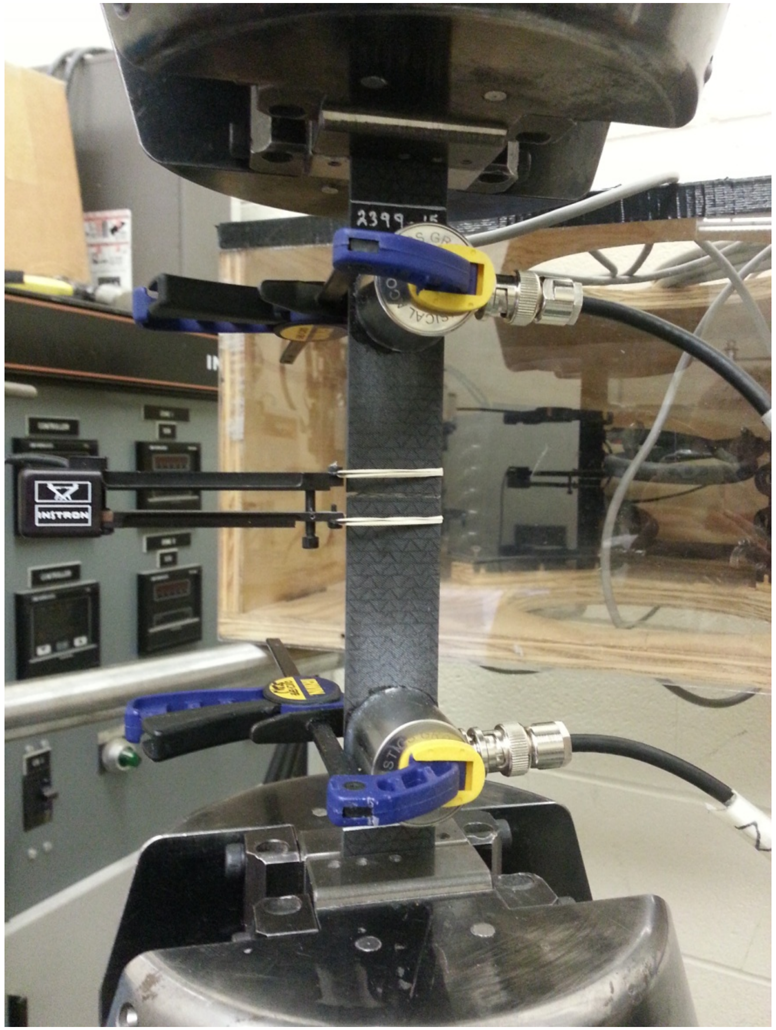


- Sensors can have different ranges and tune to specific frequencies
  - Sensitivity affects results!



Acoustic Emission Setup

- MISTRAS PCI-8 MICRO-II
  - 8 Channels, 400kHz Range
  - 3MSPS Data Rate
- Two wideband AE sensors
  - 50kHz to 1000kHz range
  - 45dB Threshold
- Linear locating setup
  - Allows external hit filter
- Held in place with clamps
  - Vacuum grease as couplant
- Sensors removed prior to failure



Application to Composites

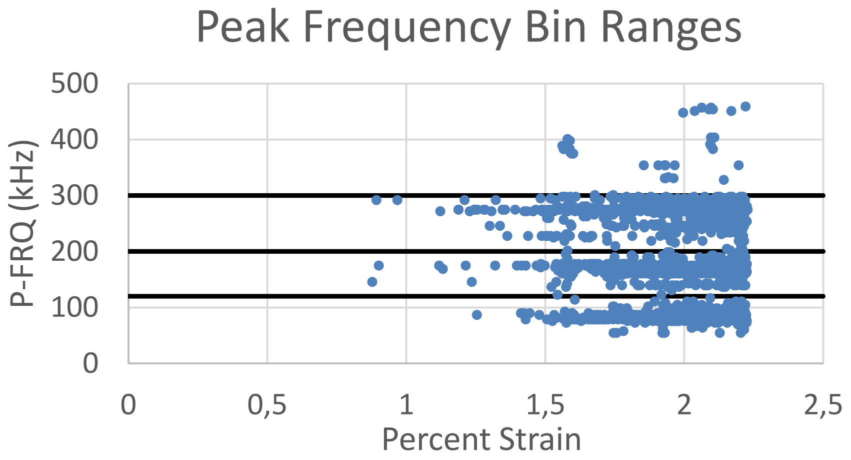
- Early researchers observed distinct bands of peak frequency activity
- Identified as particular damage mechanisms discussed earlier
- Divided into four "bins" of activity and adjusted for sensor response

