Design, Manufacturing, and Material Testing Trends in Wind Turbine Blade Structures

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Cairns' Background (to calibrate perspective)

- Began composites career in 1978 as a Staff Engineer at the University of Wyoming
  - Characterization of compression fatigue mechanisms of F18 vertical stabilizer (AS1/3501-6) for Navy
  - Hygrothermal characterization of Carbon, Glass, and Kevlar with Hercules 3501-6 for Navy and Army

- 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

- Manager of Composites Technology Hercules Materials Company
  - US largest manufacturer of structural carbon fibers
  - materials for military and commercial aerospace primary structural applications
  - $350-2,000/lb final part costs

- Joined Mechanical and Industrial Engineering at Montana State University in 1995, began working on wind turbine blade structures, <$10/lb final part cost target

The Basic Issues

Design – Designers are more savvy regarding composite materials and structures. Design staff is increasing and becoming more specialized.

Manufacturing – New large wind turbine blade structures are becoming much larger (current designs 90+m rotor diameters). Low-cost, robust manufacturing is necessary

Materials – E-glass/polyester is being replaced by carbon/vinyl ester or epoxies as an enabling technology.

The wind turbine industry cannot afford failures from either an economic perspective or a political perspective at this pivotal time

Design Trends

Some Definitions

- **Safe Life** – a structure is guaranteed to have no failures over its lifetime (usually several lifetimes for conservatism)
- **Durability** – the ability of a material/structure to sustain an event or sequence of events without damage (fatigue is a subset of durability)
- **Damage Tolerance** – the ability of a material/structure to maintain performance with damage present

Implications of Above

- Safe-Life design methodology works well for highly quantified loadings and highly quantified materials (e.g. pressure vessels, steel, automotive [up to warranty]). 1920s mentality to fatigue
- Durability is used to determine the onset of damage
- Damage Tolerance is used for residual strength, given a specified amount of damage

Blade Design Methodologies

Then	Now	Shifting Paradigm
Blade design was safe-life with little data, limited constant amplitude fatigue, Miner's Rule, notable failures obviated need for better methodologies	DOE/MSU database over a wide variety of materials, material architectures, loadings, structural configurations, environmental conditions, etc. Miner's Rule still used and still does not work (especially for spectrum loading). Some massaging with phenomenological models have improved predictions. Well established methodology for delamination growth, based on damage tolerance methodologies.	Companies recognizing deficiencies in current methodologies. Some European companies utilizing damage tolerant design methodologies. A gradual migration of composite design experts from the aerospace community, well-entrenched in Damage Tolerant Design of composites may influence design in US.

Key Elements of Damage Tolerance

Residual Strength Analysis

+

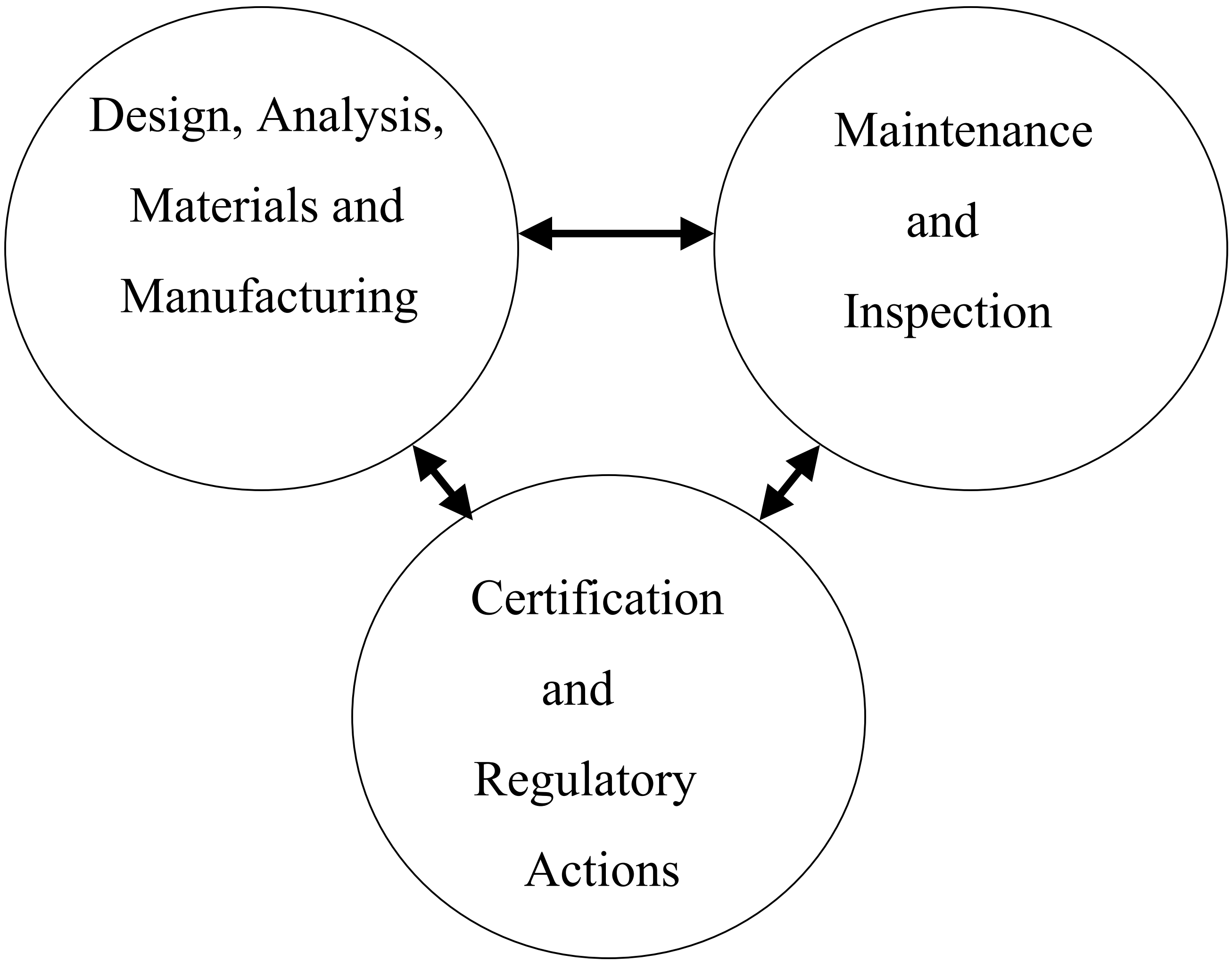
Progressive Damage Analysis (requires a damage growth model and accurate loads data)

+

Inspection Program

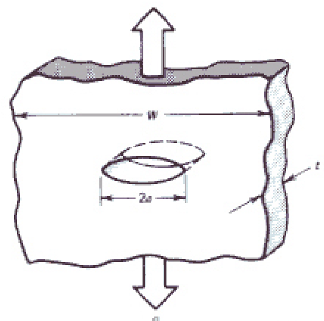
= No in-service failures

Wind Turbine Blade Reliability with Damage Tolerant Design



Metallic Structures Characterization

For limit loading:

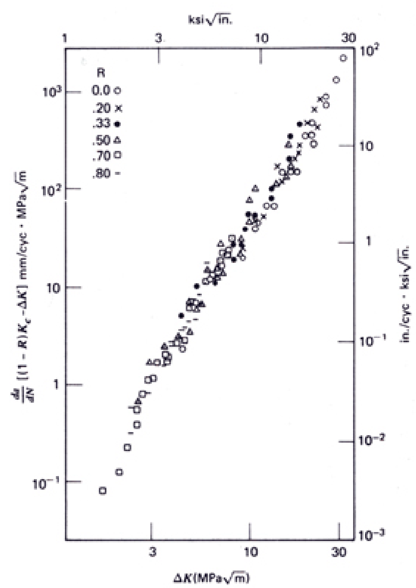


$$K_{1C} = \sigma(\pi a)^{1/2}$$

or critical strain energy release rate:

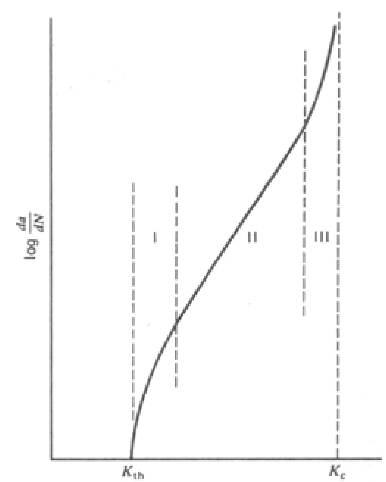
$$G_{1C} = K_{1C}^2 / E(1 - \upsilon^2)$$

