Fatigue, Damage and Failure of Composite Materials: Mechanisms, Fatigue Life Diagrams and Life Prediction

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Lecture 1: INTRODUCTION

Contents

- Lightweighting, and the role of composites
- “Big Picture” of cost-effective design with composites
- Fundamentals – Elasticity, plasticity, viscoelasticity, “strength”, fracture, failure, damage.
- Overview of failure in unidirectional composites under tension, compression and shear.
- Modeling strategies: phenomenological vs. mechanisms based.

Lightweighting – An engineering design process

Lightweighting is the process of reducing the weight of a product, component, or system for the purpose of enhancing

(1) performance,

(2) operational supportability, and

(3) survivability.

It entails

(a) Design, development, and implementation of lightweight materials, components, and technologies

(b) Cost-effective manufacturing.

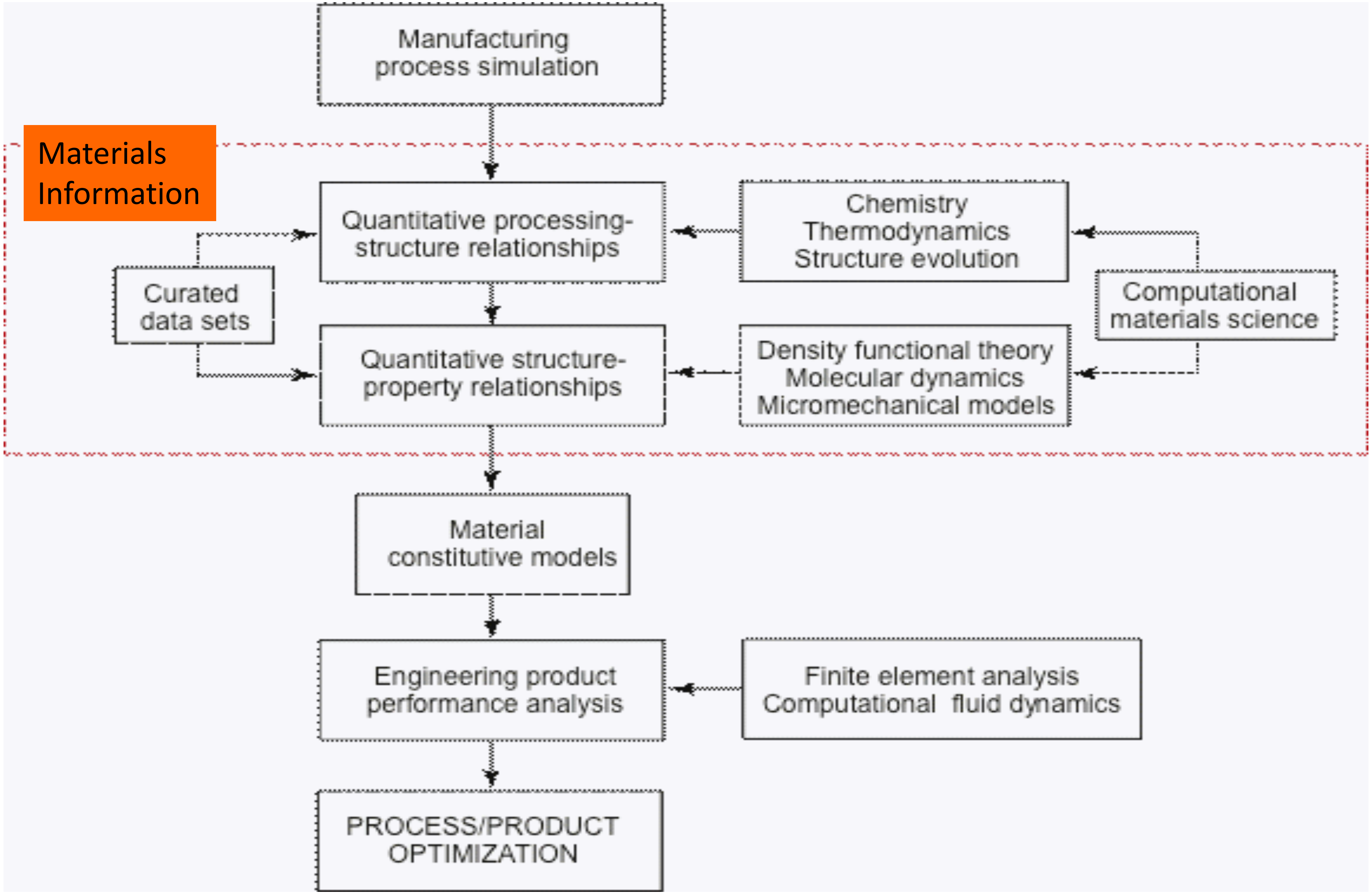
Goals of lightweighting

- Improved fuel economy of vehicles
- Higher performance (speed, mobility, maneuverability, range, and payload capacity)
- Better operational supportability (transportability, durability, repairability, and maintainability)
- Improved survivability (impact resistance, damage tolerance).

Elements of lightweighting design with composites

- Creative fiber architecture (coupled response, multifunctionality)
- Engineered manufacturing (effects of defects)
- Physics-based failure analysis (beyond “strength” criteria)
- Integrated computational materials engineering (ICME)

Integrated Computational Materials Engineering (ICME)