Peak Frequency Bin Ranges

Bin	Freq Range	Identified Mechanism
F1	0-120kHz	Matrix Cracking
F2	120-200kHz	Fiber slip/pullout
F3	200-300kHz	Fiber/Matrix Debond
F4	300kHz +	Fiber Break

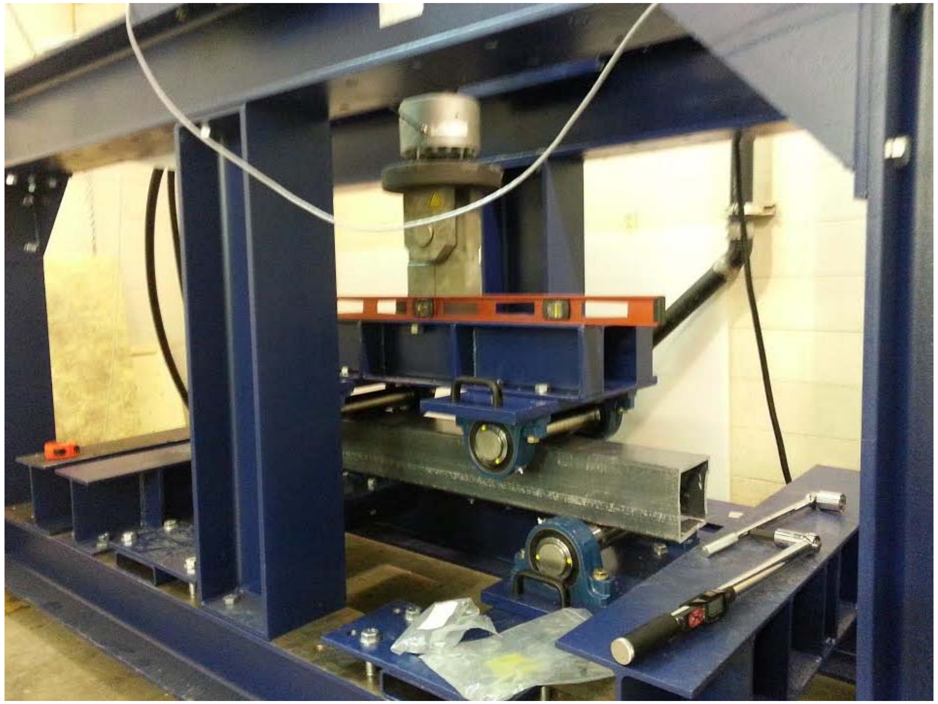
Why do we care about peak frequency?

- Identify and locate damage as it occurs; characterize the material
- Changes could indicate damage state of material

