Modeling and Simulations of Aircraft Structures – Stiffness, Damage, and Failure Prediction for Laminated Composites

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funded the Austrian Ministry of Economics and Labour

Related Publications by ILSB

Daxner T., Luxner M.H., Rammerstorfer F.G.: *Thermo-mechanically interacting composite pipes optimised by genetic algorithms*; in Proc. “11th European Conference on Composite Materials”, Paper C041, European Society of Composite Materials, London, UK, 2004.

Pahr D.H., Rammerstorfer F.G.: *A fast multi-scale analysing tool for the investigation of perforated laminates*; Comput. and Struct., **82**, 227-239, 2004.

Pahr D.H., Rammerstorfer F.G.: *Experimental and numerical investigations of perforated CFR woven fabric laminates*; Comp.Sci.Tech., **64**, 1403-1410, 2004.

Pahr D.H., Schuecker C., Rammerstorfer F.G., Pettermann H.E.: *Numerical Investigations of Perforated Laminates in the Presence of Residual Ply Stresses;* J.Comp.Mater., **38**, 1977-1991, 2004.

Schuecker C., Pahr D.H., Pettermann H.E.: *Numerical Simulation of Composite Structures – First Ply Failure under Non-Proportional Loading;* in “6th International Conference on Mesomechanics”, (Eds. Sih G.C., Kermanidis T.B., Pantelakis S.G.), Patras, Greece, May/June, 2004.

Pahr D.H., Seitzberger M., Rammerstorfer F.G., Böhm H.J., Billinger W.: *Global/Local Analysis of the Stiffness and Failure Behavior of Perforated Laminates*; in Proc. “Seventh Annual Interantional Conference on Composites Engineering”, (Ed. Hui D.), Denver, Colorado, 2000.

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Abstract

Properties of advanced composite materials are governed by the interaction of the constituents on various length scales. Hierarchical modeling concepts for constitutive descriptions and structural analyses are presented by means of examples.

For perforated laminates the overall stiffness and the first ply failure strength is predicted by a unit cell type approach. An integrated tool consisting of a pre-processor, a commercial FEM-solver, and a post-processor is developed. The configuration of the holes as well as the effect of their free surfaces is evaluated. In a further step, the obtained material data are used for structural analyses of components containing such perforated laminates.

Tools for first ply failure predictions under combined load scenarios are developed. Various load cases are classified as being either constant or variable, giving more detailed information on the risk for failure. The use of Puck's criterion allows the prediction of the failure mode additionally. The tool is hooked up to a commercial FEM-package as a post-processing routine, to perform structural analyses and failure predictions of complex shaped and loaded components.

A modeling concept for the prediction of progressive damage is developed. For the onset of damage the previous failure models are adapted accordingly. The damage evolution and the stiffness degradation are described by forth order tensors based on continuum damage mechanics. The model is implemented as a constitutive material law on ply level. It is general in conception, allowing for damage evolution for various causes, such as monotonic quasi-static loading, fatigue loading, etc.

Outline

- Overview ILSB
- First Ply Failure (FPF) concept
  - combined stress states
- Hierarchical Modeling
- Progressive damage of laminates
  - continuum damage modeling
- Summary

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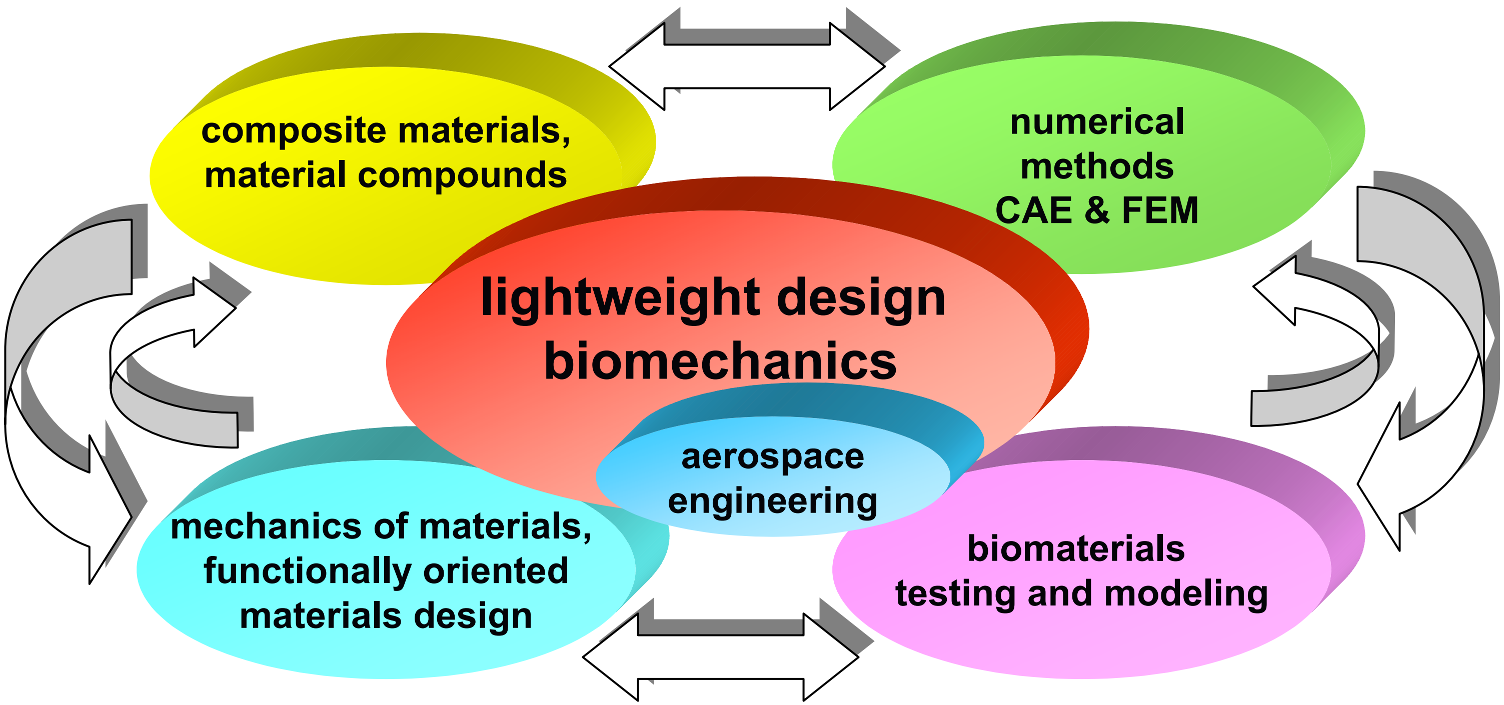