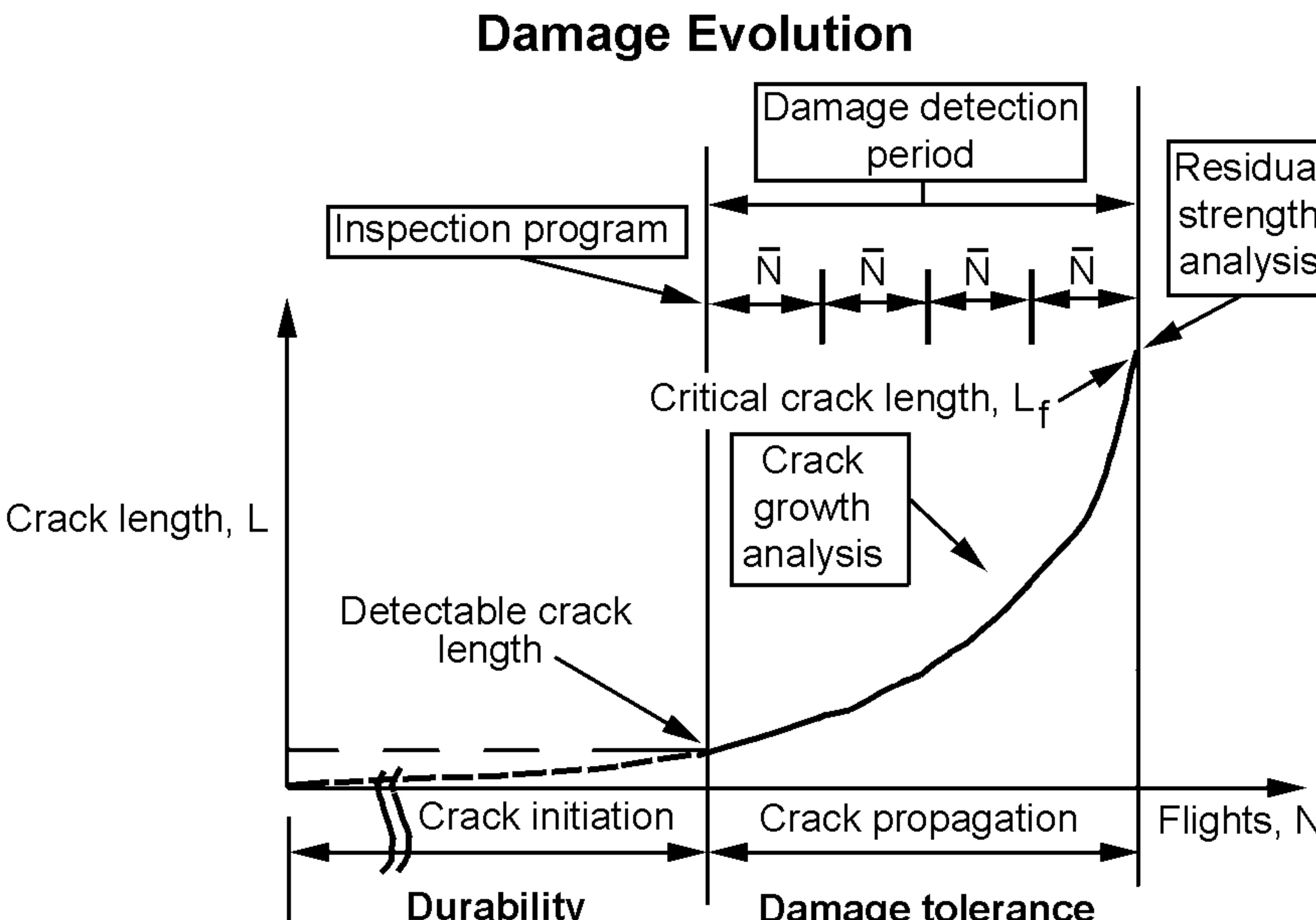
For durability:



Paris' law for crack growth:

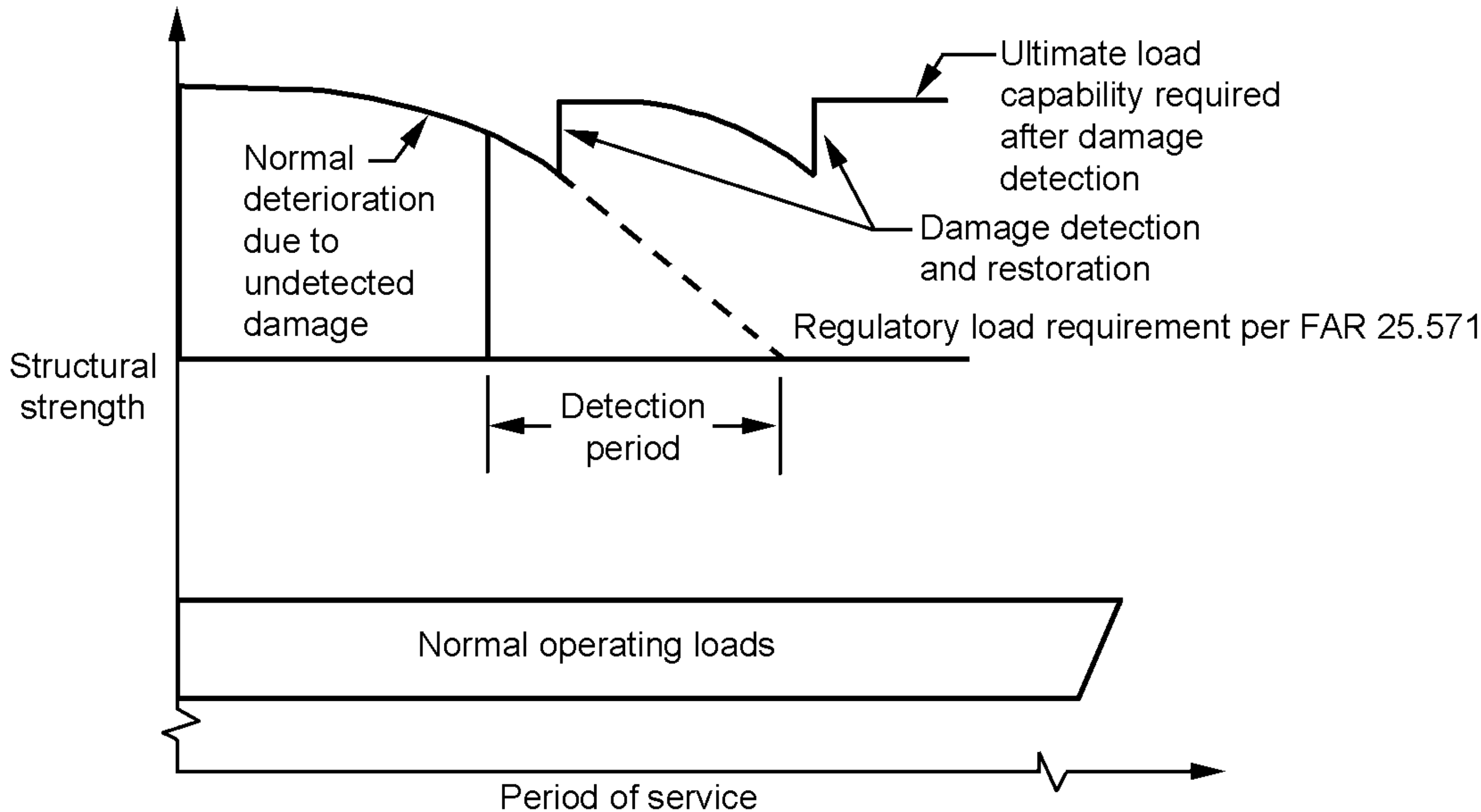
da/dn vs. ΔK



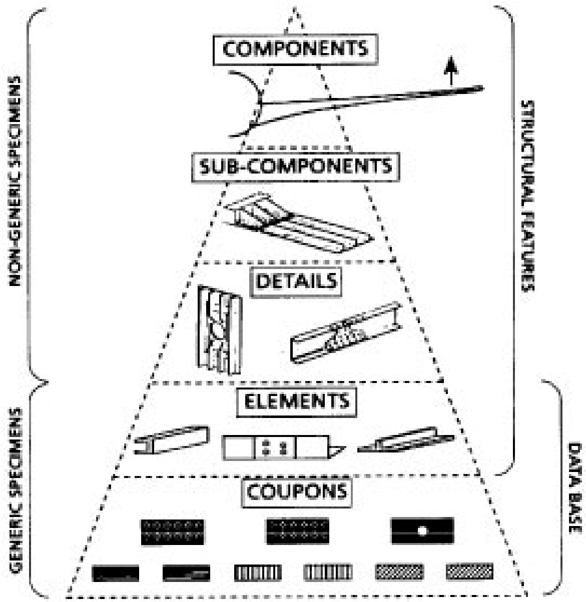


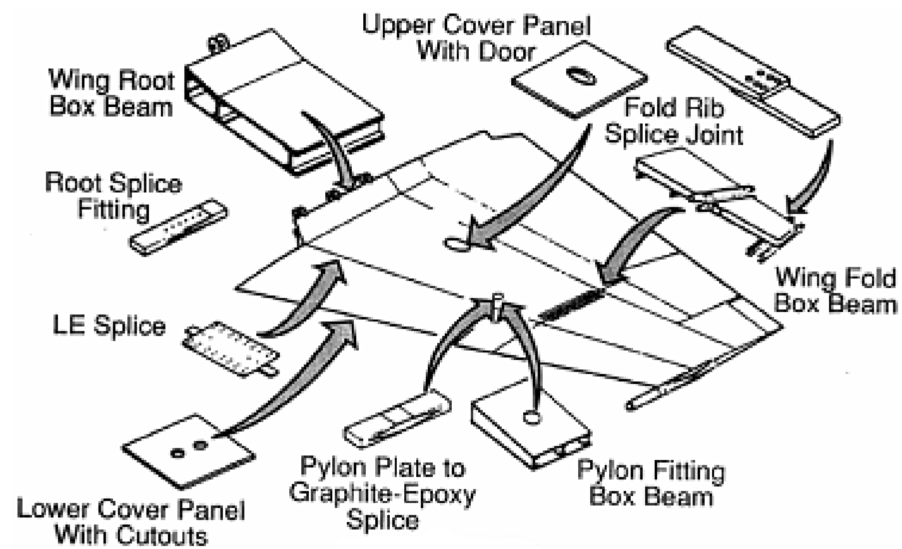
Damage Evolution
Damage detection period
Inspection program
Residual strength analysis
N̄
N̄
N̄
N̄
Critical crack length, L_f
Crack growth analysis
Crack length, L
Detectable crack length
Crack initiation
Crack propagation
Flights, N
Durability
Damage tolerance