Manufacturing process simulation

Materials Information

Quantitative processing-structure relationships

Chemistry
Thermodynamics
Structure evolution

Computational materials science

Curated data sets

Quantitative structure-property relationships

Density functional theory
Molecular dynamics
Micromechanical models

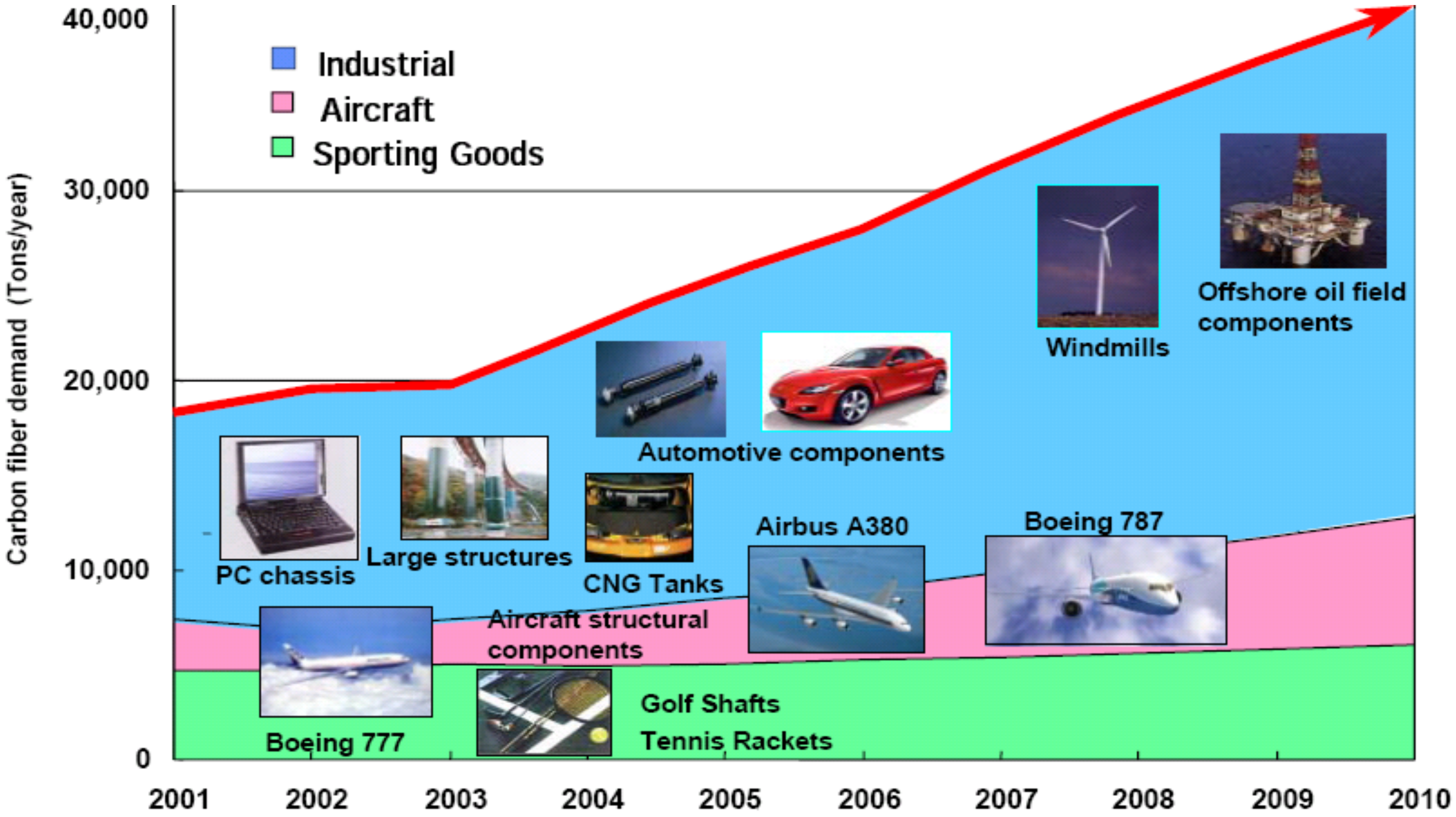
Material constitutive models

Engineering product performance analysis

Finite element analysis
Computational fluid dynamics

PROCESS/PRODUCT OPTIMIZATION

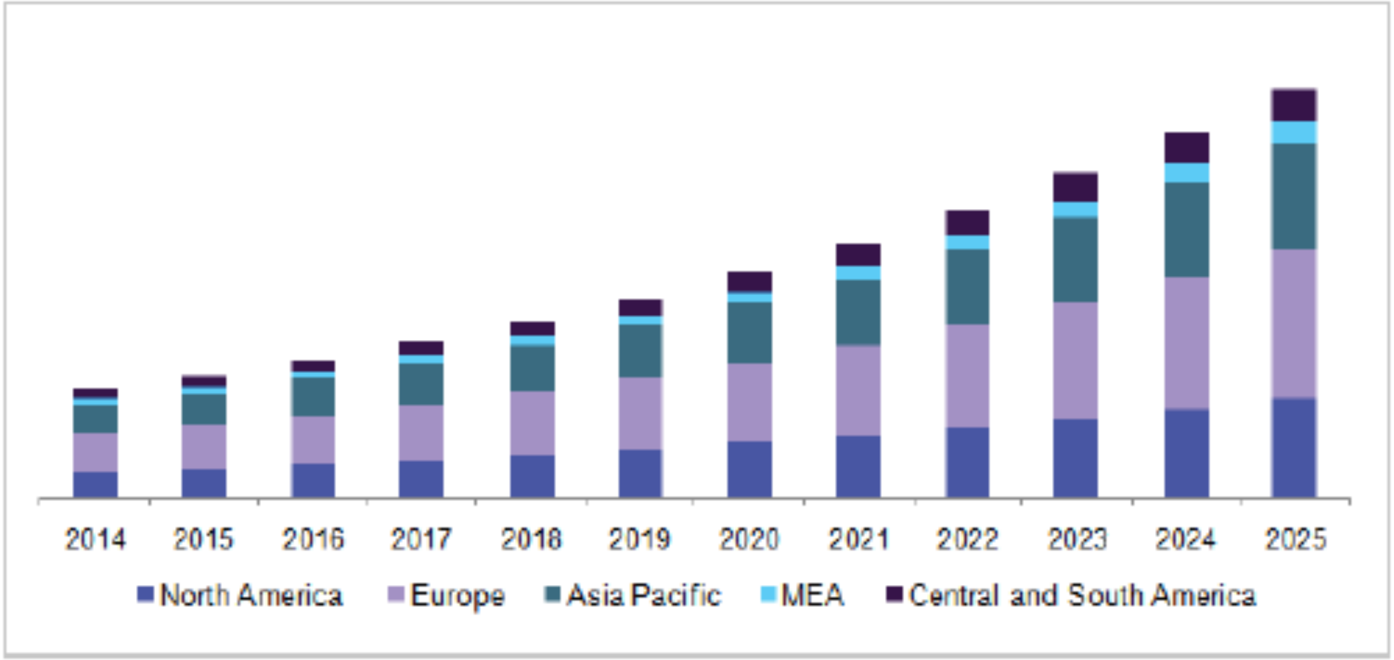
Market expansion of carbon fibers



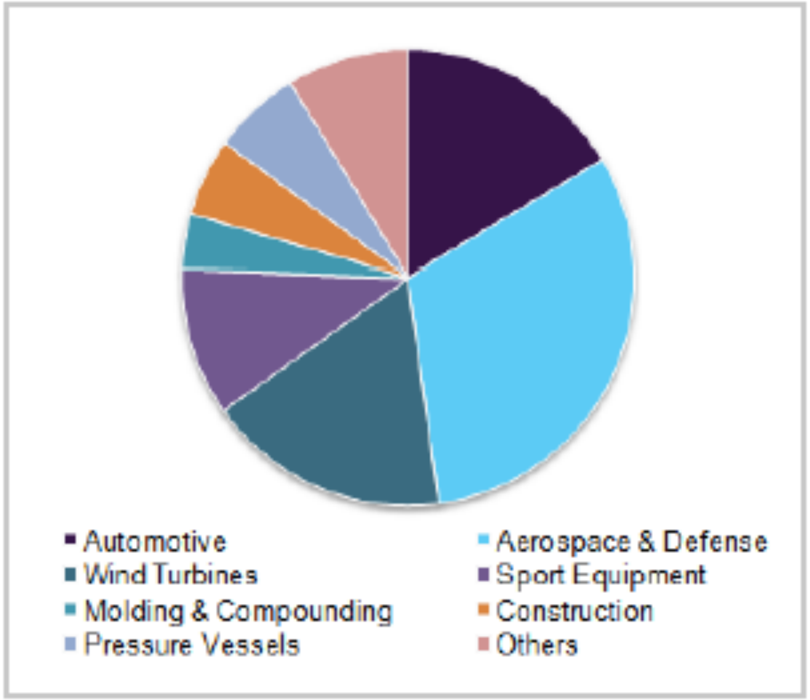
Source: Toray.com

Continuing expansion of carbon fiber usage

Carbon fiber market volume by region, 2014 - 2025 (Tons)

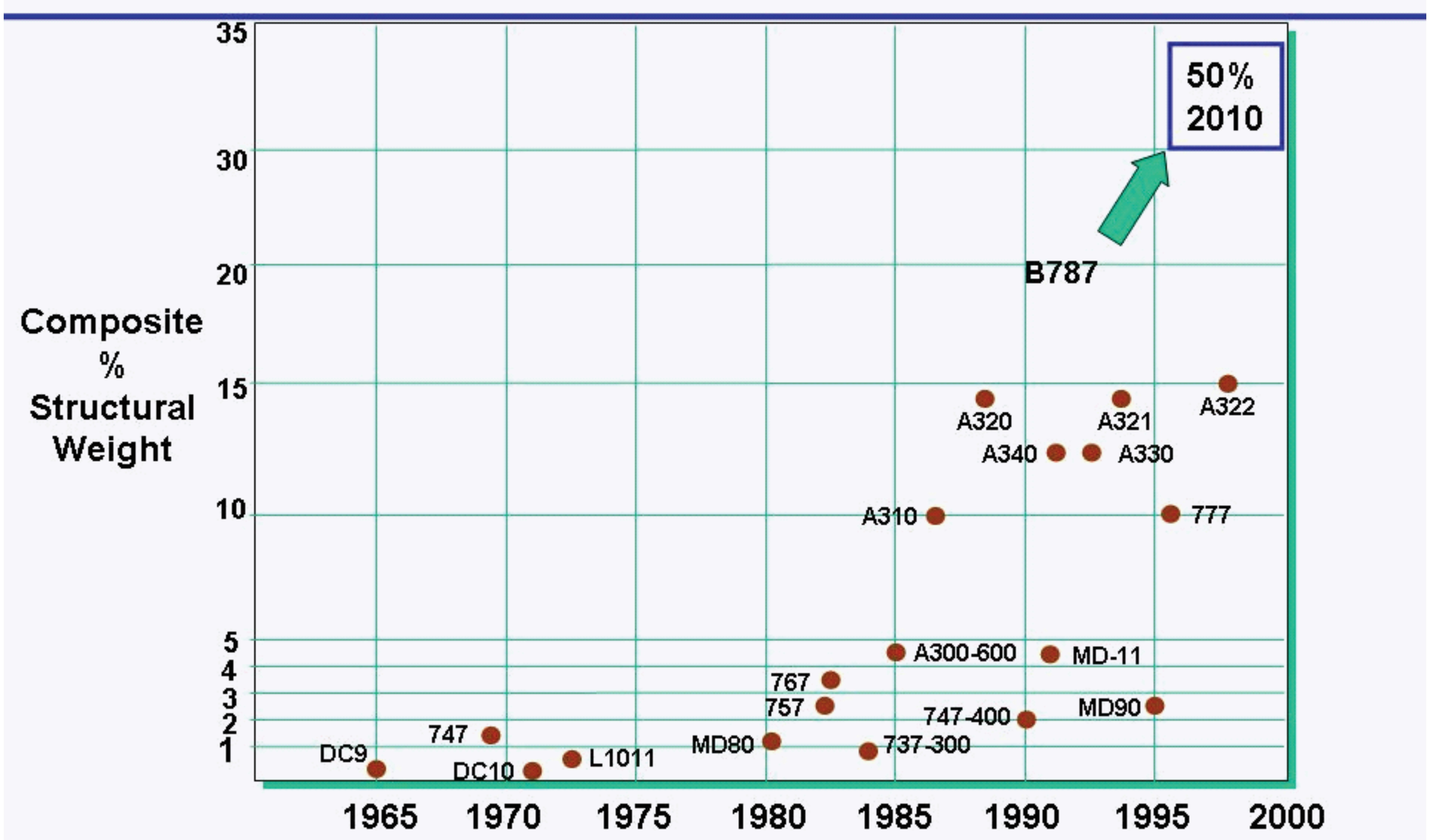


Global carbon fiber market volume share by application, 2016 (%)