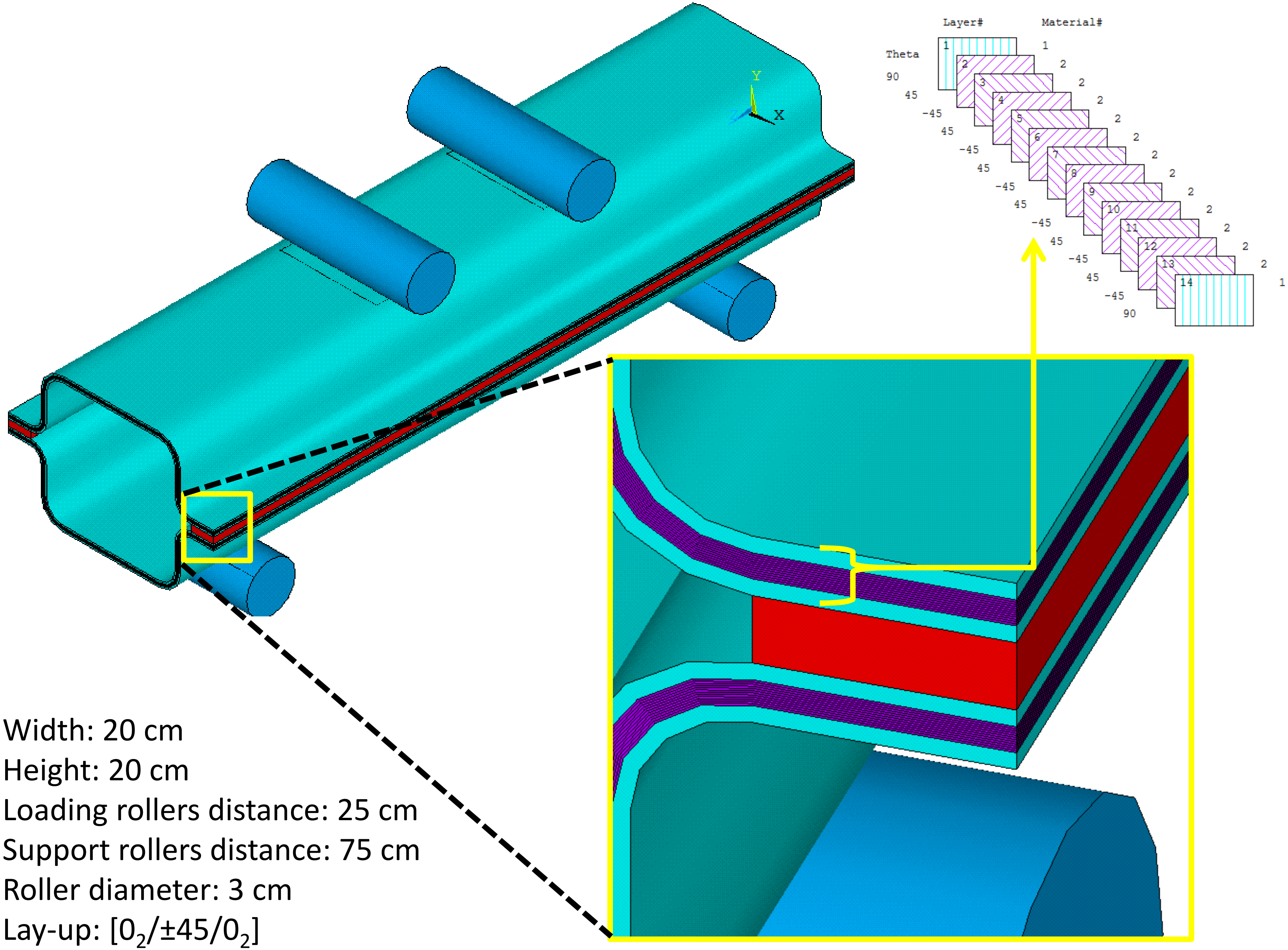


MSU Subscale Test Facility

- Designed, analyzed last year
- Load frame assembled and tested last year
- Operational and Calibrated 2/14
- Used for research Summer 2014