Strength Requirements For Damage Tolerant Structure



The Equivalent Approach for Composites





Building Block Approach,

MIL HDBK 17

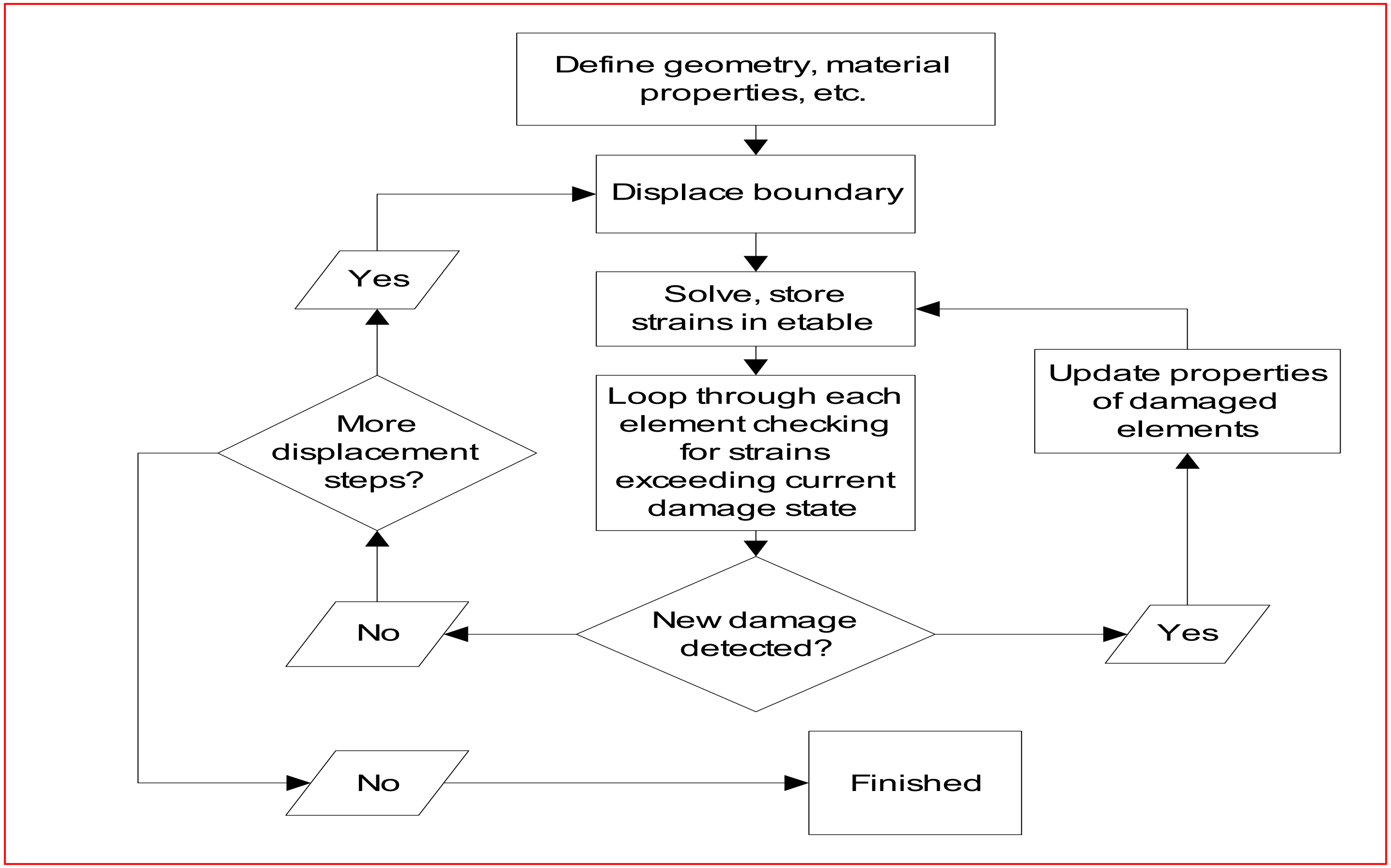
Statistical Variability for each level established

Specific Validation Tests for F18 E/F Composite Wing Structure

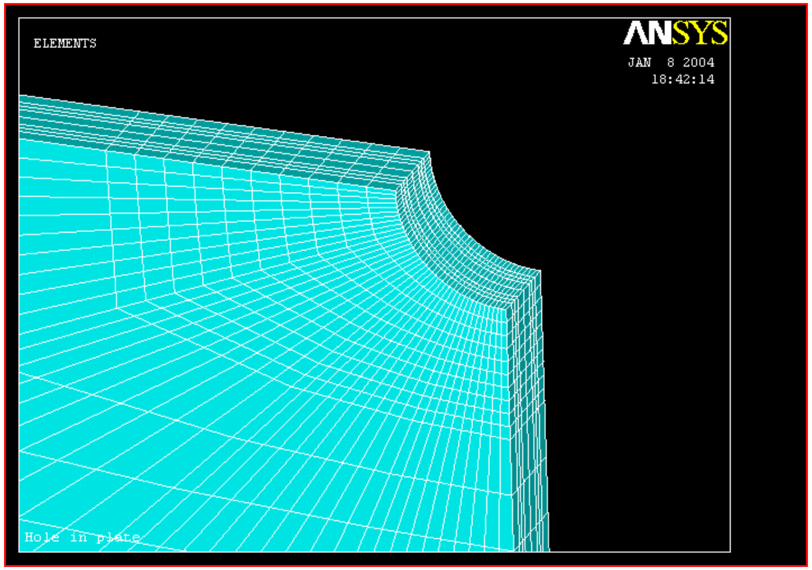
The Bad News

- None of the Key Elements (Residual Strength, Progressive Damage Analysis, and Inspection Programs) are mature for composite materials and structures
  - Residual Strength most mature
  - Notable exception - delamination residual strength, growth analysis, inspection; just like crack growth in metals

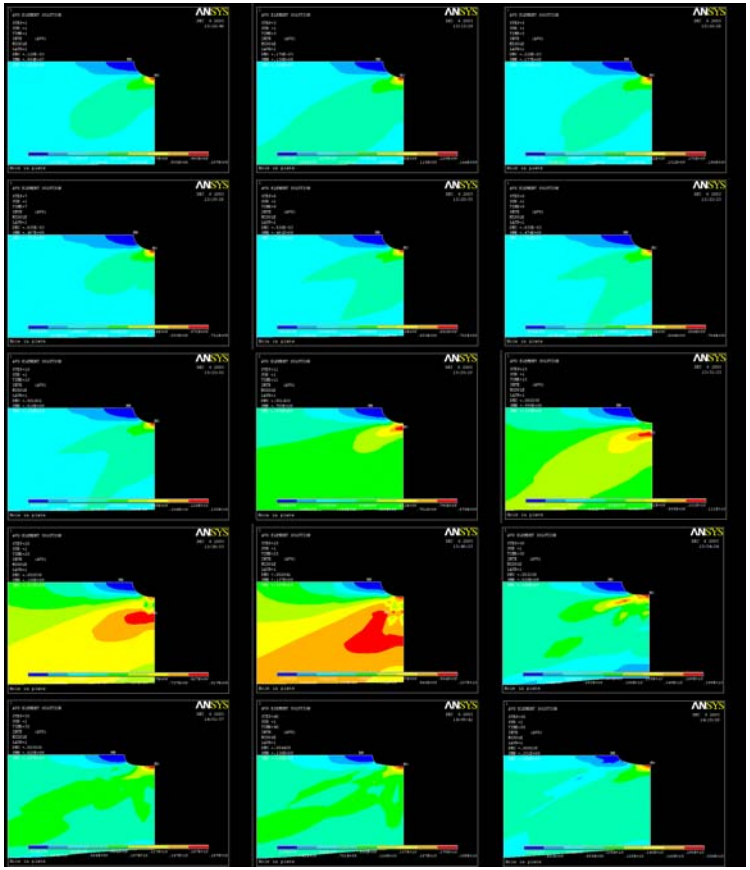
MSU is Engaged in Progressive Damage Modeling



MSU is Engaged in Progressive Damage Modeling (cont.)