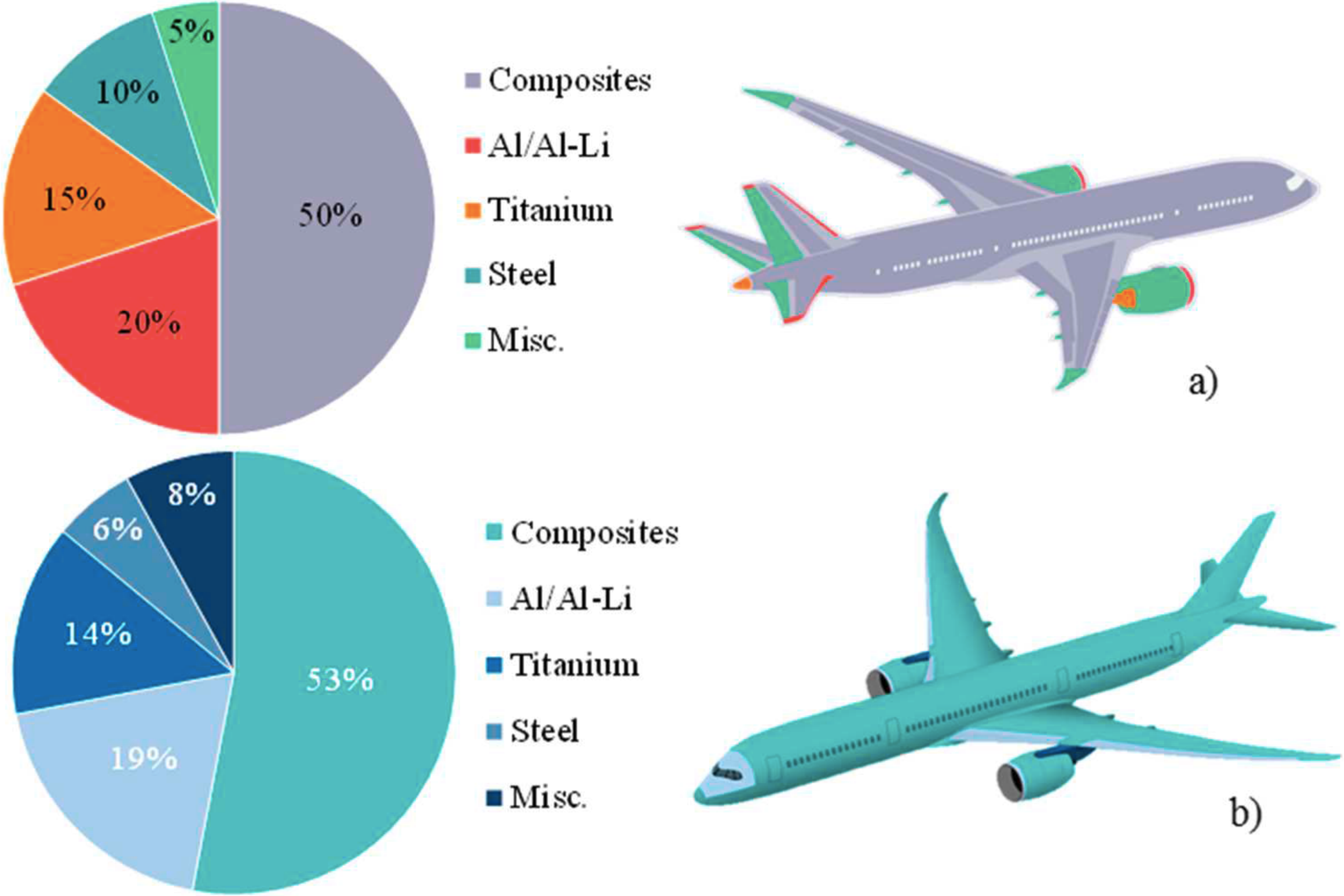


Source: Toray.com

Composites in Commercial Aircraft

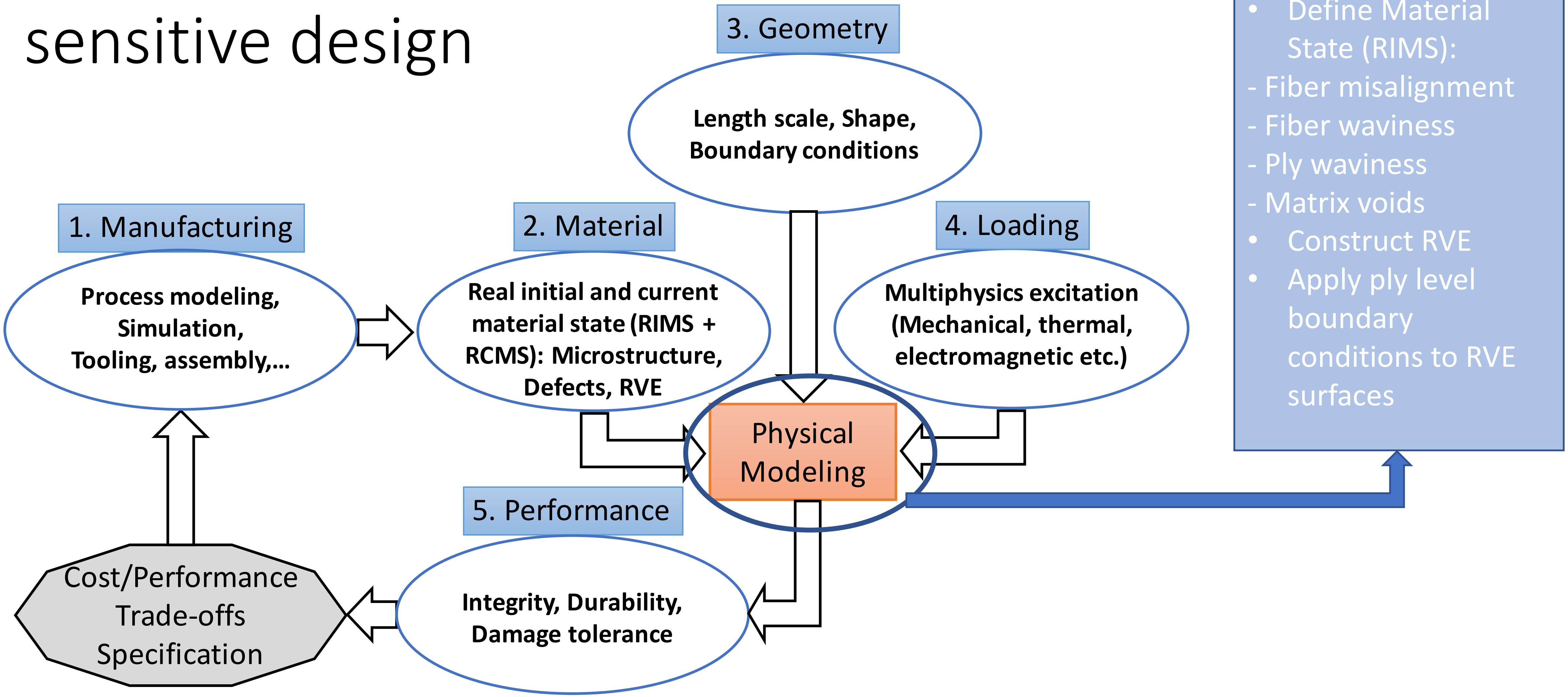


Boeing B787



a) Boeing B787 b) Airbus A350

The "Big Picture" of manufacturing sensitive design



3. Geometry

Length scale, Shape, Boundary conditions

1. Manufacturing

Process modeling, Simulation, Tooling, assembly,…

2. Material

Real initial and current material state (RIMS + RCMS): Microstructure, Defects, RVE

4. Loading

Multiphysics excitation (Mechanical, thermal, electromagnetic etc.)

Physical Modeling

5. Performance

Integrity, Durability, Damage tolerance

Cost/Performance Trade-offs Specification

- Define Material State (RIMS):
  - Fiber misalignment
  - Fiber waviness
  - Ply waviness
  - Matrix voids
- Construct RVE
- Apply ply level boundary conditions to RVE surfaces

Manufacturing methods for polymer matrix composites

- Manual methods (No process control)

- Hand layup
- Spray layup
- Manual prepreg layup

- Automated methods (Fiber dominated, limited process control)

- Filament winding
- Fiber and prepreg placement (multiple axes of motion)
- Pultrusion

Manufacturing methods for polymer matrix composites, continued

- Various molding methods with fiber and textile preforms

- RTM (resin transfer molding)
- VARTM (vacuum-assisted RTM)
- Resin film infusion
- \-

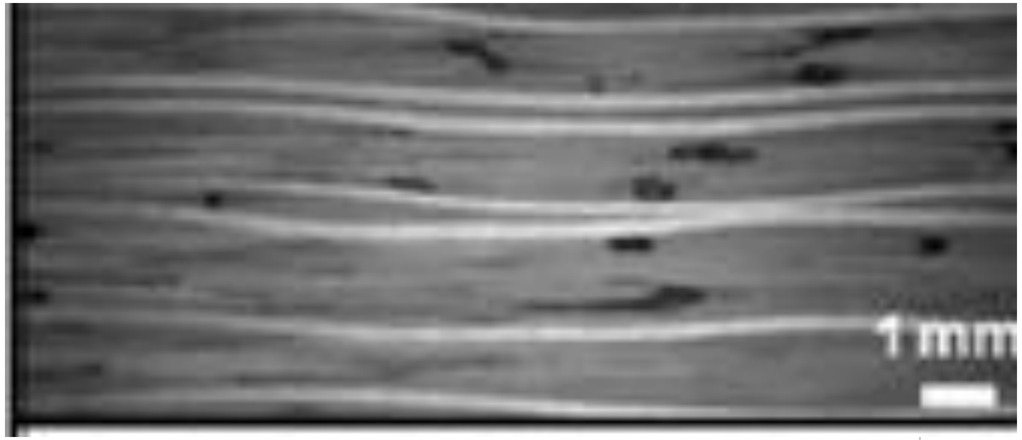
- Thermoforming

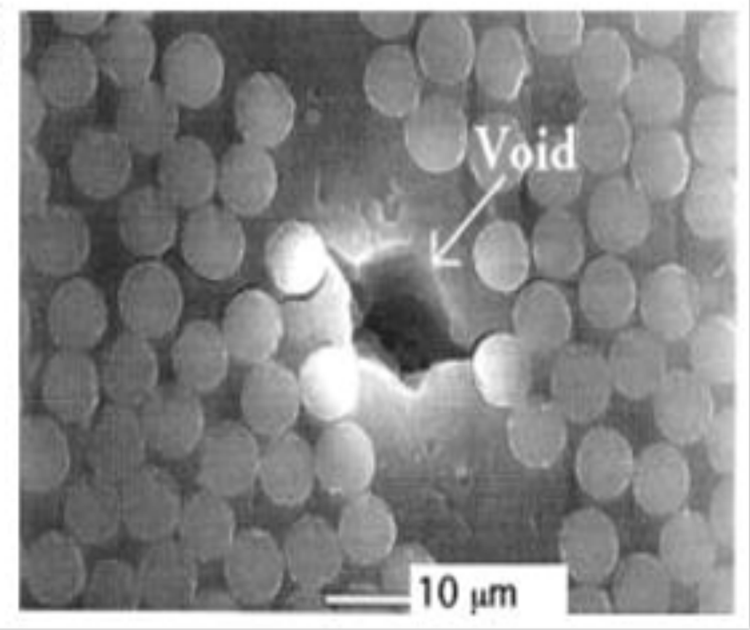
Process control varies depending on the method and cost