SHORT INTRODUCTION TO THE ILSB

- Scientific staff
  - 2 professors + 2 associates + 4 assistants funded by university, approx. 6 researches funded externally
- Research fields
  - lightweight structures, computational methods, micromechanics of materials, biomechanics, aerospace engineering
- Emphasis on cooperation with industrial and international partners
  - projects with industry
  - EU programs
  - Austrian programs (e.g. CDL)
  - Austrian Aeronautics Research - competence network

MATERIALS-RELATED RESEARCH FIELDS

development and application of continuum mechanics models for lightweight structures and advanced materials

- models' length scales span from size of constituents in inhomogeneous materials to structural level
  - hierarchical models (micro-meso-macro approach)
  - advanced materials – composites, cellular materials, graded materials
  - nonlinear behavior – stiffness, strength, damage, conductivity, ...
- computational simulation tools
  - numerical – Finite Element Method
  - (semi)analytical models are used where possible
- testing of biomaterials (micro- and nanomechanics)

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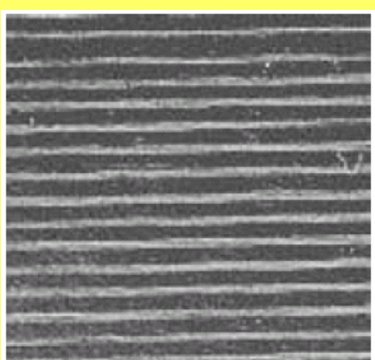
Modeling scales

structure

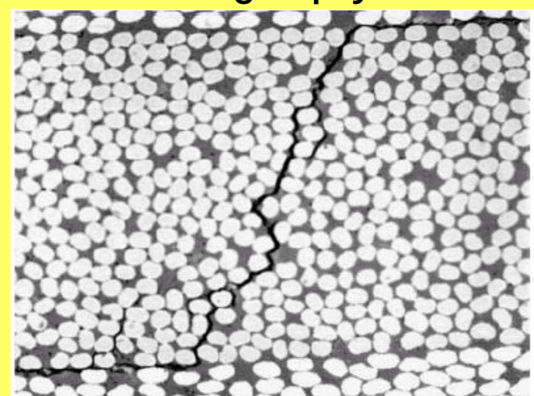
macro scale

laminate



[Yousefpour et al, 2004]

single ply



[Lafarie-Frenot et al, 2001]

meso scale

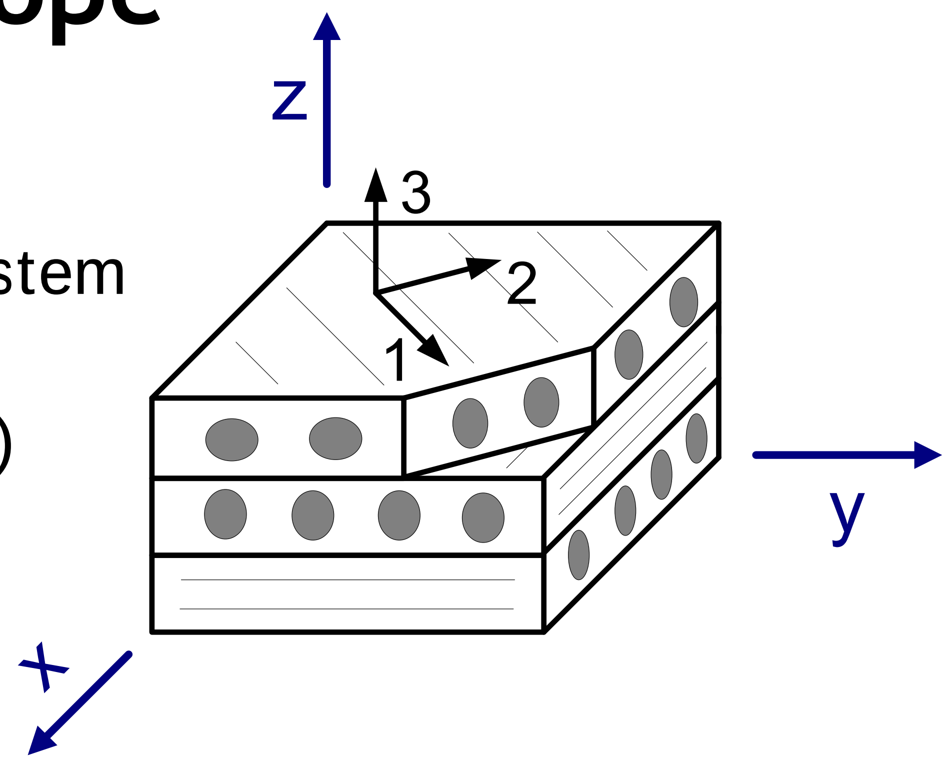
fibers

[Lee et al, 1999]

micro scale

Scope

- Modeling on ply level
  - local ply-coordinate system
  - effective ply material (transversally isotropic)
  - no micro–stress fields, micro-damage, etc.