ANSYS Finite Element Model
(quarter symmetry, hole in laminate)



Damage Progression in 0 degree layer

Wants versus Reality

- Wind turbine industry **wants** a safe-life structure, no failures for 30 year lifetime
- The **reality**: Materials have high statistical variability, manufacturing has statistical variability, loadings have statistical variability – makes safe life difficult or impossible
- A practical **compromise** may be available, no failures between regularly scheduled maintenance, e.g. every 2 ½ years, inspect, and re-certify

Design Staff

Then	Now	Shifting Paradigm
Design was done by a few industry experts. In a typical scenario, companies engaged consultants and job shoppers	Full-time engineering staff skilled in the art of composite design. This small staff is typically in charge of all aspects of materials selection, preliminary design, manufacturing, testing and certification. Designers skilled in Damage Tolerant design methodologies are trickling in to wind turbine industry from aerospace.	Specialists emerging, (e.g. dynamical design, detailed finite element modeling, materials selection, manufacturing, testing, etc.) These specialists are very thorough in their discipline. This approach is rigorous, but requires someone in charge of seeing that the “big picture” converges.

The Future in Blade Design

- Damage Tolerant design may play a role since it deals with actual damage and actual damage accumulation

- Current areas of research may bear fruit
  - Progressive Damage Models
  - Inspection techniques
  - Probabilistic design methodologies (convolve materials variability → manufacturing variability → loads variability to produce an accurate probability of failure (used on a limited basis in Airbus design)

- Embedded sensors have promise to raise a flag under overloading conditions (to be discussed subsequently)

Manufacturing Trends

Manufacturing/Materials

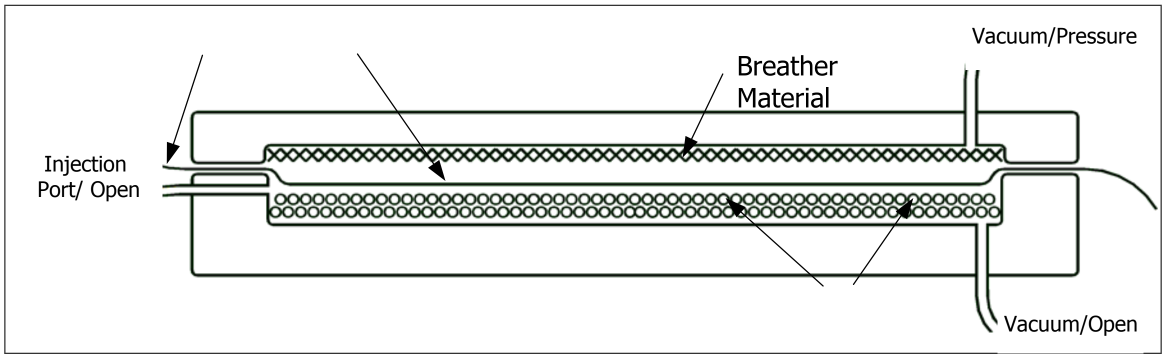
Then	Now	Shifting Paradigm
Hand lay-up with E-glass polyester or even wood. Direct application of manufacturing techniques of lightly loaded structures such as boats; some limited use of Resin Transfer Molding (RTM) cited in Europe	Hand lay-up still plays an important role, but Resin Infusion (low pressure or vacuum only one-sided molds) being baselined as the next-generation manufacturing. Process modeling done by specialists.	Carbon fiber is being used to meet scaleup demands, increased manufacturing diligence is necessary. Hence, Prepreg is gaining inroads to reduce fiber waviness. Infusion processes on a large scale will be the next generation. Process modeling being shifted to those responsible for manufacturing in lieu of it being an academic exercise.

Manufacturing Techniques

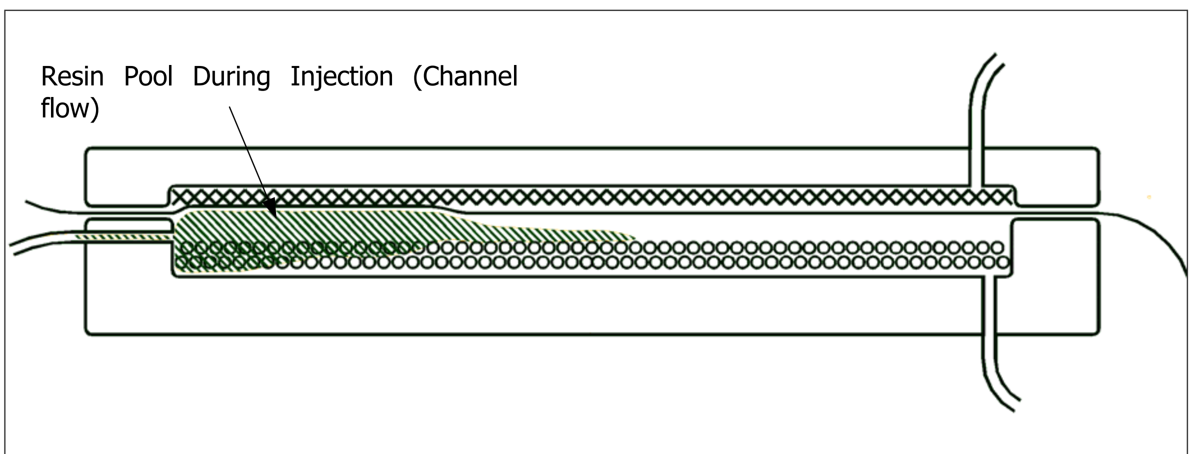
Process	Basic Principles	Advantages	Disadvantages
Hand Lay-up	Open mold Manual infusion One sided mold	Low cost Fastest implementation	Volatile emissions Health risks Inconsistent results Less efficient material usage
RTM	Closed mold In-plane resin flow Two-sided mold	Higher dimensional consistency Less volatile emissions Both sides finished	Higher mold cost Resin flow pattern critical Costly equipment required Lowest volume per port
VARTM	Closed mold In-plane resin flow Two-sided mold Evacuated mold	Higher dimensional consistency Less volatile emissions Both sides finished Higher quality products than RTM	Higher mold cost Resin flow behavior critical Costly equipment required Complexity of vacuum porting
SCRIMP	Closed mold In-plane resin flow One-sided mold Evacuated mold	Higher dimensional consistency Less volatile emissions Higher quality products than RTM	Proprietary process One side finished
FASTRAC	Closed mold Channel flow One-sided mold Evacuated mold	High quality High dimensional consistency Less volatile emissions Largest injection volume per port	Added cost of FASTRAC layer Highest complexity Possible artifacts from bag Costly equipment required

MSU Infusion Studies – Two Stage Injection (Stage I)

Pulling a vacuum on entire mold

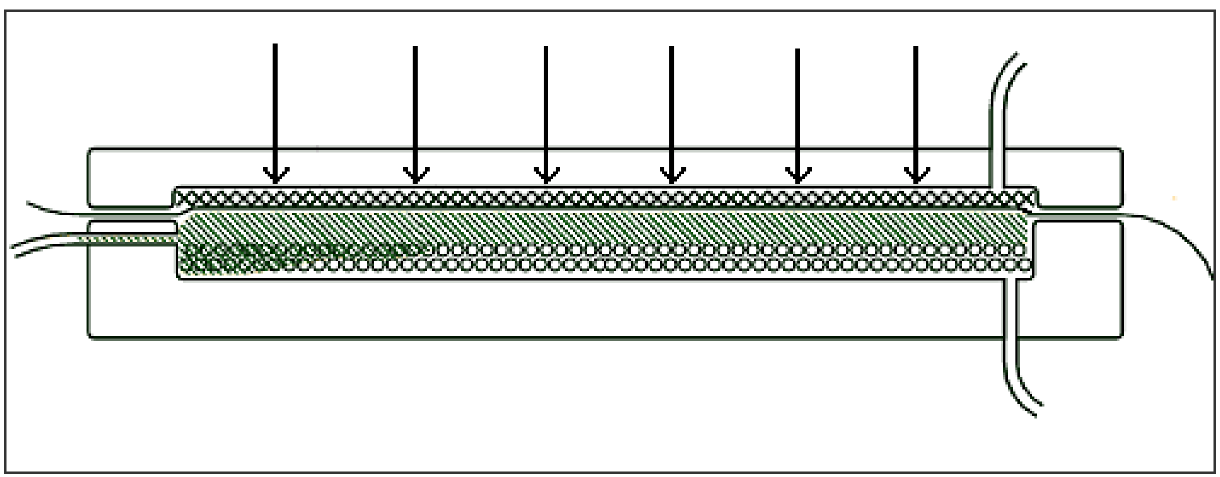


Injecting resin into the mold gap

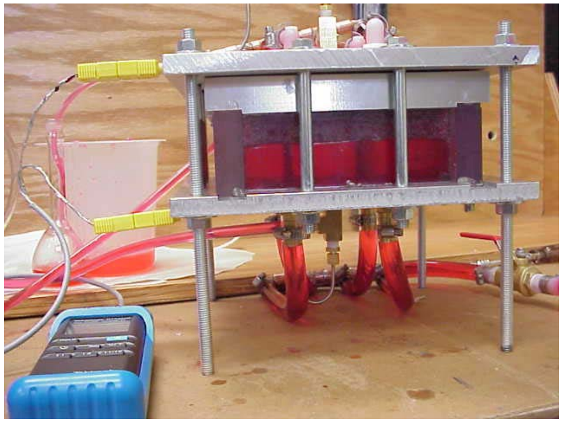


MSU Infusion Studies – Two Stage Injection (Stage II)