Labor intensive manufacturing process

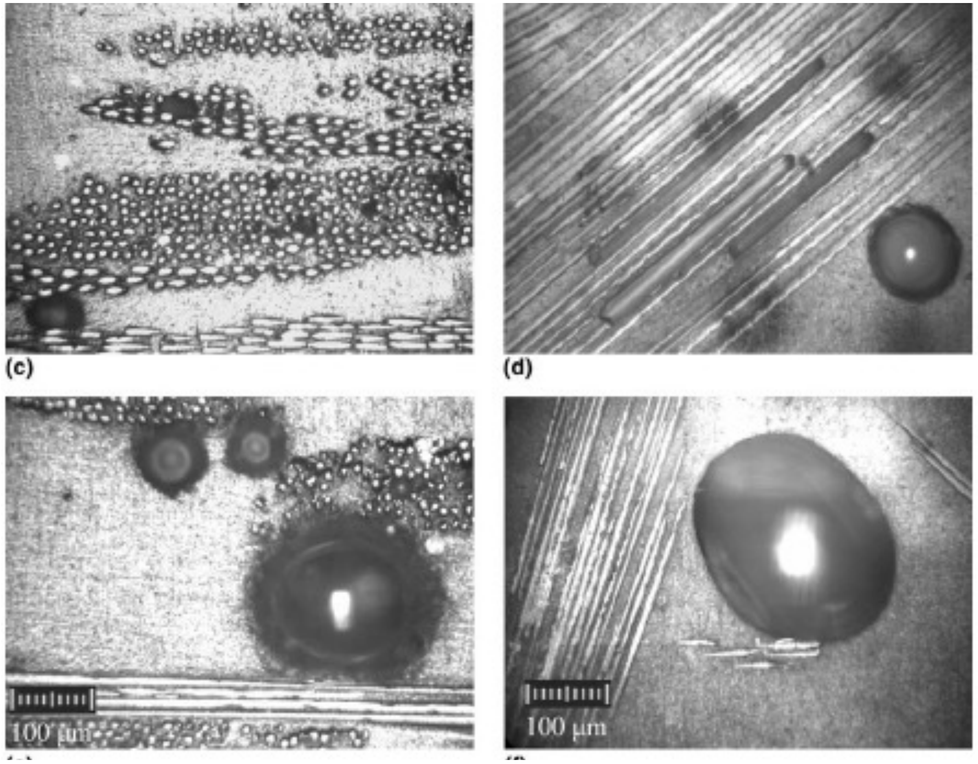
Cairns, et al, Sandia Report, 2011

Manufacturing defects: Voids



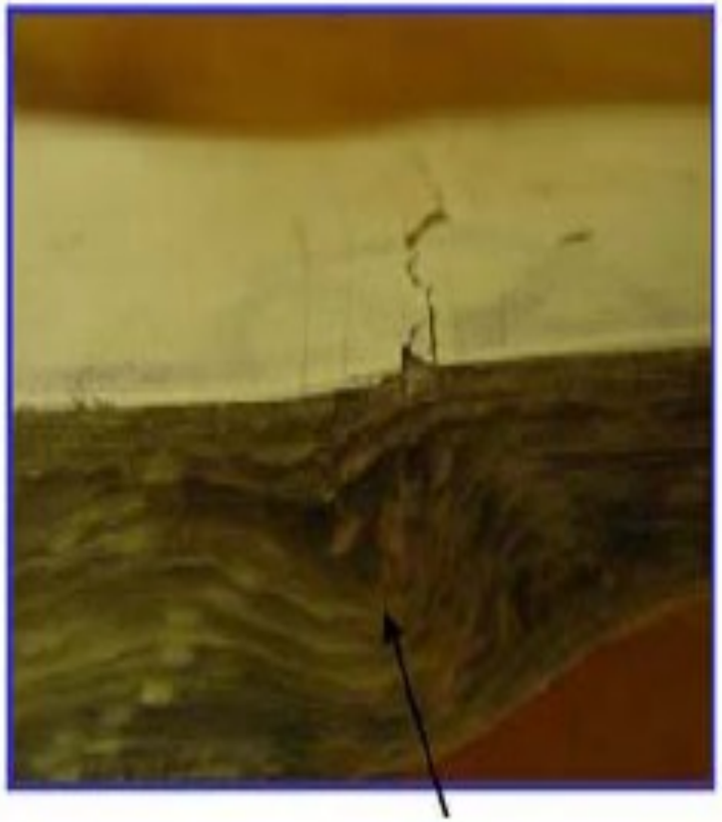


Moisture induced voids



RTM induced voids

Manufacturing defects: Fiber waviness and misalignments



Defects in large wind turbine blades

Cairns, 2009

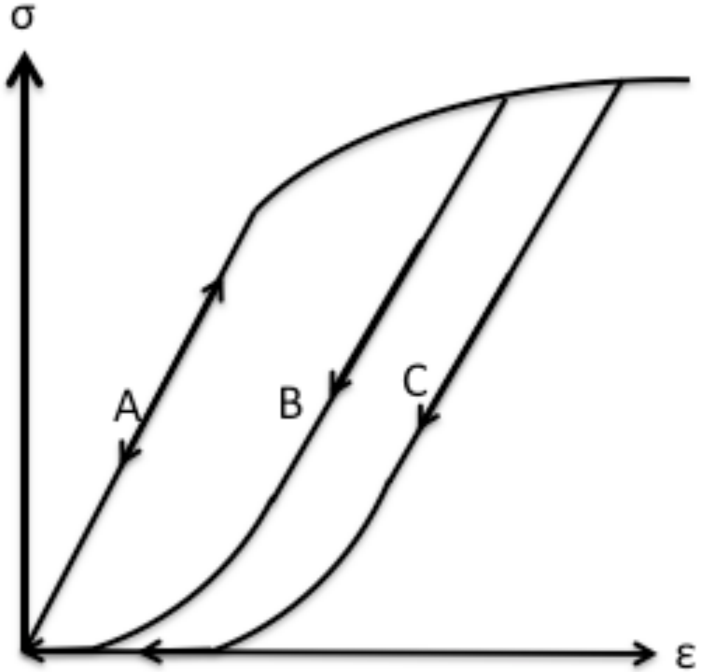
Fundamentals of deformation and failure

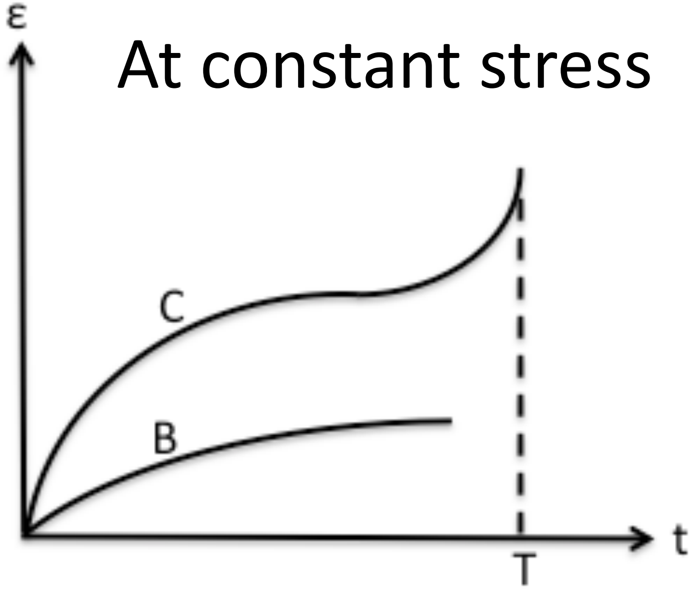
- ➔ Elasticity
- ➔ Plasticity
- ➔ Visoelasticity
- ➔ Viscoplasticity
- ➔ “Strength”
- ➔ Fracture
- ➔ Damage

Relevance of the fundamentals to understanding of fatigue

- Fatigue can only occur if *IRREVERSIBILITY* exists
- Irreversibility, which is manifestation of energy dissipation, causes material response to change from the first load application to the next
- Accumulation of this change can become critical, causing fatigue failure

Characteristics of deformational response

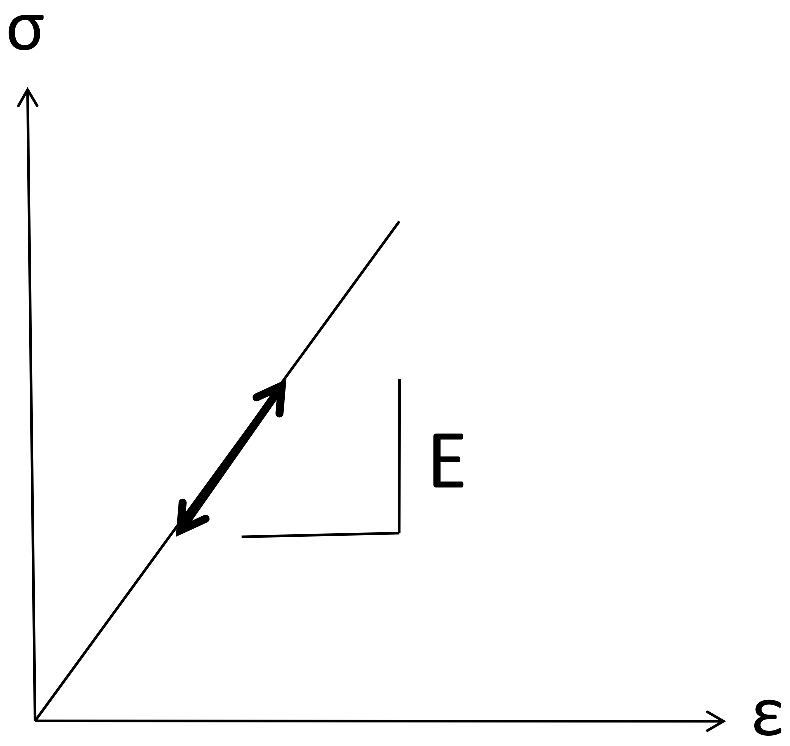



At constant stress

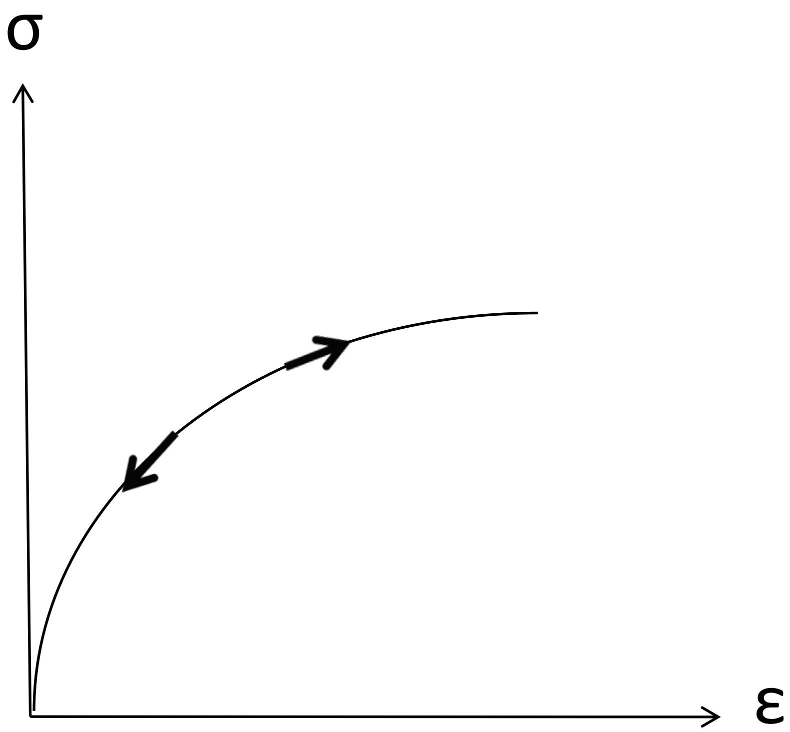
t = time
T = time to rupture

A: Time-independent Reversible (Elasticity)
B: Time-dependent Recoverable (Viscoelasticity)
C: Time-dependent Irrecoverable (Viscoplasticity)