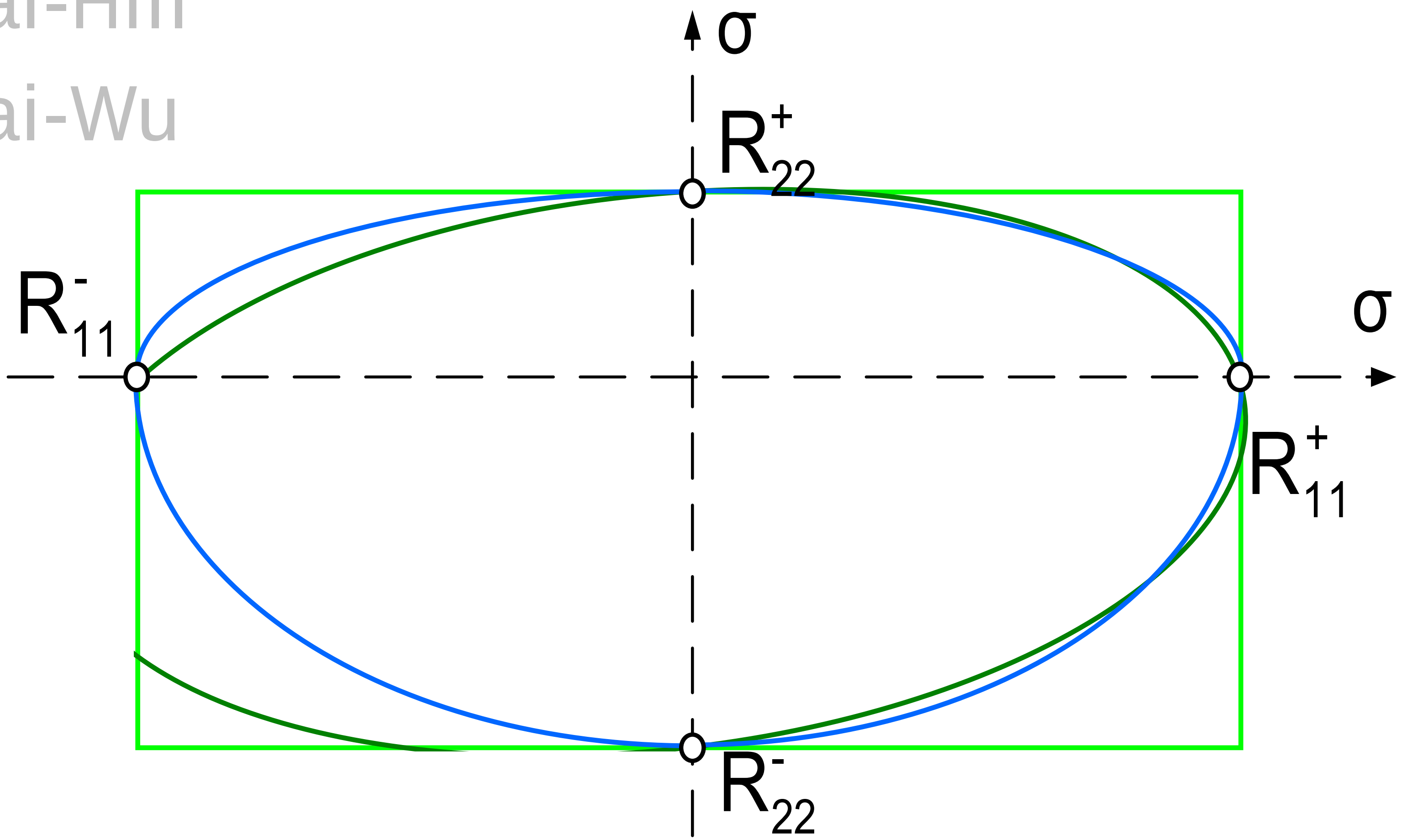
but: application on macro-level by lamination theory and/or implementation in FEM

First Ply Failure (FPF)

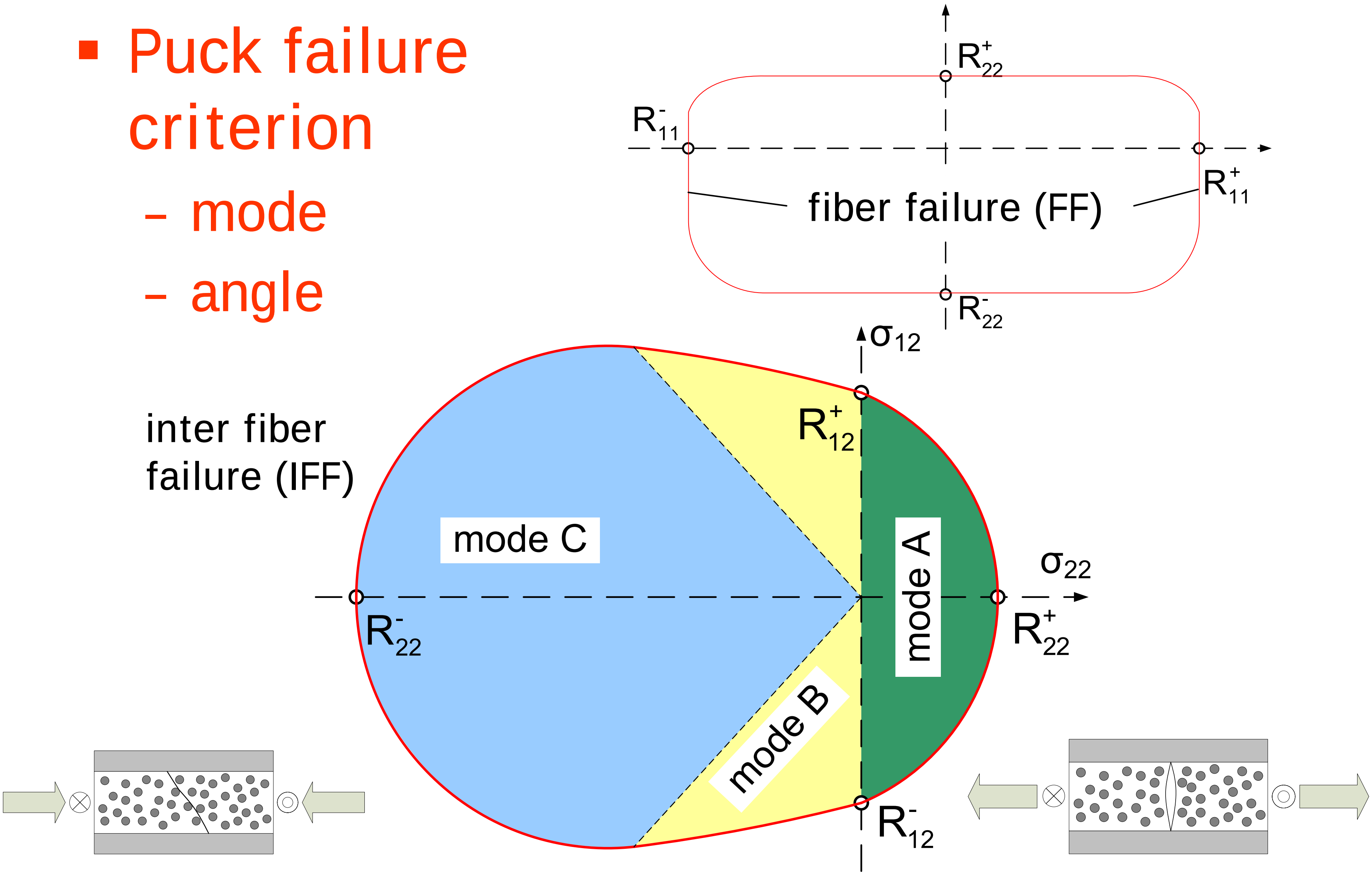
- Linear material behavior
- “Laminate failure if stress in one layer reaches stress limit”
  - determine layer stresses (analytically, numerically)
  - define “stress limit” → FPF-criteria