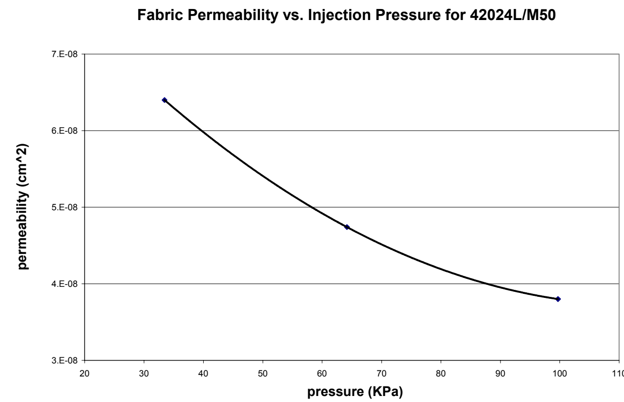
Pressure is applied to bagging to force resin through preform



Thick Composite Manufacturing Research



Thick Composite Permeability Test Facility



Permeability as a function of pressure (higher pressure, less permeability)

Closed form process modeling (predictions for processing time t)

Channel flow for resin distribution

$$t_{tot} = \left[\frac{L_{tube}^{2}\cdot\mu\cdot 32}{\left(P_1 - P_2\right)\cdot D_t^{2}}\right] + \left[\frac{1}{\left(P_1 - P_2\right)}\left(\frac{C\cdot\mu}{Dh^{2}\cdot 4}\cdot L_{mold}^{2} + \frac{256\cdot L_{tube}\cdot\mu\cdot h\cdot w}{D_t^{4}\cdot\pi\cdot N_t}\cdot L_{mold}\right)\right]$$

1-d Darcy's Law for impregnation

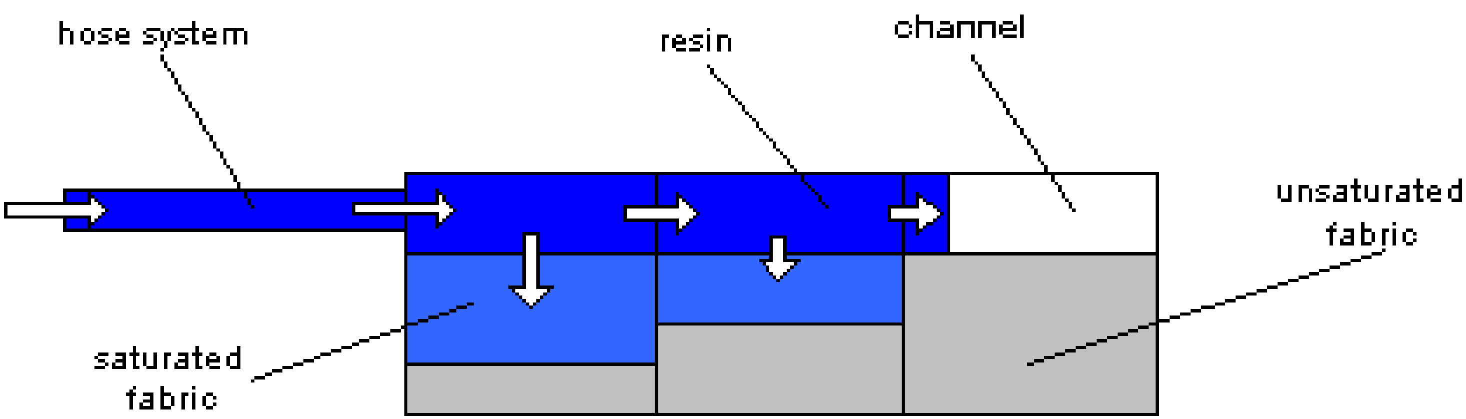
$$v = \frac{-K}{\mu}\cdot\frac{dP}{dz}$$

Solved for saturation time

$$t_{sat} = \frac{T^{2}\cdot\mu}{2\cdot P\cdot K}$$

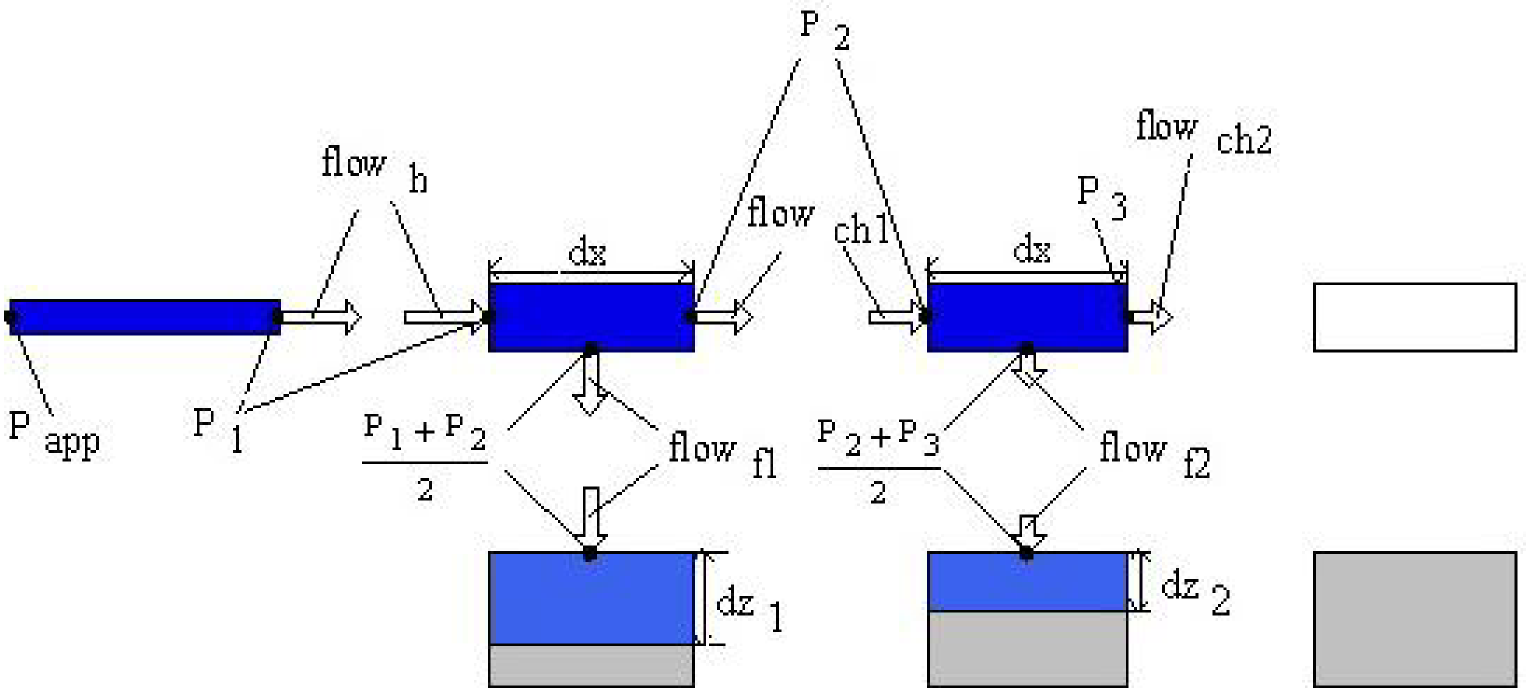
Comprehensive Model

- A comprehensive model has been developed to model flow through the channel and fabric simultaneously

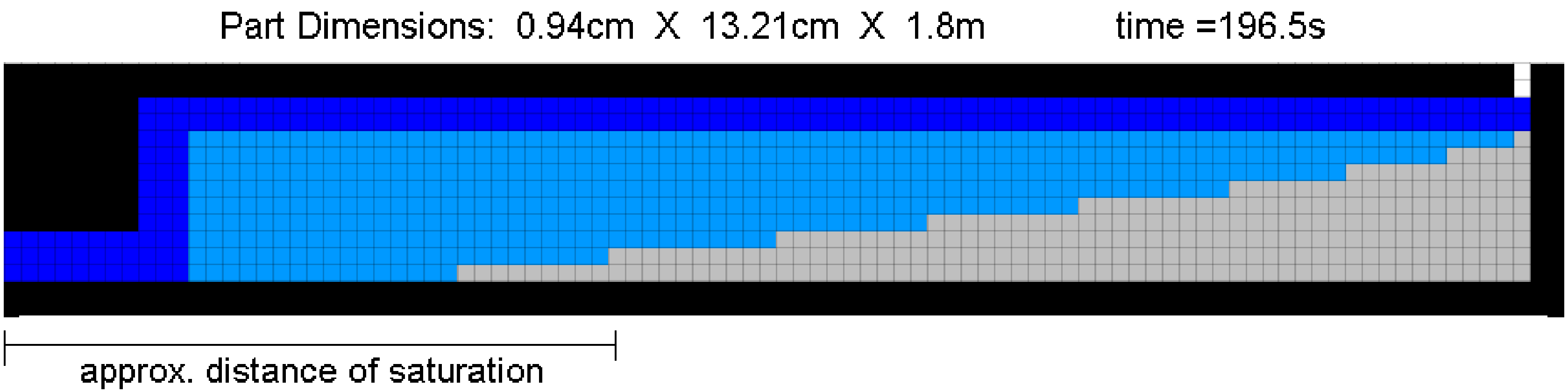


Comprehensive Model

Using conservation of mass, and the governing flow equations, the unknowns are calculated in matrix form.