Elasticity

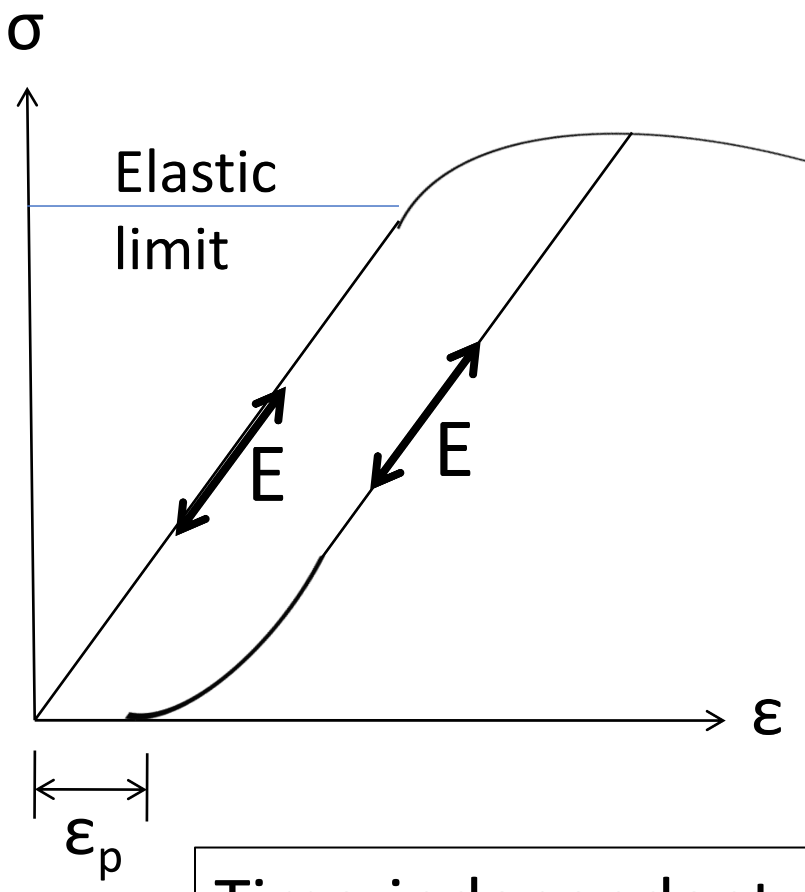


Linear: Typical of metals and ceramics



Nonlinear: Typical of rubbers and elastomers

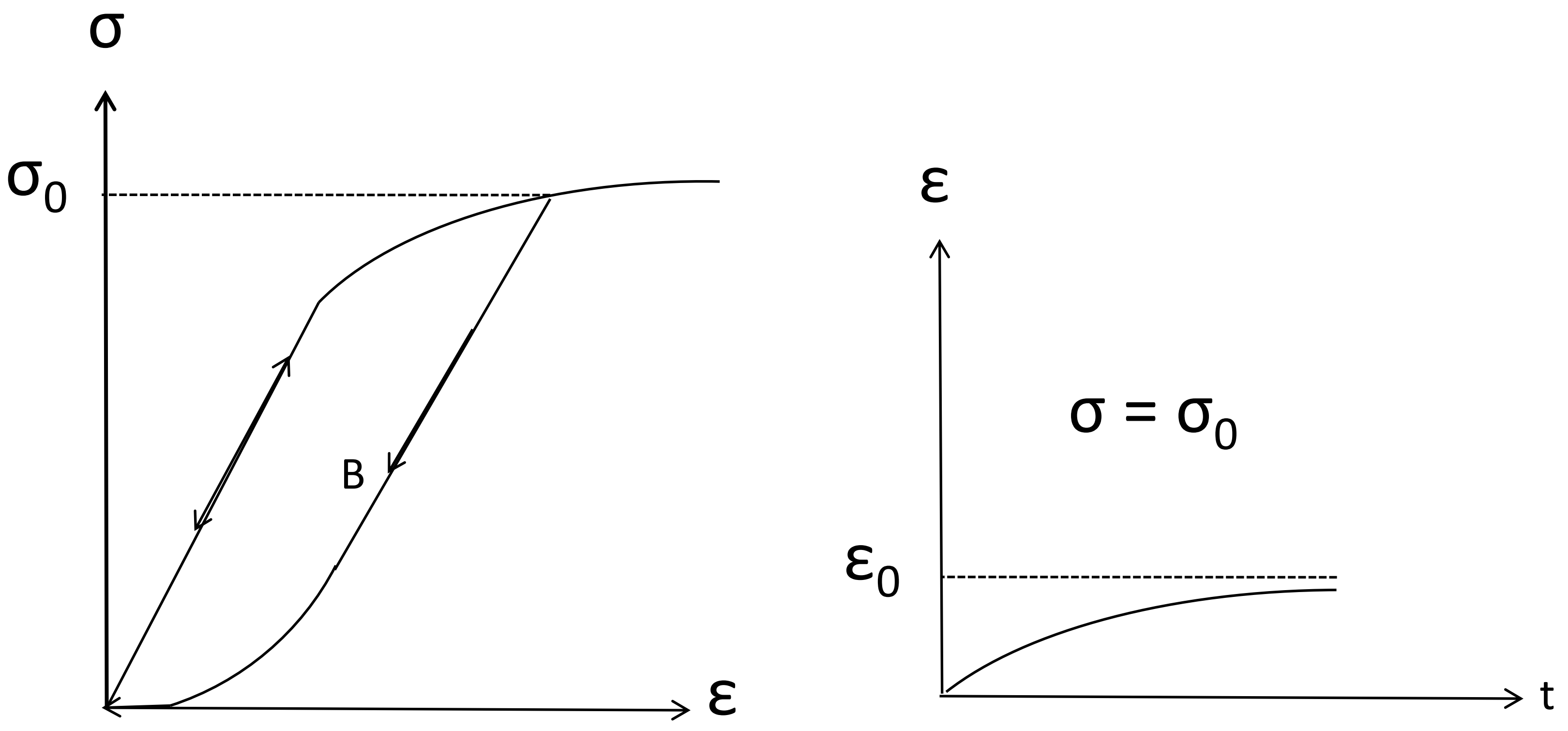
Plasticity



Typical of polycrystalline materials (e.g. metals) where energy dissipation in dislocation motion takes place

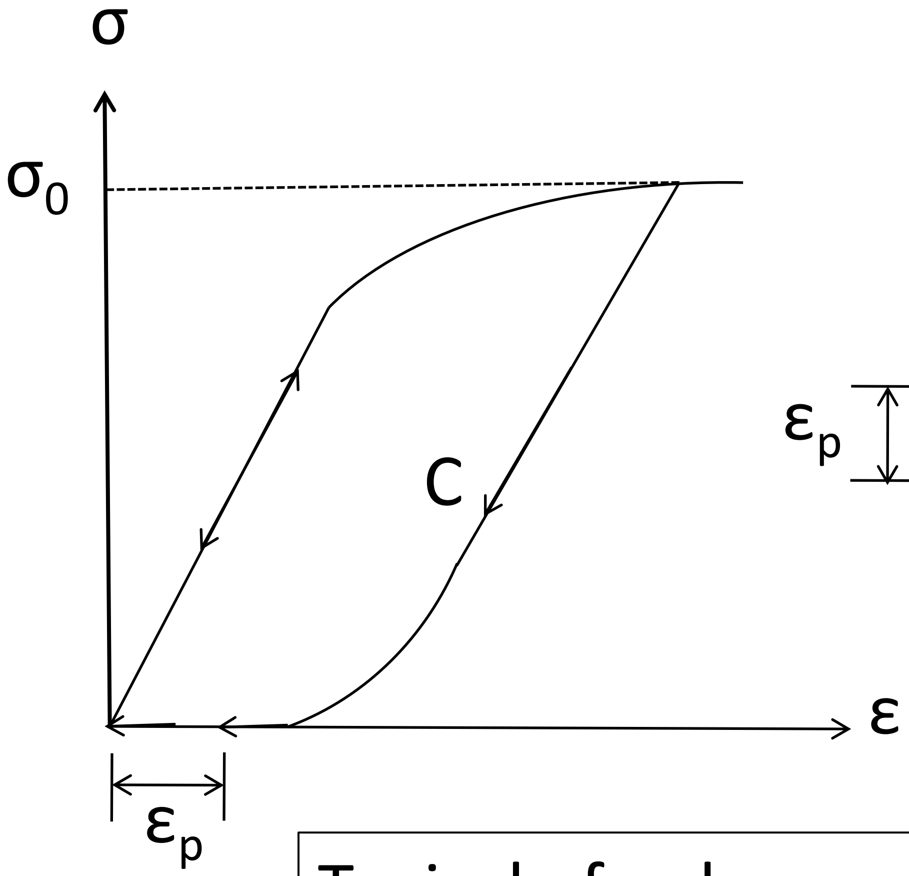
Time-independent permanent strain on unloading

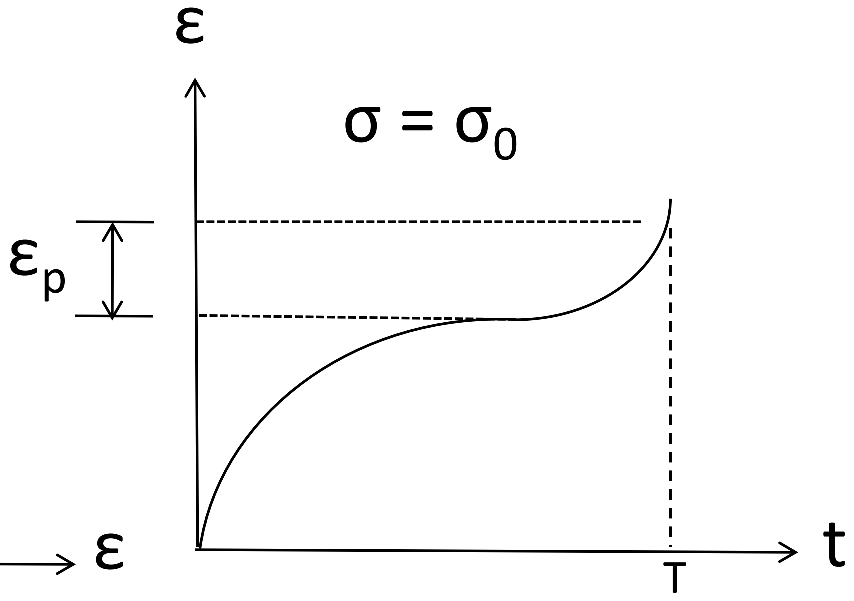
Viscoelasticity



Typical of polymers in which internal changes can be recovered in time

Viscoplasticity





Typical of polymers in which internal changes are only partly recovered in time

How about composites?

The deformation behavior described for homogeneous materials must be understood as it applies to heterogeneous materials.

Following observations are useful.