FPF criteria

- Max. stress
- Tsai-Hill
- Tsai-Wu

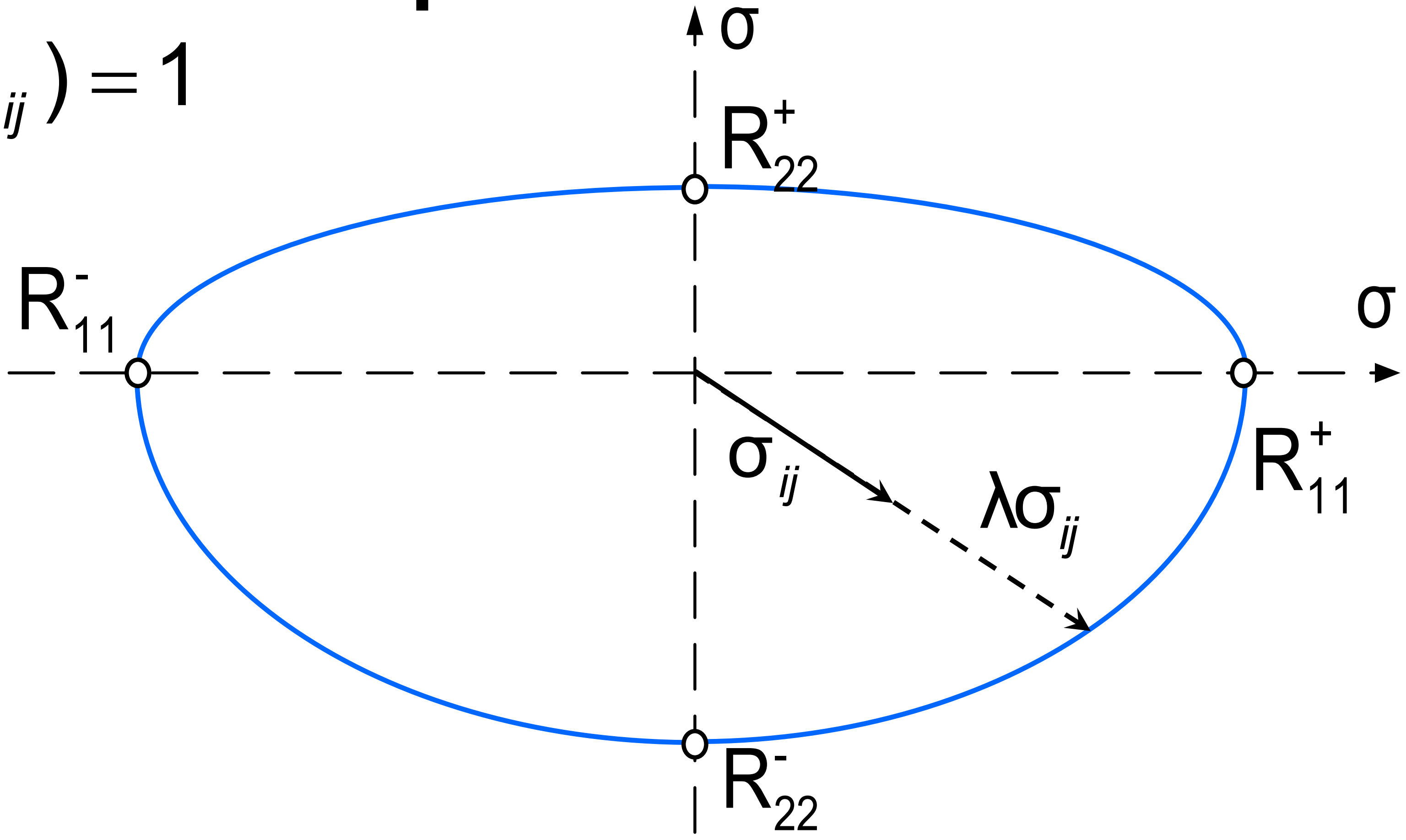


- Puck failure criterion
  - mode
  - angle



Risk parameter λ

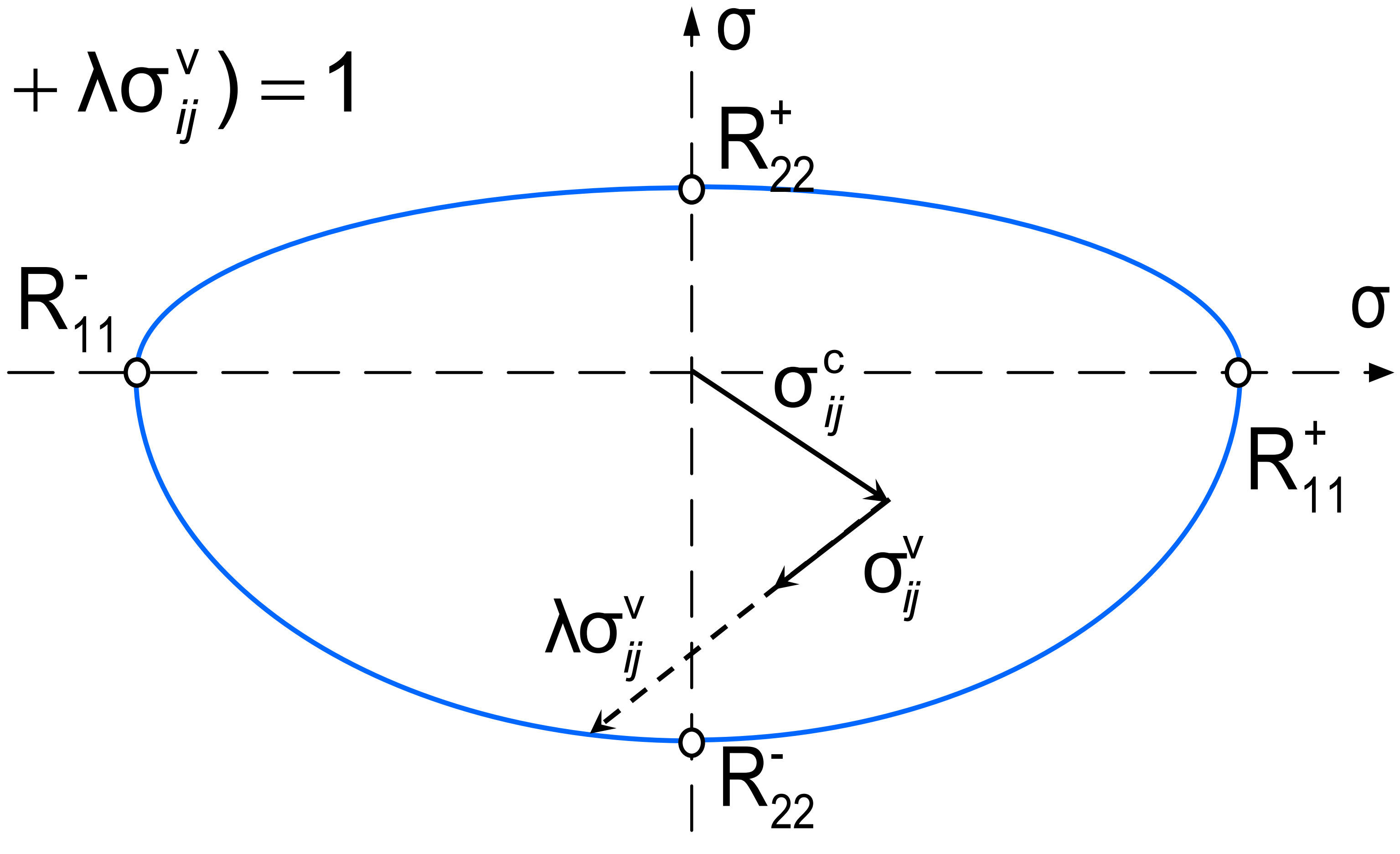
$$F(\lambda\sigma_{ij}) = 1$$



→ **proportional increase of all stress components**