Comparison to Test Results



Predicted time = 196 s

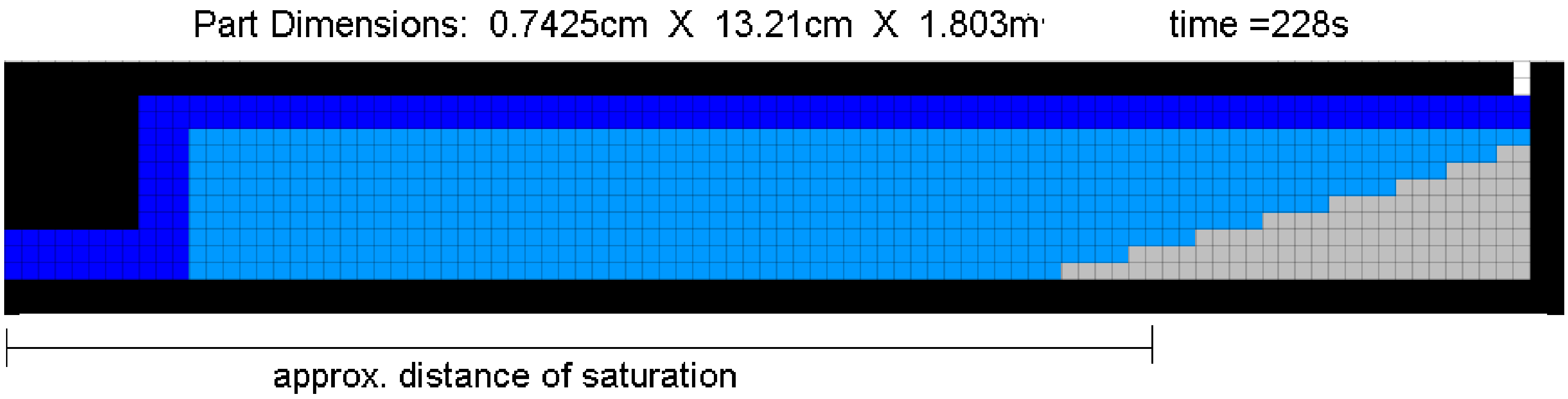
Actual time = 179 s

Error = 9%

Sources of error:

- Instrumentation error
- Fabric compressing
- Fabric variability
- "Racetracking"
- In plane flow
- Temperature effects
- Approximate surface tension