- Fibers are (linear) elastic
- Matrix is constrained by (stiff) fibers, and is therefore generally under triaxial stress state
- Interfaces exist

Sources of irreversibility in polymer matrix composites

- Fiber breakage (dissipation of fracture surface energy)
- Matrix viscoplasticity (dissipation as hysteresis energy)
- Fiber/matrix interface failure (dissipation of fracture surface energy)
- Interlaminar cracking in laminates (dissipation of fracture surface energy)

Fracture and Damage (definitions)

- Fracture:

Formation of surfaces by breakage of bonds (cracks)

- Damage:

Collective reference to all energy dissipating events

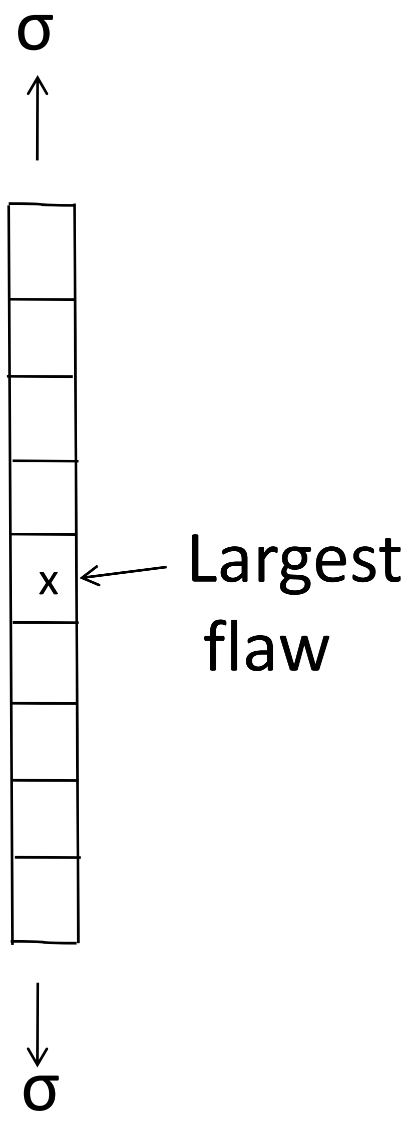
(multiple fracture, irrecoverable internal changes, etc)

“Strength”: What is it for composites?

- Composites do not fail at a specific value of applied stress, but have a sequence of “failure events” depending on the failure mode.

- As examples, let us look at failure of unidirectional composites under axial tension, axial compression and in-plane shear

Single fiber failure in axial tension



Fiber failure from random flaws

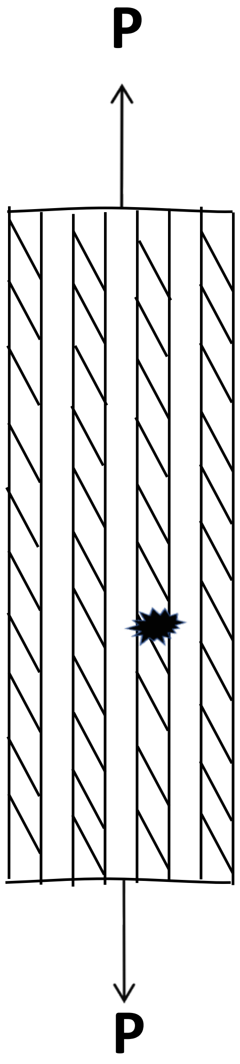
Weakest-link theory (Weibull, 1939):

Probability of fiber failure

$$P_f = 1 - \exp\left(\frac{\sigma - \sigma_0}{\sigma_c}\right)^c$$

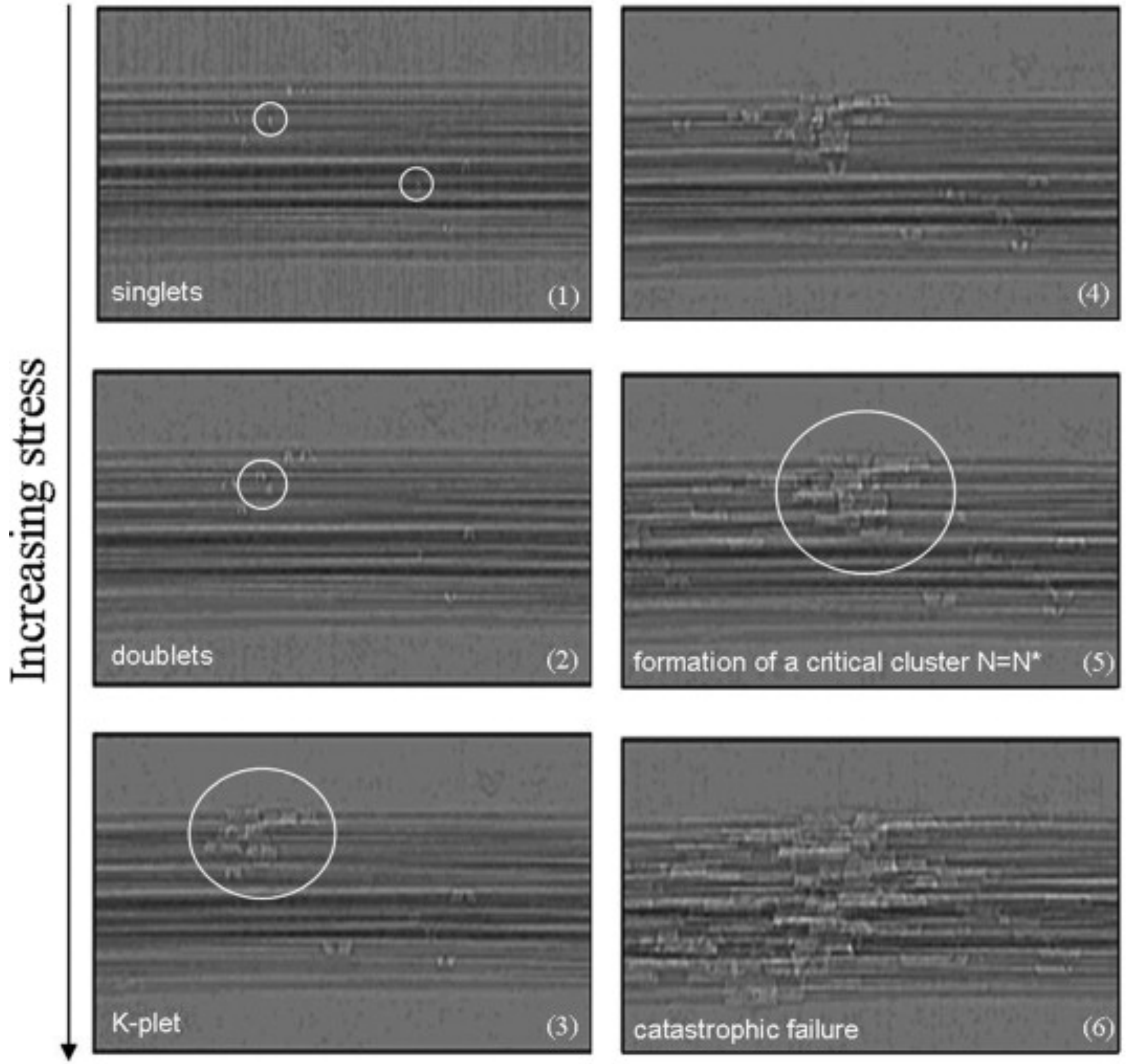
σ_0 = minimum fiber strength
σ_c = characteristic fiber strength
c = distribution shape parameter

Fiber bundle failure



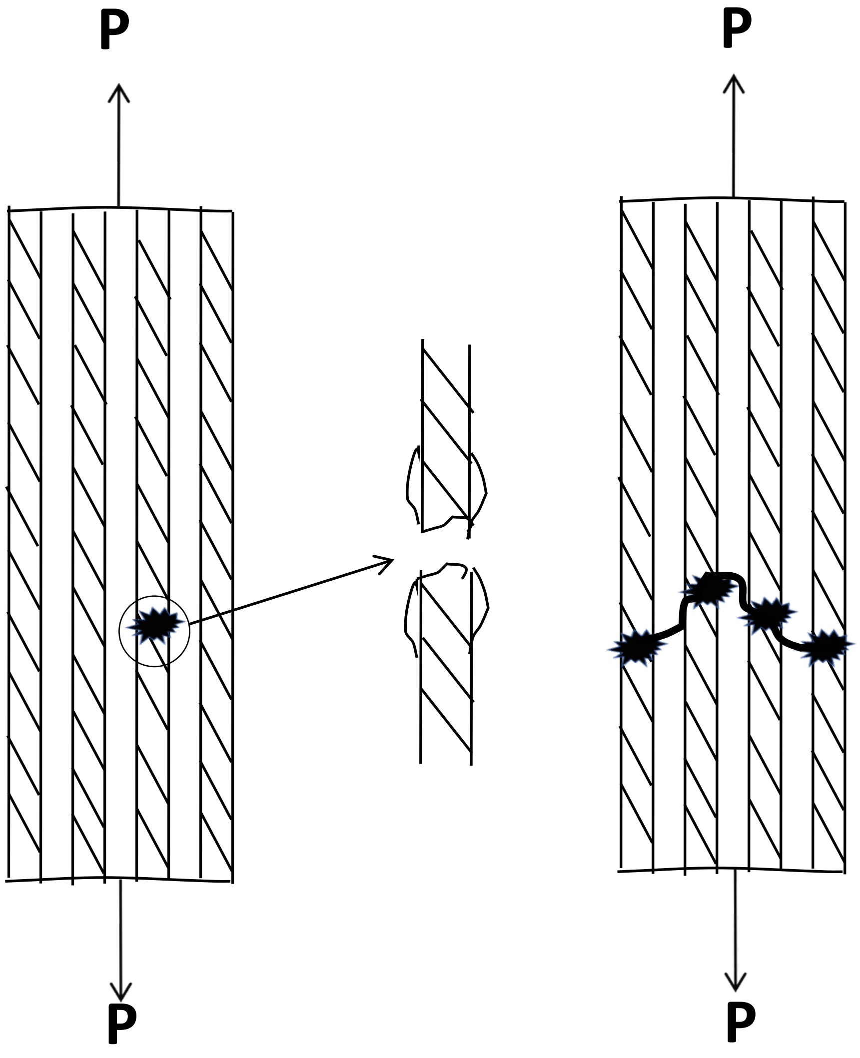
Sequence of fiber failures:
Weakest fiber fails first,
Surviving fibers share load equally,
Next weakest fiber fails next, etc.

Observed fiber failure process



Aroush et al
2006

Final failure from fiber breakage in a composite under increasing load

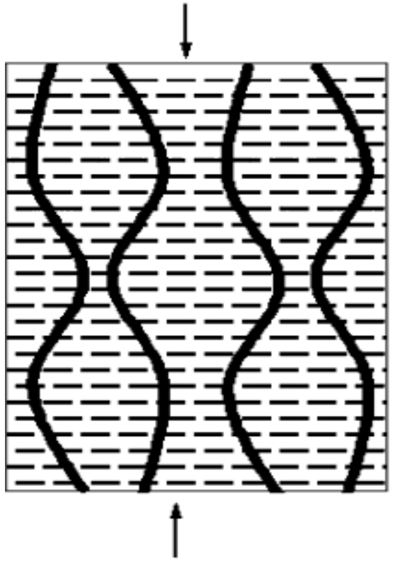


Final failure occurs from unstable growth of a "core" formed by a cluster of broken fibers.