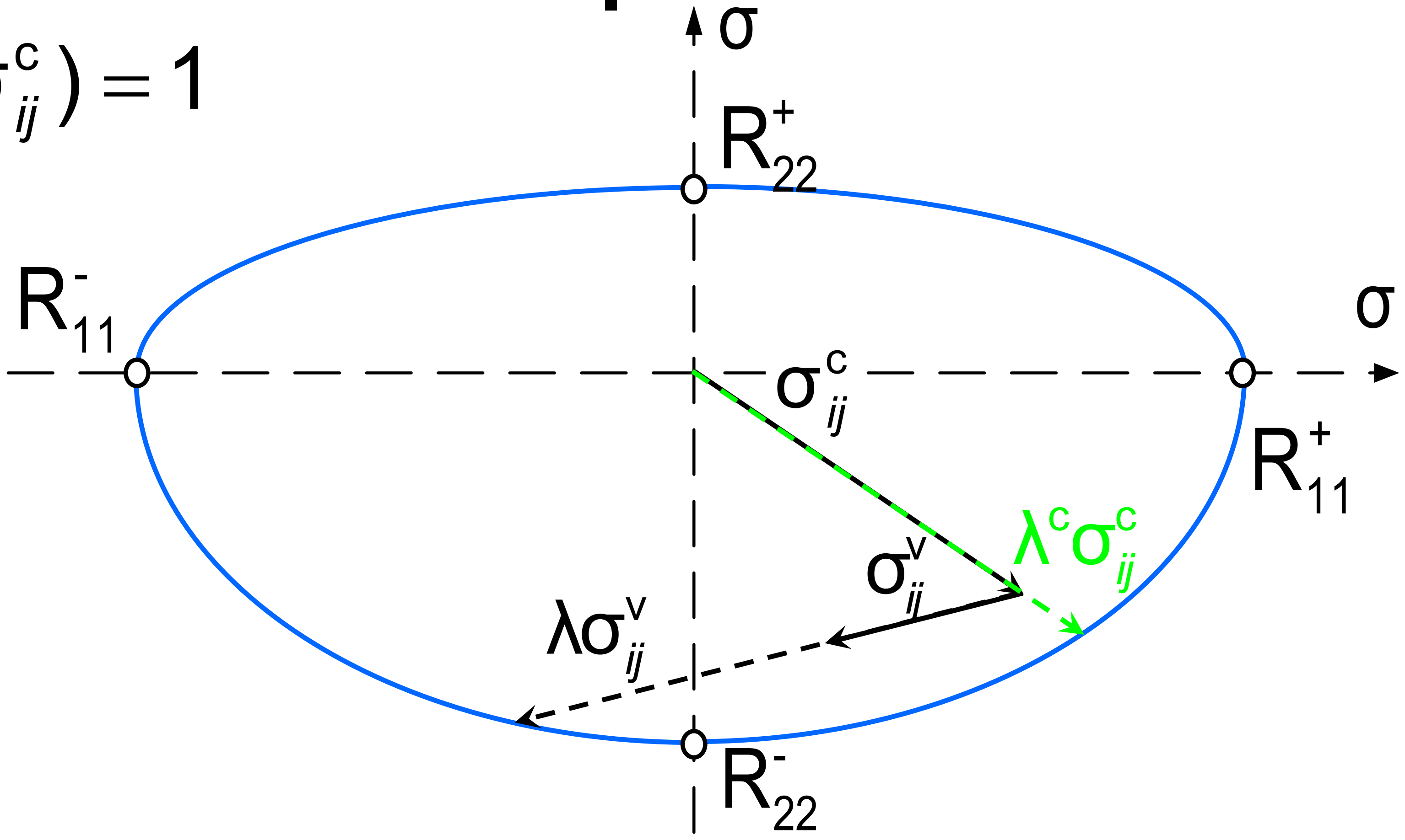
Combined stress states

$$F(\sigma_{ij}^{c} + \lambda\sigma_{ij}^{v}) = 1$$



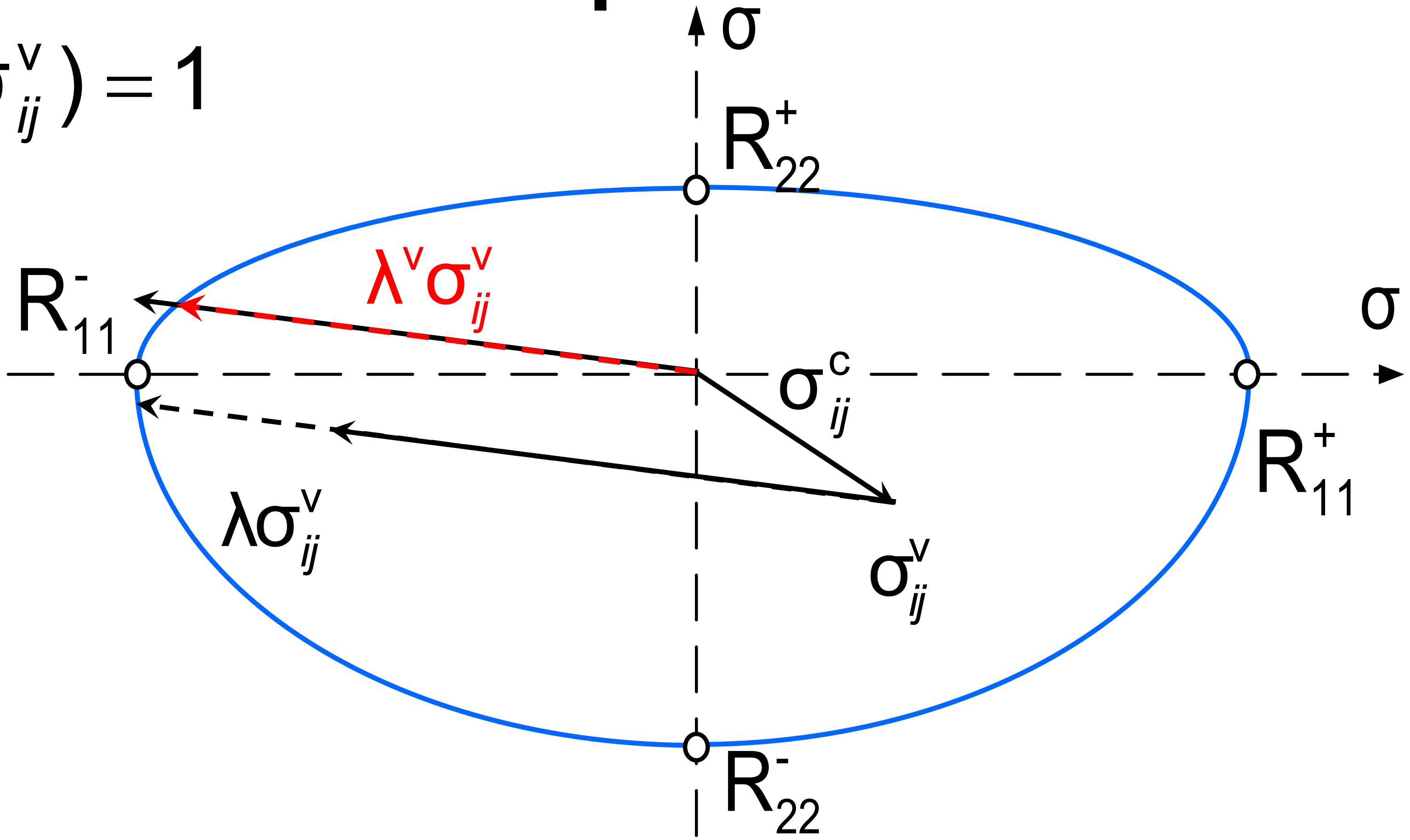
Constant risk parameter λ^c

$$F(\lambda^c \sigma_{ij}^c) = 1$$



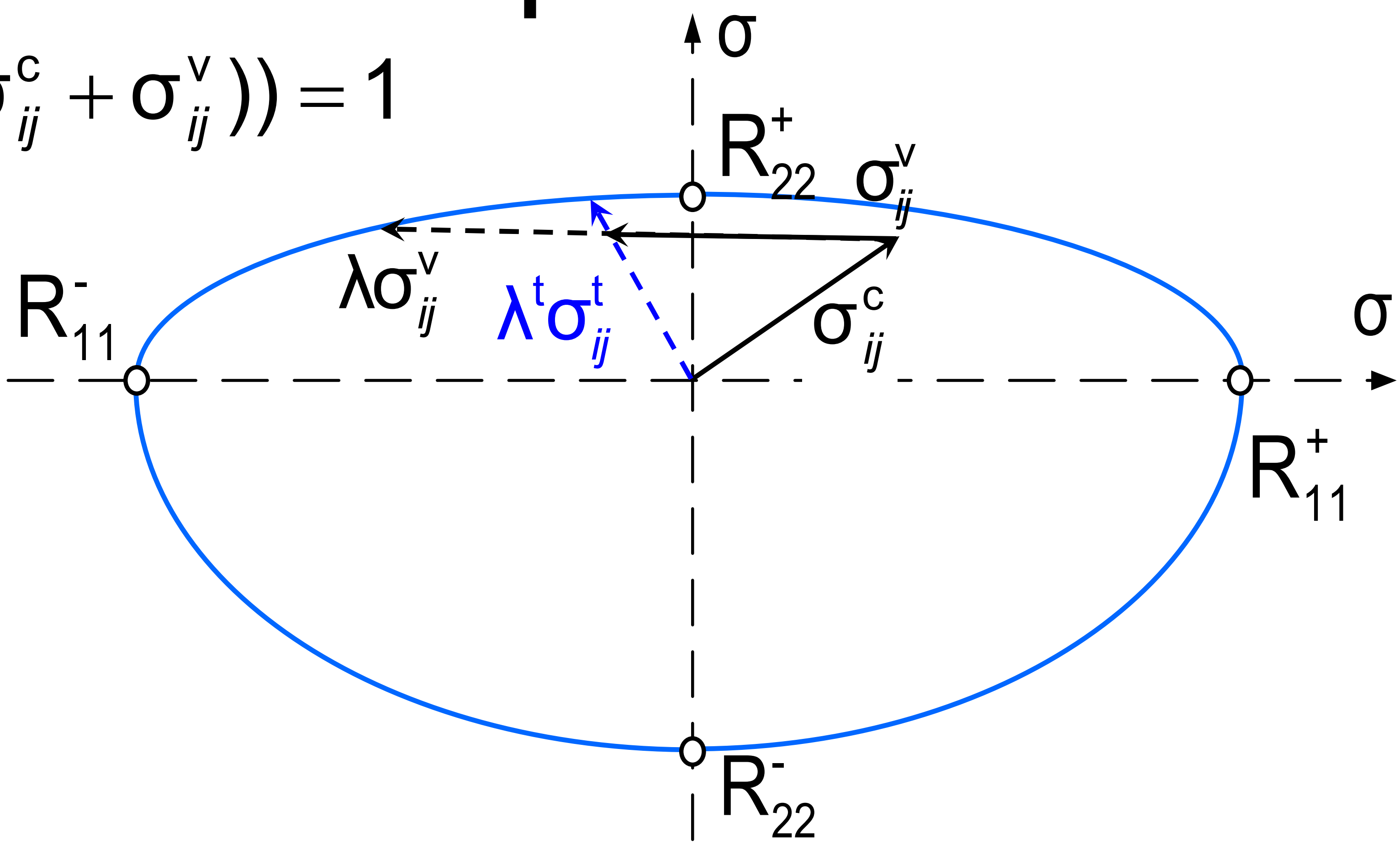
Variable risk parameter λ^v