Comparison to Test Results

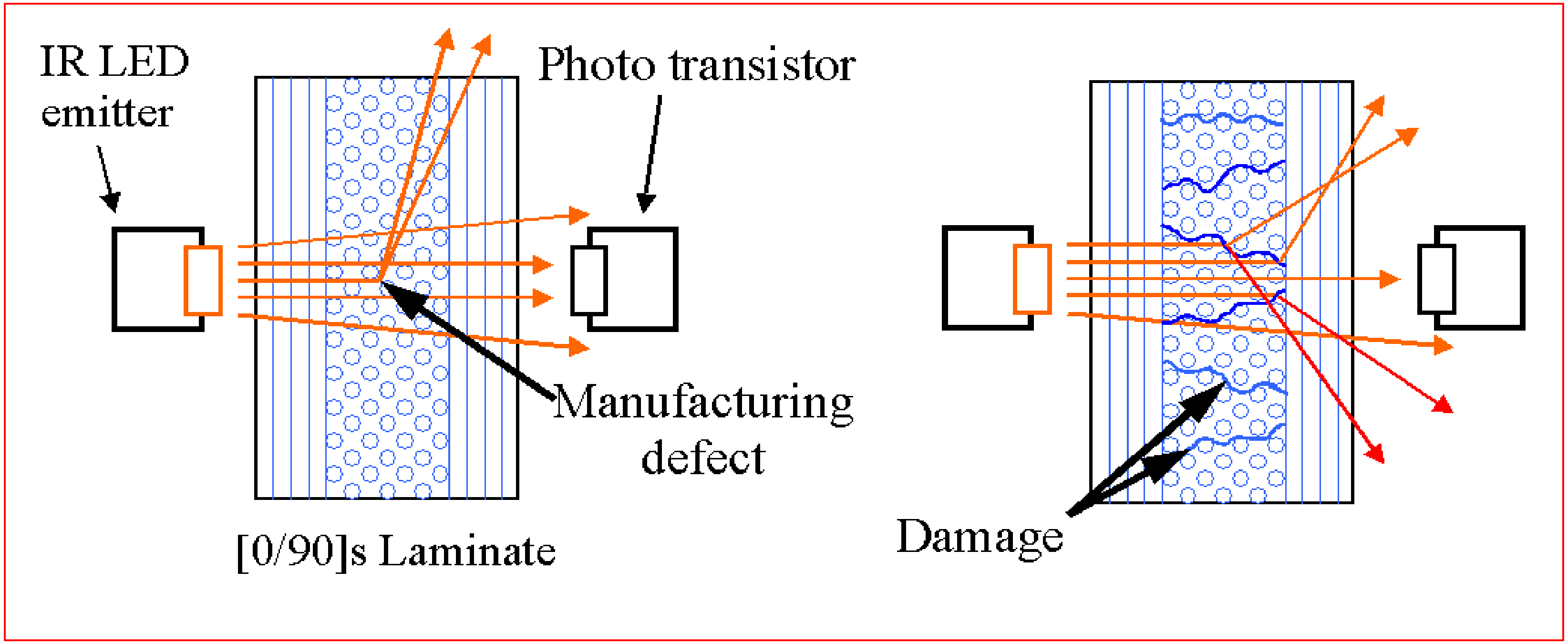


Predicted time = 228 s

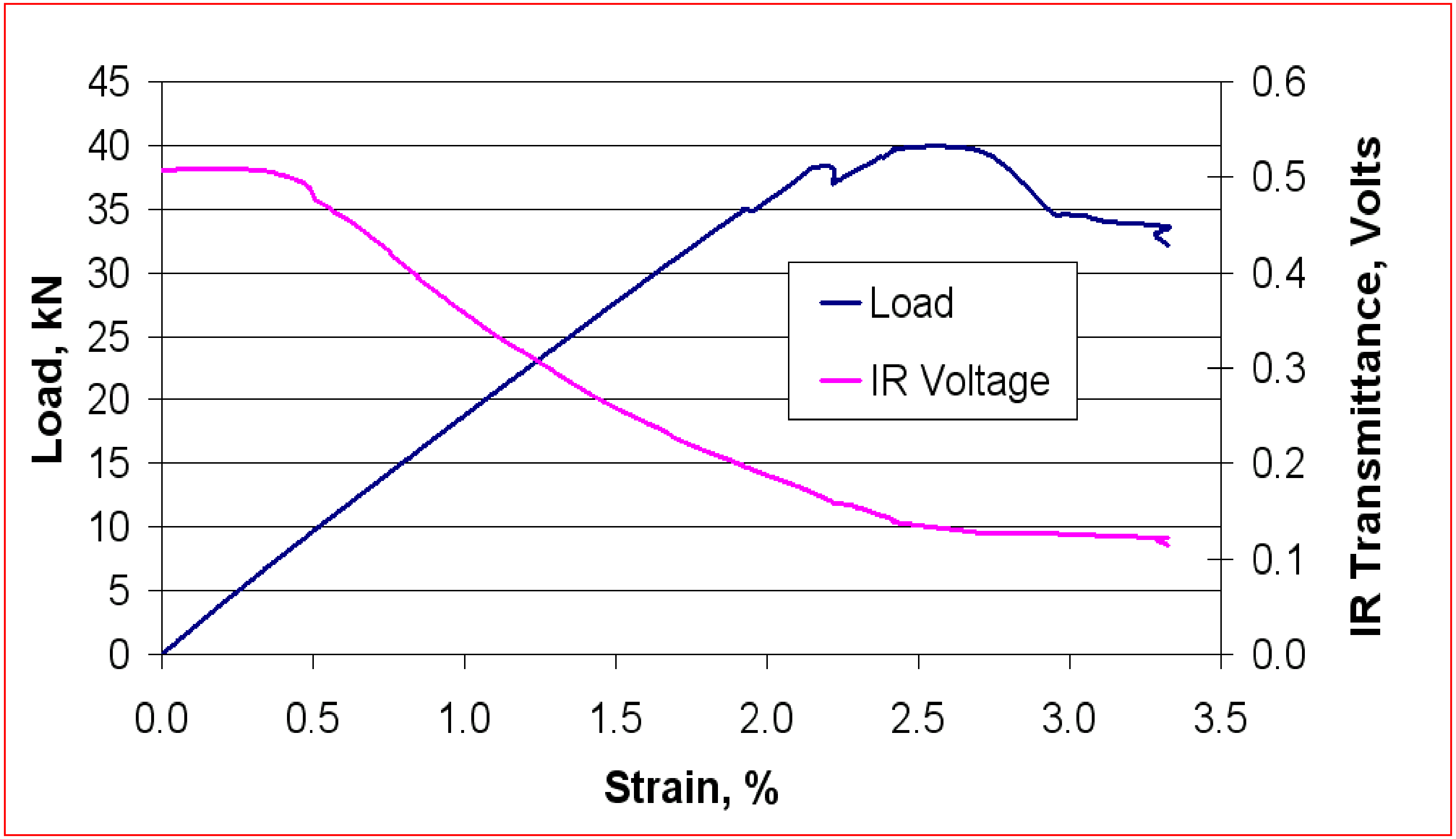
Actual time = 241 s

Error = 5%

Infrared Transmittance as a Laminated or Embedded Sensor



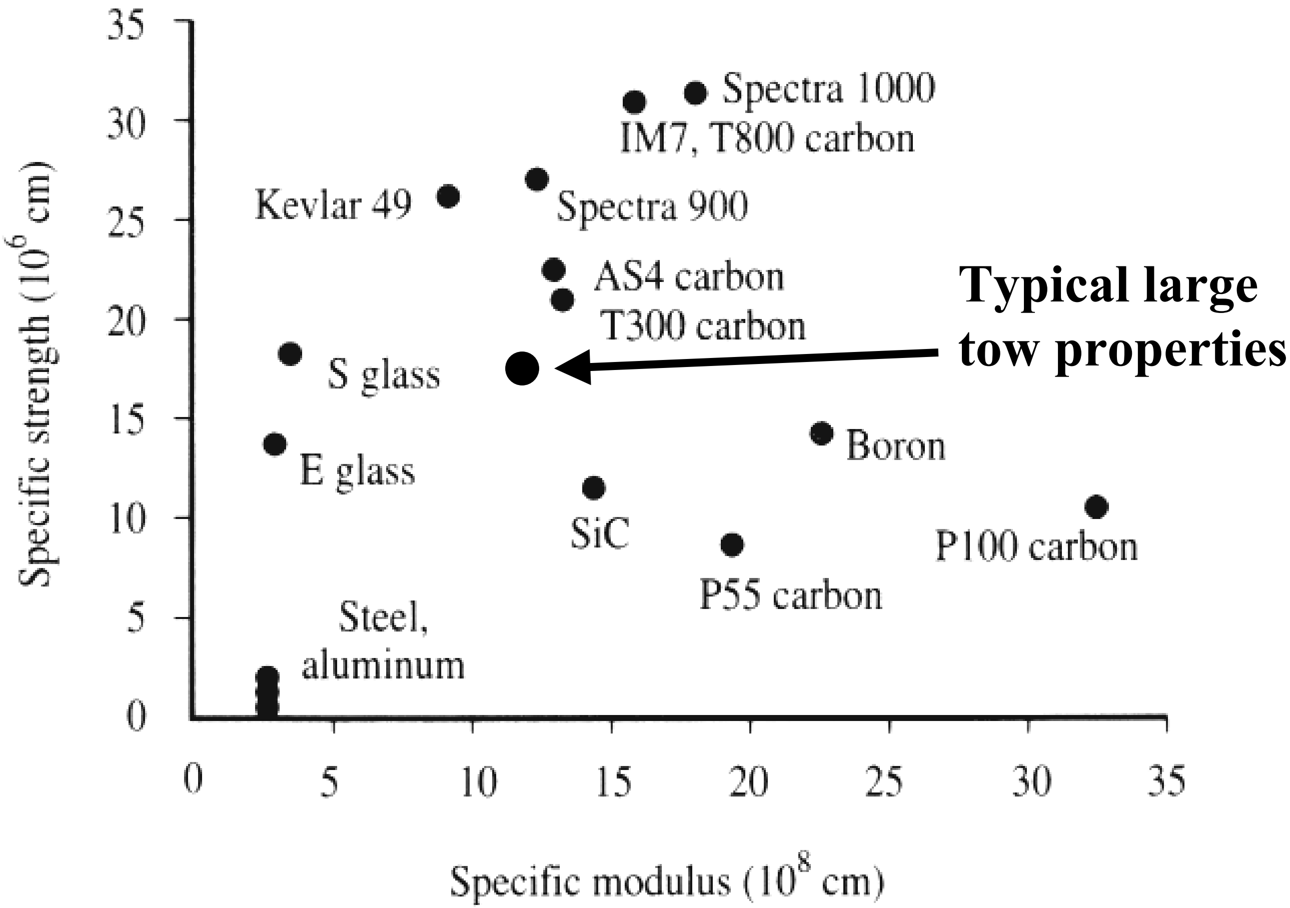
Infrared Transmittance as a Laminated or Embedded Sensor (cont.)



From testing of unidirectional laminates, 0.5% strain is the onset of matrix cracking; technique appears to be very sensitive over a wide strain range