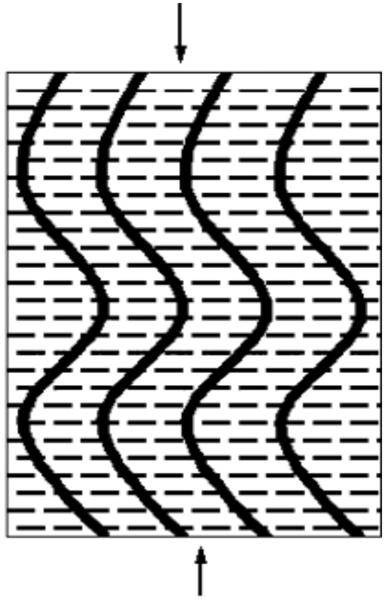
Matrix deformation and failure, and fiber/matrix debonding, play roles.

Failure in axial compression

- Fiber misalignment plays a major role
- Matrix inelasticity in shear governs failure Initiation
- Final failure governed by fiber failure

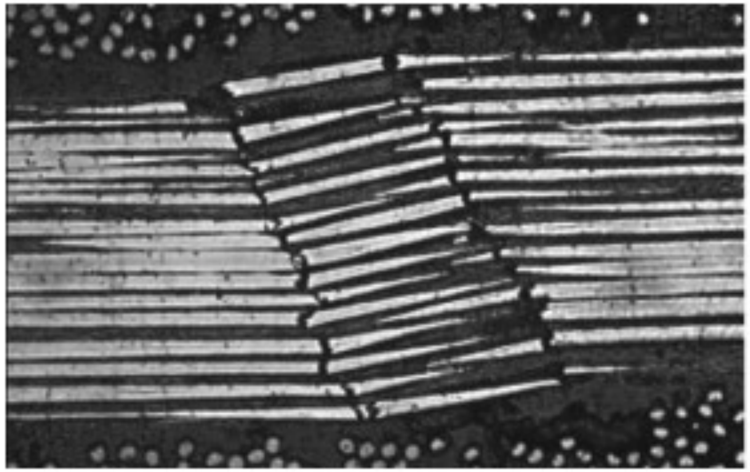


Extensional Mode

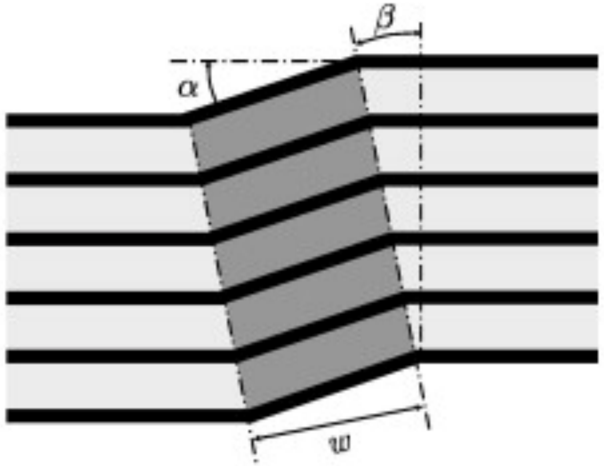


Shear Mode

More likely failure initiation mode



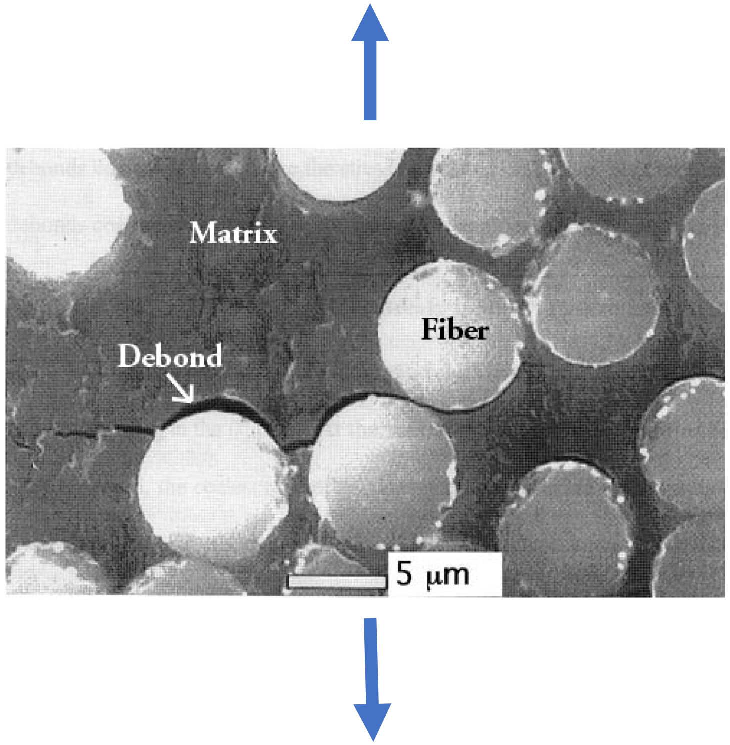
(a) Micrograph from experiments in CFRP [1].

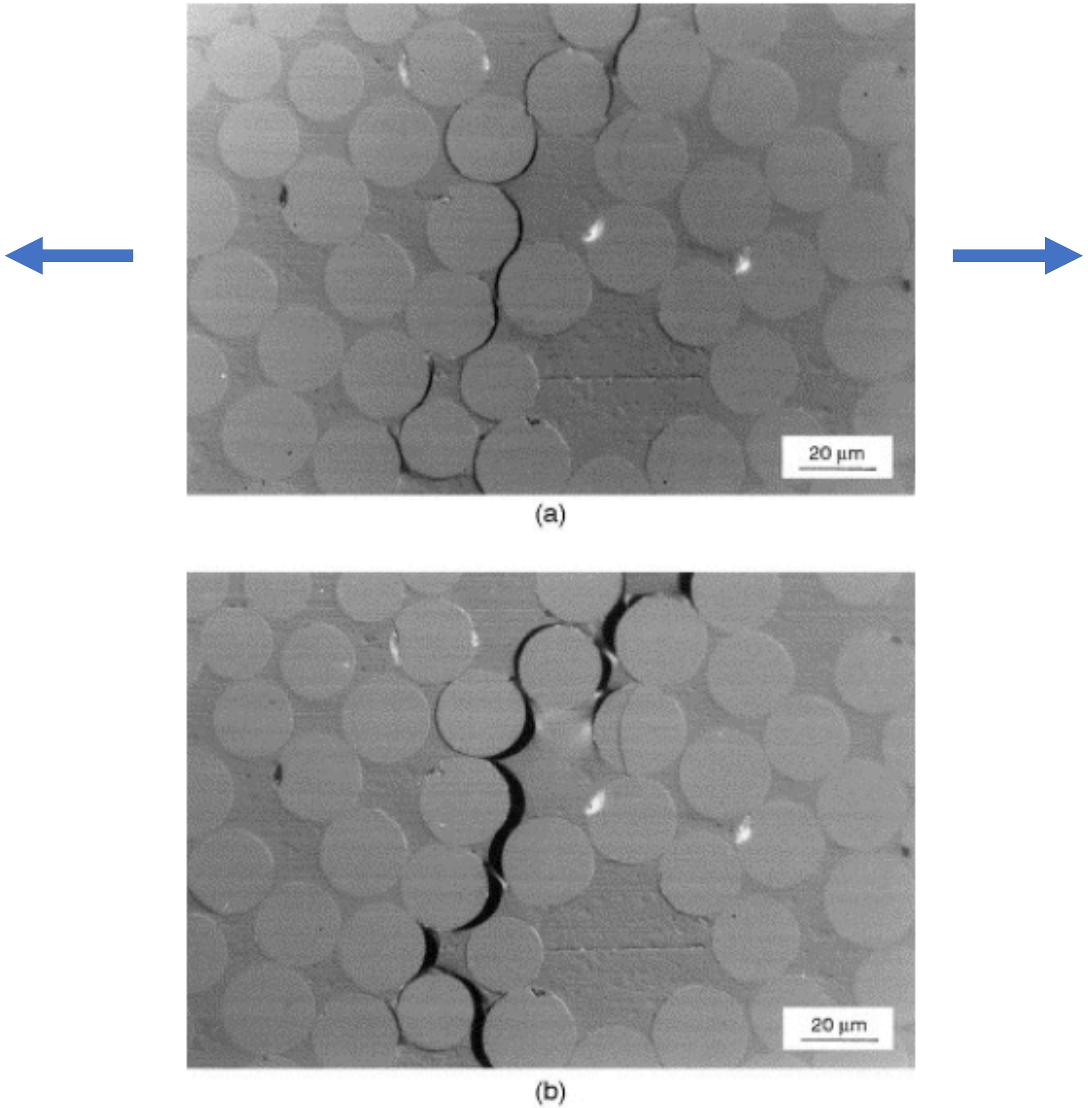


(b) Schematics and definition of the kink–band geometric parameters: fibre angle α, band angle β, and band width w.