$$F(\lambda^v \sigma_{ij}^v) = 1$$



Total risk parameter λ^t

$$F(\lambda^t(\sigma_{ij}^c + \sigma_{ij}^v)) = 1$$



Implementation:

- Modular structure
  » easy extension to various failure criteria
- 2D and 3D stress states
- 4 risk parameters
- Failure mode
- Fracture plane angle (when available)
- Combination with FEM-program

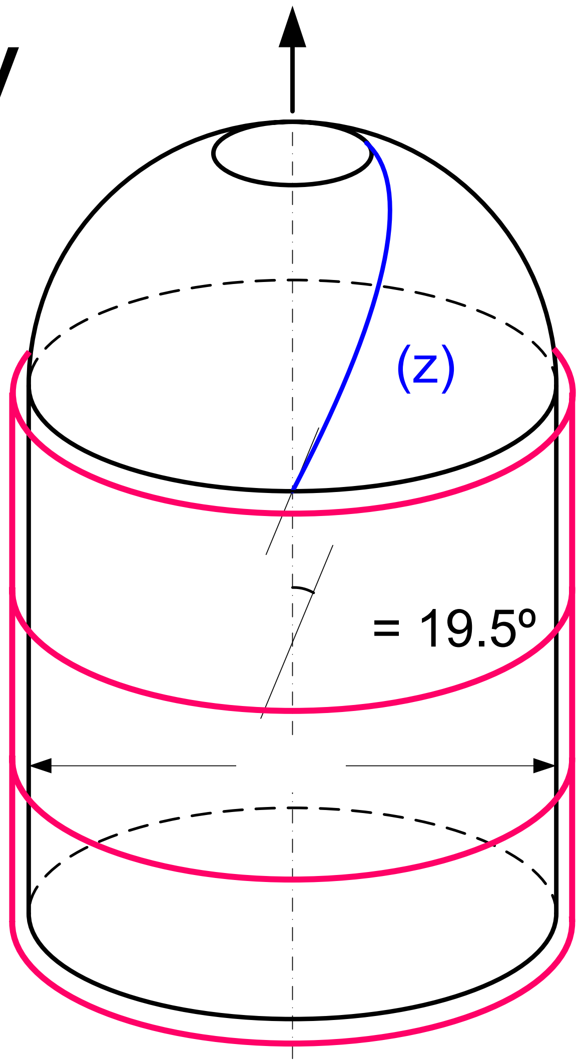
Example Problem

Pressure vessel geometry

Material: AS4/3501-6
carbon/epoxy

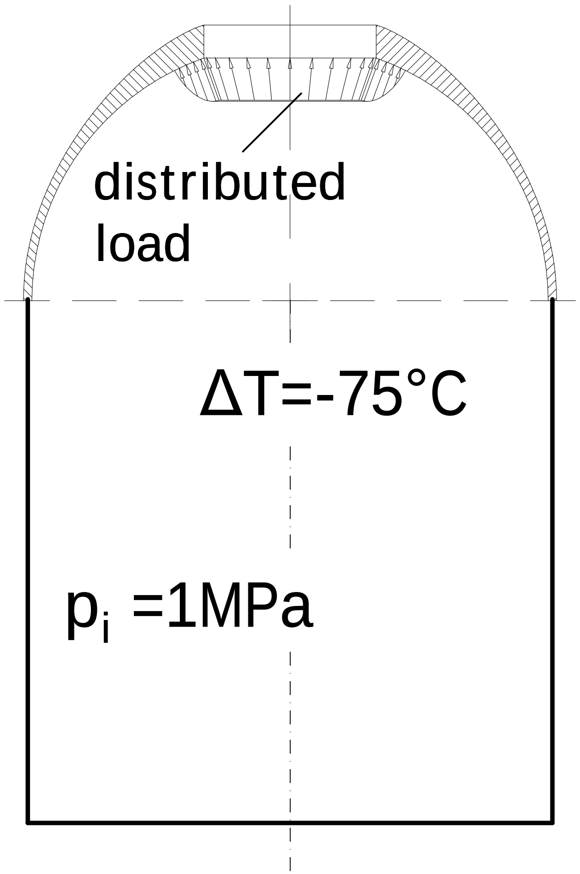
Layup:
symmetric angle ply
$[+\gamma/-\gamma]_s$; γ=19.5°... 90°