Materials Trends

Carbon is the Emperor

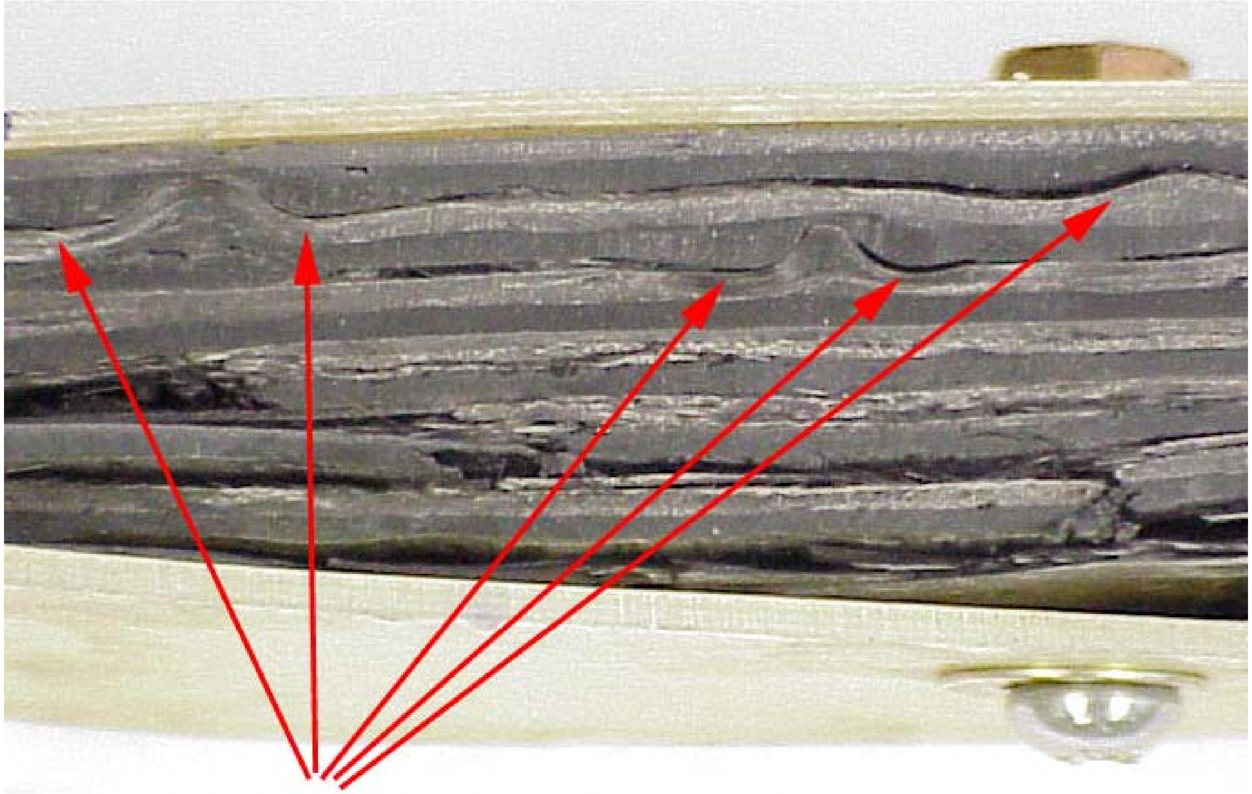


Carbon fiber is an enabling technology for new generation wind turbine blades

The Emperor's New Clothes

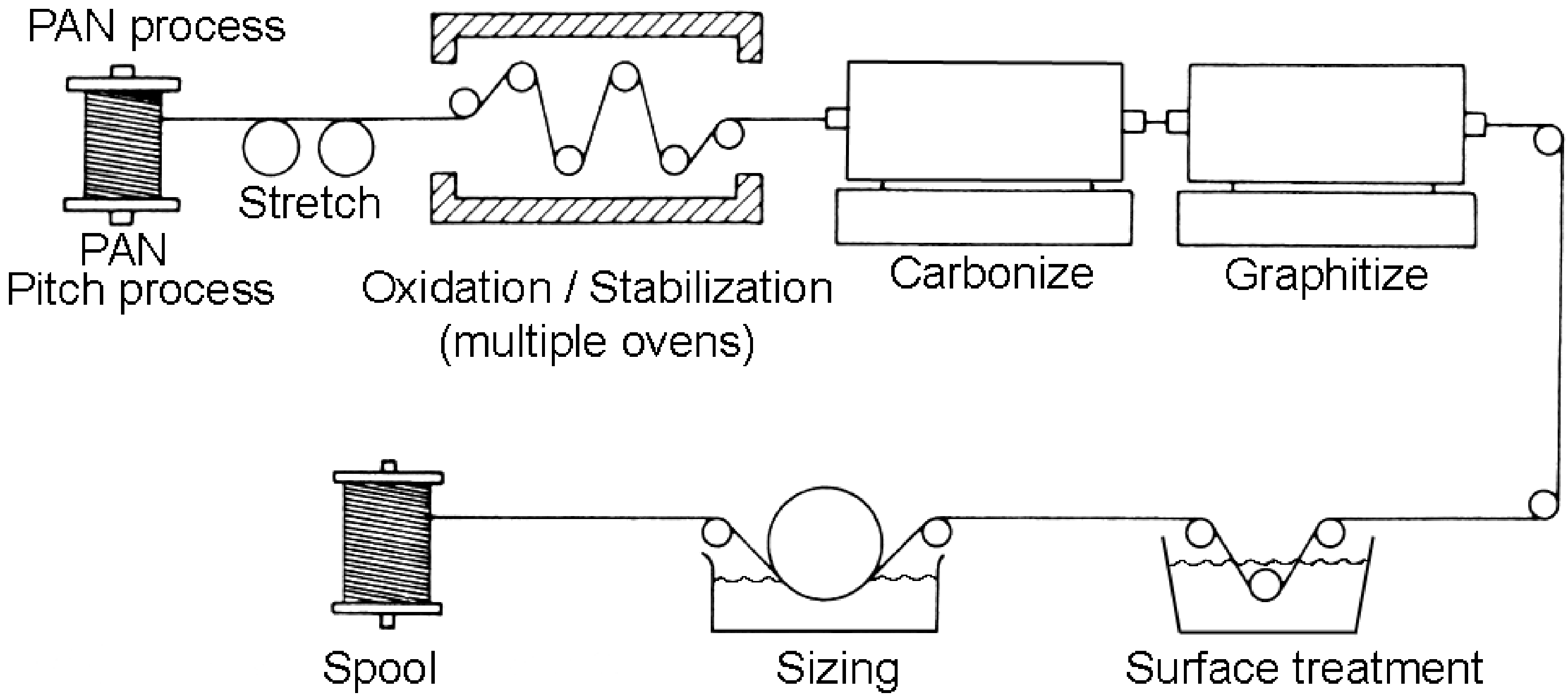
- Carbon fiber has a high orthotropy ratio $E_{\text{fiber direction}}/E_{\text{transverse to fiber}}$
  - E-glass = 3.5
  - Average modulus carbon = 15
- Result much more sensitive to fiber mis-alignment from manufacturing process
- Carbon Fiber is expensive; about 8X E-glass fibers (in-depth discussion following)

Consequence of Misalignment in Large, Composite Structure



DELAMINATIONS ASSOCIATED WITH WAVES

Background – Carbon Fiber Manufacturing



What Your Materials Supplier is Telling You (Source: Carbon Fiber Outlook 2002)

Process Step	Cost $/lb Carbon Fiber
Precursor (45% mass conversion rate)	1.90
Pre-treatment/Oxidation	0.83
Carbonization	0.69
Sizing, surface treatment, packaging, quality control	0.81
Mill cost/lb	$4.23/lb
20%Margin/ 7%Margin	$5.83/5.20/lb

Why less than $6.00/lb Carbon Fiber is Not Sustainable with Current Manufacturing

- Carbon fiber that cost $25+/lb in the 1980s can be had for less than $10/lb today (You can't get blood out of a turnip!)
- The above assumes $0.86/lb precursor
- The commodity price for structural quality precursor is $1.50/lb to $1.75/lb
- With economies of scale, it may be possible to get the price of precursor down to $1.20/lb
- Structural quality precursor exceeds $2.20/lb

Why less than $6.00/lb Carbon Fiber is Not Sustainable with Current Manufacturing (Today's Typical Costs)

Process Step	Cost $/lb Carbon Fiber
Precursor (45% mass conversion rate)	4.44
Pre-treatment/Oxidation	0.83
Carbonization	0.69
Sizing, surface treatment, packaging, quality control	0.81
Mill cost/lb	$6.77/lb
20%Margin/ 7%Margin	$8.37/7.74/lb

Why less than $6.00/lb Carbon Fiber is Not Sustainable with Current Manufacturing (Today's Bests Costs)

Process Step	Cost $/lb Carbon Fiber
Precursor (45% mass conversion rate)	3.61
Pre-treatment/Oxidation	0.83
Carbonization	0.69
Sizing, surface treatment, packaging, quality control	0.81
Mill cost/lb	$5.94/lb
20%Margin/ 7%Margin	$7.54/6.91/lb

Why less than $6.00/lb Carbon Fiber is Not Sustainable with Current Manufacturing (Best Case Scenario)

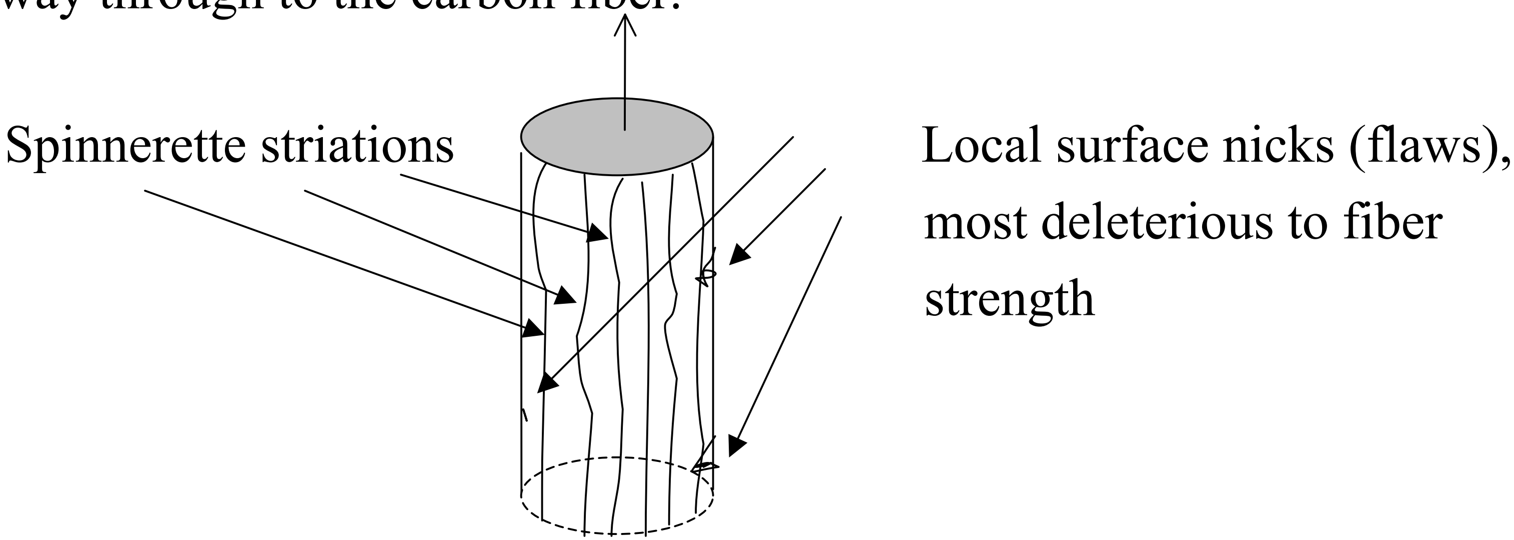
Process Step	Cost $/lb Carbon Fiber
Precursor (45% mass conversion rate)	2.67
Pre-treatment/Oxidation	0.83
Carbonization	0.69
Sizing, surface treatment, packaging, quality control	0.81
Mill cost/lb	$5.00/lb
20%Margin/ 7%Margin	$6.60/5.97/lb

Issues with "Large Tow" Carbon Fiber

- Advantages to Large Tow Carbon Fiber (>36K bundles)
  - Slightly more throughput in carbon fiber process
  - Larger bundles have advantage for material handling in thick structures (more material applied/process step)
- Facts associated with large tow processing
  - Oxidation, the rate limiting step is diffusion-controlled and exothermic (presents limits and safety constraints)
  - Uniformity of oxidized density has a profound impact on mass conversion yields and final product uniformity (mass per unit length [dimensional control], carbon fiber strength)
  - It is unlikely that you will save much more than $1.00/lb mill costs for large tow, and you will pay dearly in structural performance (especially strength) and consistency; may need to add 20% or more more material mass to compensate (a losing battle)

Other Issues with Precursor

- Modulus is a bulk property, dependent on the microstructure of the fiber (which is controlled by processing conditions) – easily obtained with low cost precursor
- Strength is a local property, depends on high quality, low flaw density on precursor (more expensive); any flaw on precursor is carried all the way through to the carbon fiber.



All carbon fiber manufactures using textile precursor facilities have had to make significant facility modifications and quality improvements (read-more expensive) to meet demands for structural carbon fibers.

The Future of Low Cost Carbon Fiber

- A "chicken and egg" game
  - A large volume business is needed to stimulate sustainable low cost carbon fiber
    - Automotive/transportation
    - Off-shore oil
    - Wind energy can provide "pull through," but does not have the autonomous clout
  - If the market does not exist, carbon fiber manufacturers will not invest for long term. Conversely, the market will not exist unless there is low cost carbon fiber
- Structural grade precursor needed at textile grade prices (precursor is either good or bad, but not intermediate regarding flaw distribution)
- "Best guess" sustainable price for PAN-based carbon fiber ($7.00/lb)
- Economy of scale is necessary but not sufficient for sustainable lower cost carbon fiber – New technology is needed

Questions?