Failure from kink band in shear mode

Failure in transverse tension

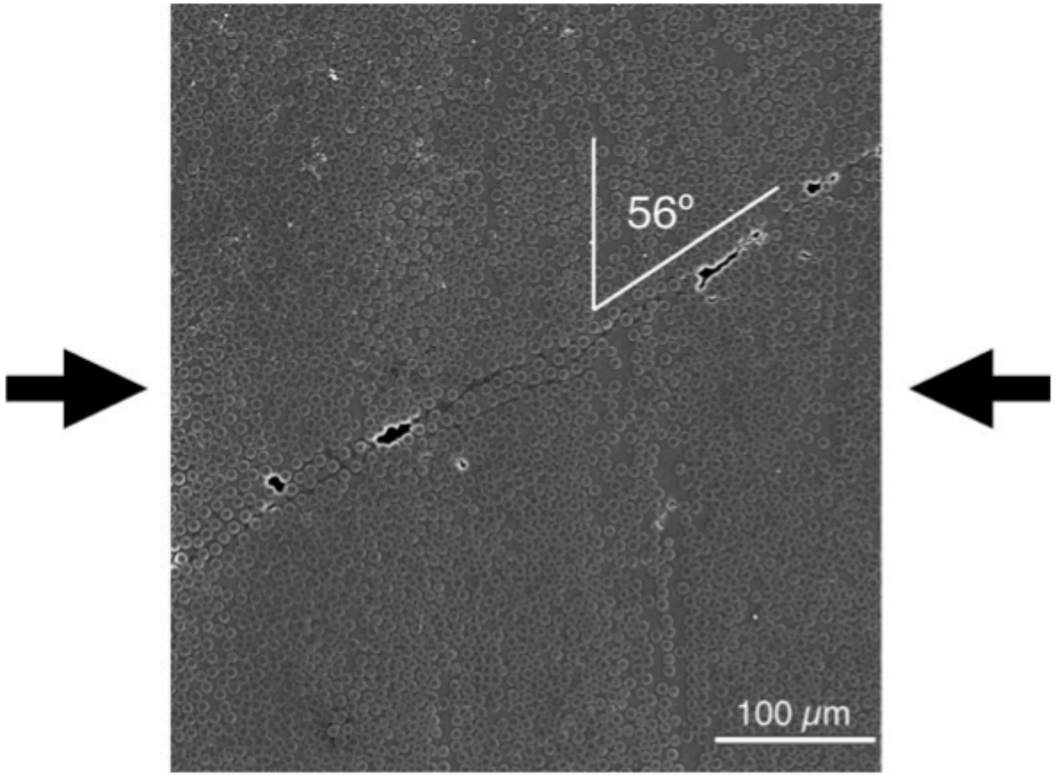




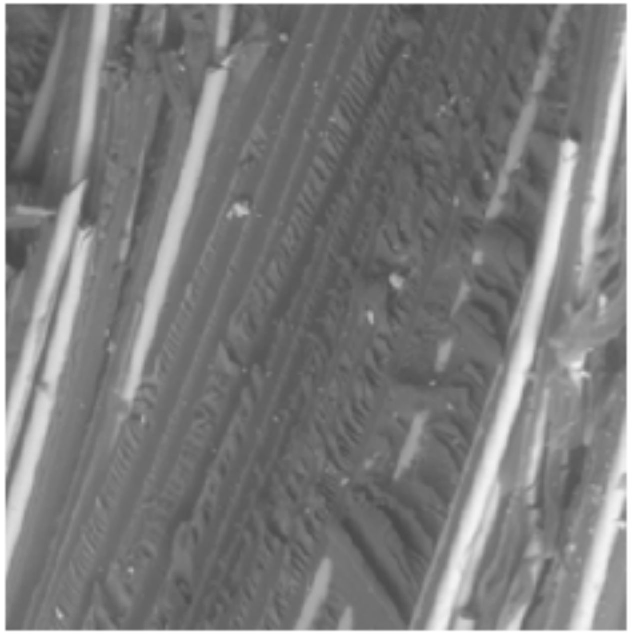
Sequence of failure events:

- Fiber-matrix debonding
- Link-up of debond cracks
- Crack growth, stable, then unstable to failure

Failure in transverse compression

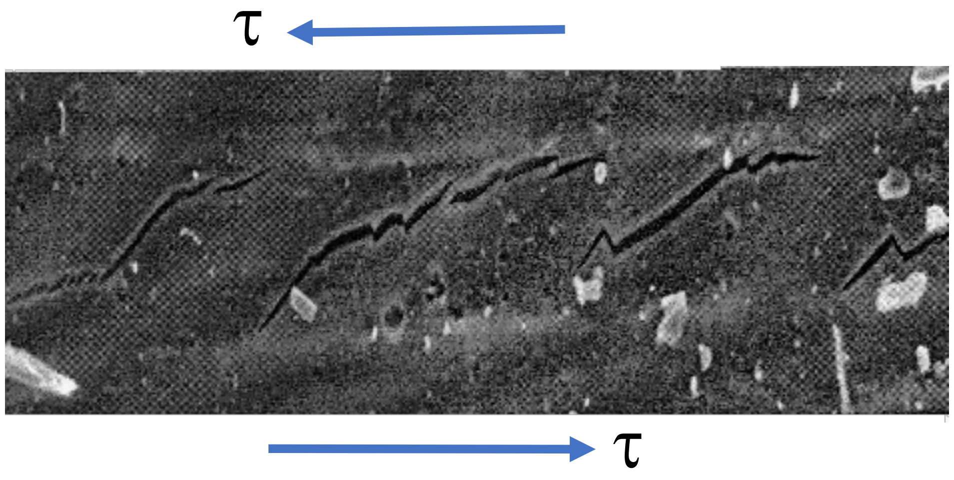


Gonzalez and Llorca, 2007

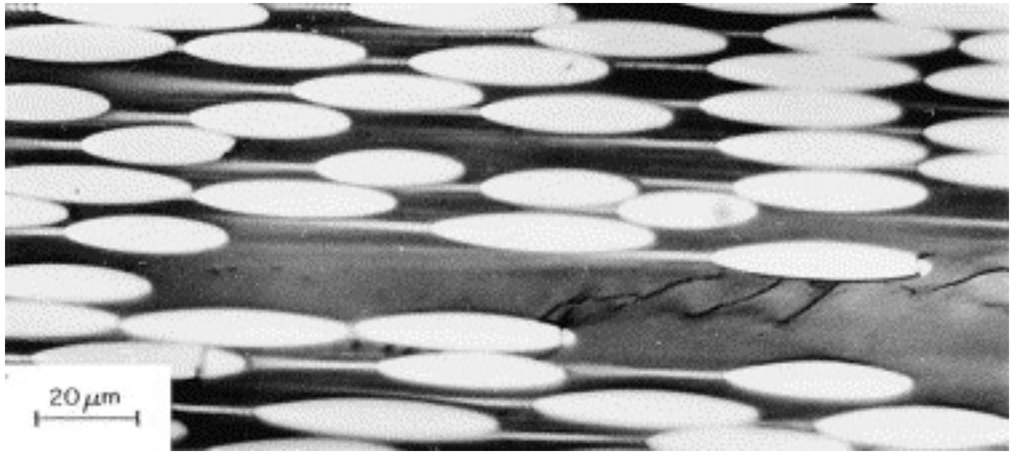


Fracture surface shows evidence of Failure by shear (hackles)

Failure in “axial” shear



Redon (2000)

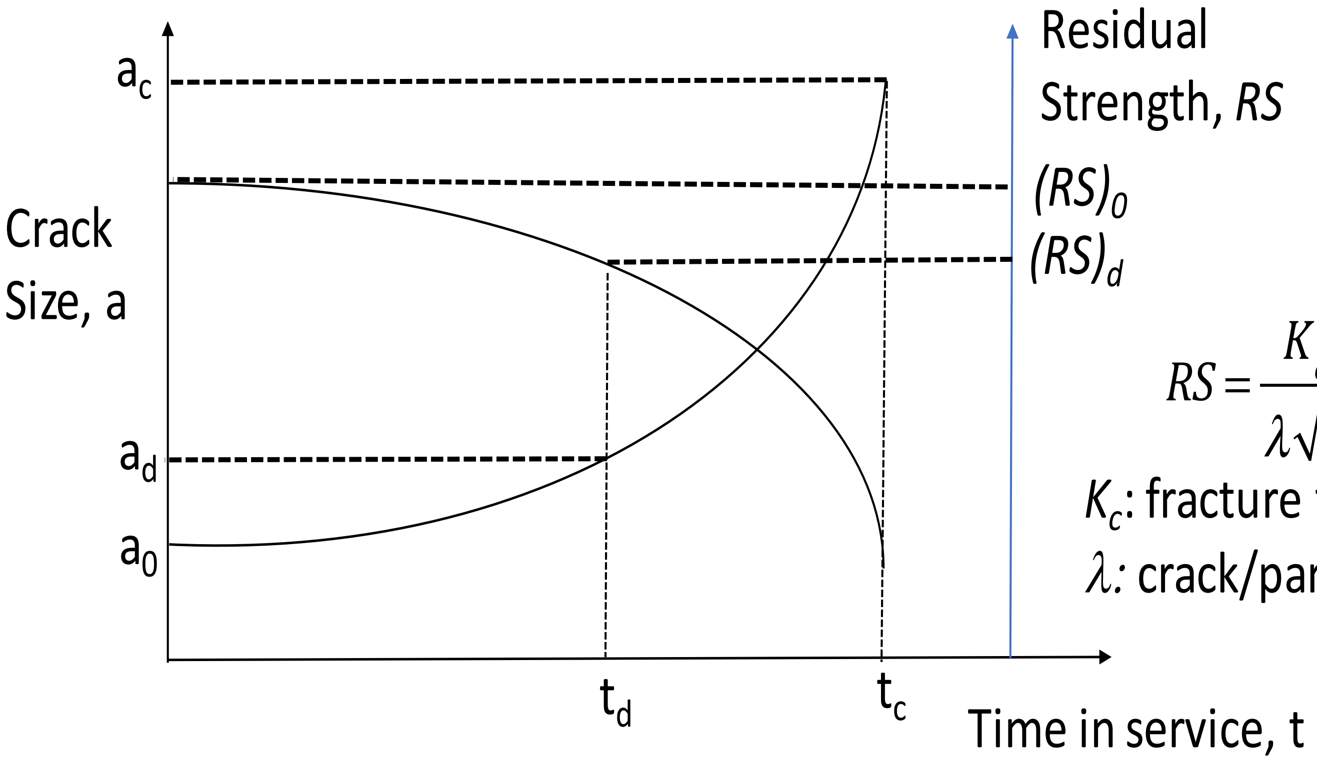


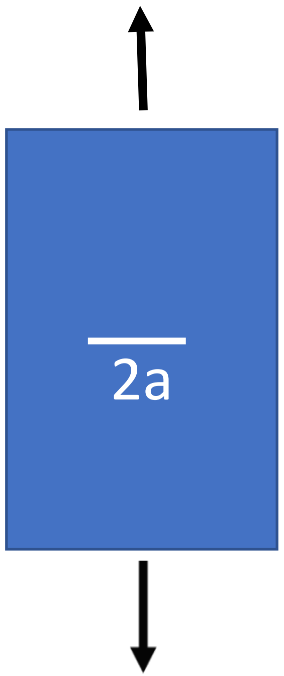
Plumtree and Shi (2002)

Key features

- Multiple, inclined cracks of “Sigmoidal” shape
- Cracks connect near fiber surfaces to form “fracture plane”
- Fracture surface shows hackles

“Strength” and “Residual strength” for a part with a crack





$$RS = \frac{K_c}{\lambda\sqrt{a}}$$

K_c: fracture toughness

λ: crack/part geometry factor

Does this apply to composites?
(Or any heterogeneous solid)

Modeling strategies: Phenomenological vs. mechanisms based

- Following metal fatigue, many empirical and semi-empirical approaches have been proposed. None works reliably.
- Since there is no single crack growth, fracture mechanics type approaches (Paris crack growth laws) are not applicable except for delamination (even that is problematic).
- Mechanisms based approach is the only rational way. It requires experimentation (observations, measurements), simulations, and analysis.

Most of all, it requires thinking composites, not metals!