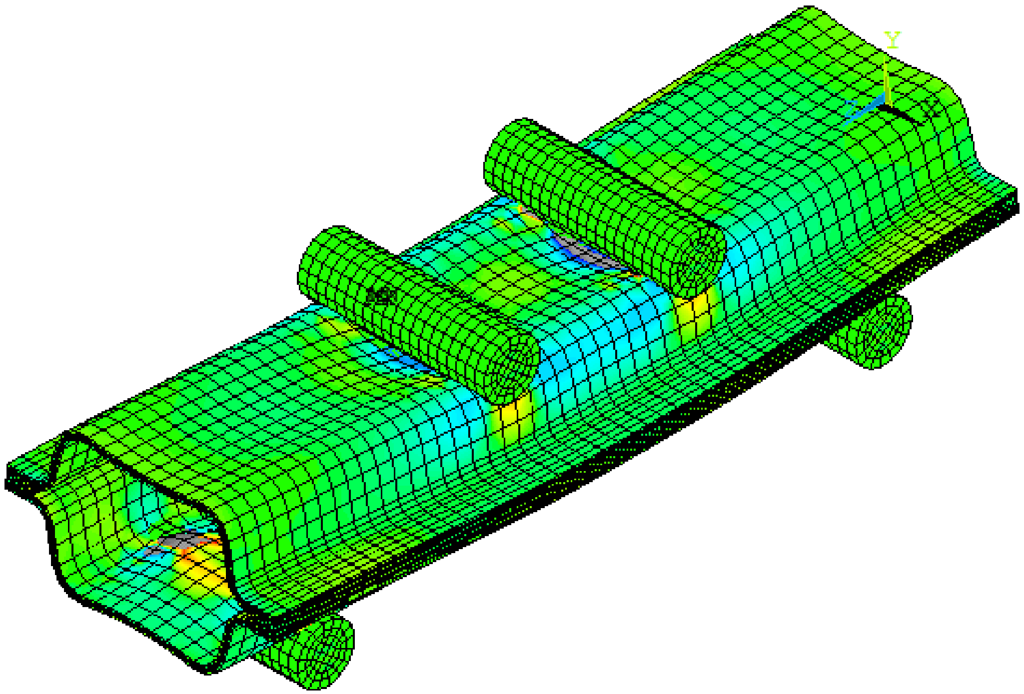


Sub-Scale Test Frame with a 1 meter long box beam loaded for four-point bending; torsion actuator to be installed



Width: 20 cm
Height: 20 cm
Loading rollers distance: 25 cm
Support rollers distance: 75 cm
Roller diameter: 3 cm
Lay-up: $[0_2/\pm45/0_2]$

Color Contour: Strain in Axial Direction (z-direction)



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ANSYS 14.0
NODAL SOLUTION
STEP=1
SUB =4
TIME=1
EPTOZ      (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.020573
SMN =-.081556
SMX =.065182
     -.01
     -.008769
     -.007846
     -.006615
     -.005692
     -.004769
     -.003538
     -.002615
     -.001692
     -.462E-03
     .462E-03
     .001692
     .002615
     .003538
     .004769
     .005692
     .006615
     .007846
     .008769
     .01
```

Maximum displacement: 20.6 mm
Load applied: 206 kN

Statement of Work developed early 2014, 3 Year Effort with options

Task 1. Adhesive Joints; Impetus: extend the understanding of fracture of adhesive joints, to understand parameters to increase manufacturing tolerances (decrease manufacturing costs)

Task 2. Multi-Axial Testing of Composite Materials; Impetus: validation of multi-axial failure criteria

Task 3. Progressive Damage Modeling for Composite Materials; Impetus: extend the work which has been conducted on wind turbine composites to aerospace structures; Impetus: To develop analysis methods for Damage Tolerance and to streamline the Building Block Approach for DT certification of composite structures.

Many people have invested into building a long-term, sustainable research relationship between MSU and Boeing

Today's Goal: Determine the remaining steps to GET A CONTRACT IN PLACE

Summary

- Montana State University has tremendous experience and investments for the above technologies: ***development, validation, experimental/analytical correlations for practical use***

- Boeing can exploit these investments (since 1989 decades, $Millions of other’s money) for modest costs

- This work could be result in a paradigm shift for Boeing to beat its competitors with ***faster, better, lower cost qualification and certification of composite structures for primary aerospace applications***