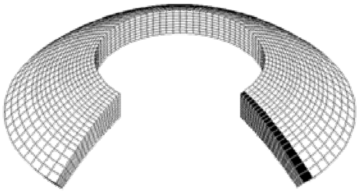
+ 90º reinforcement
in cylinder section

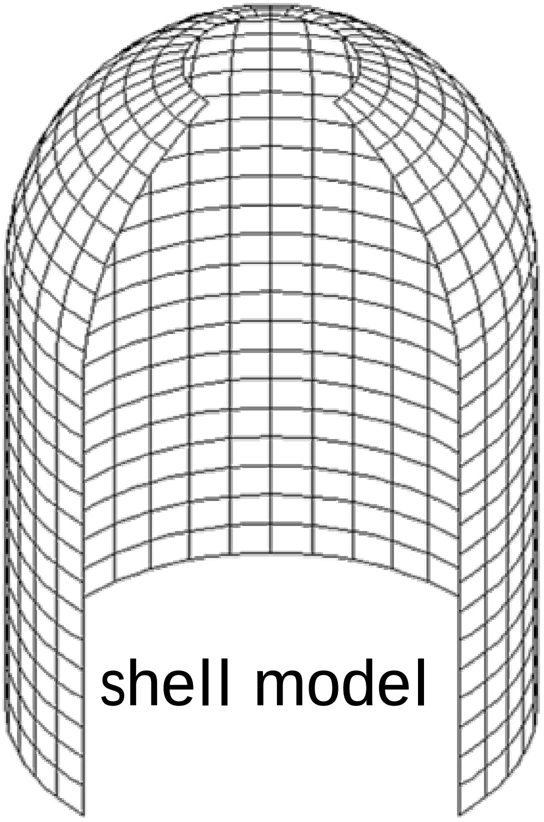


Example Problem

Pressure vessel loads & modeling

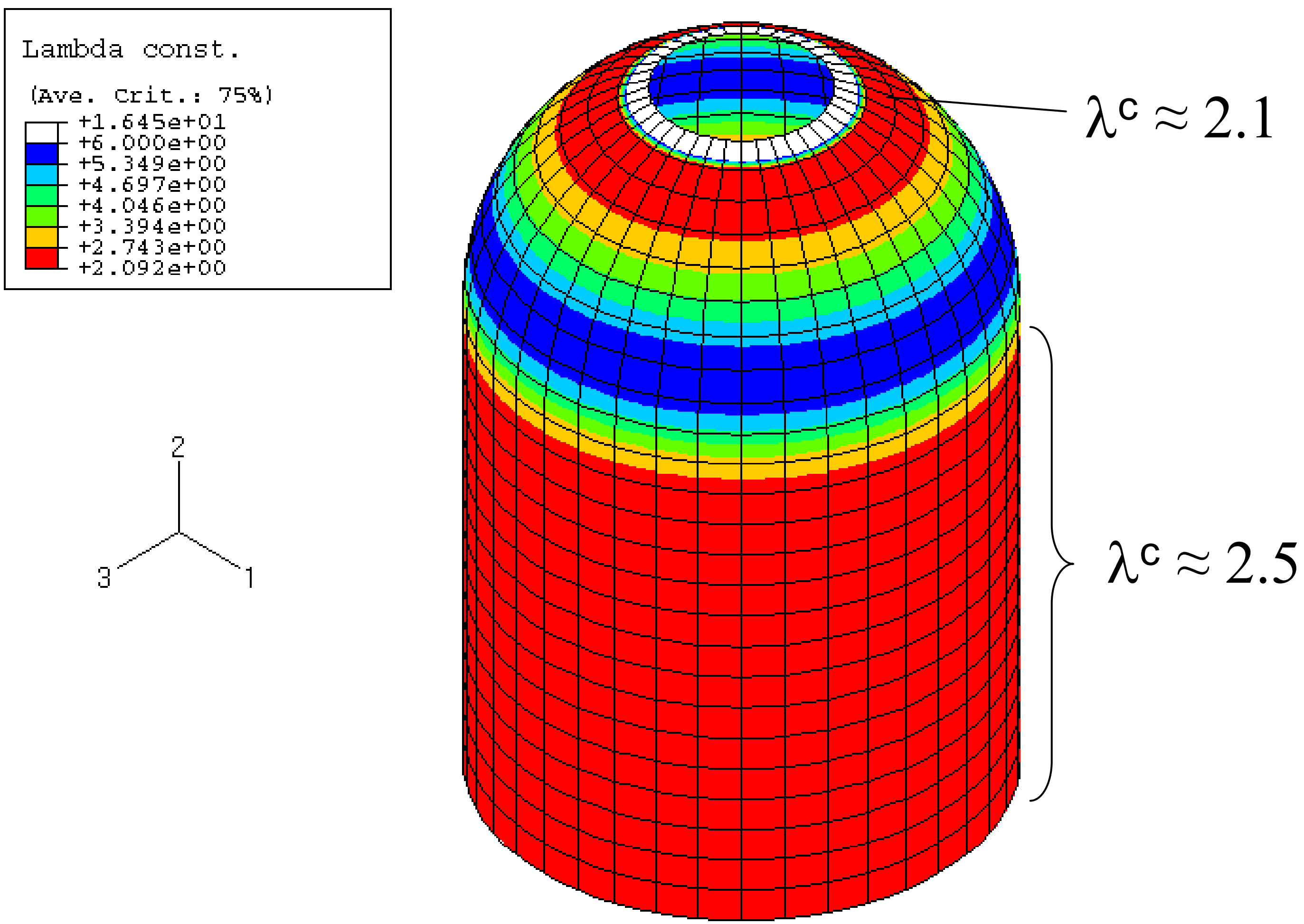






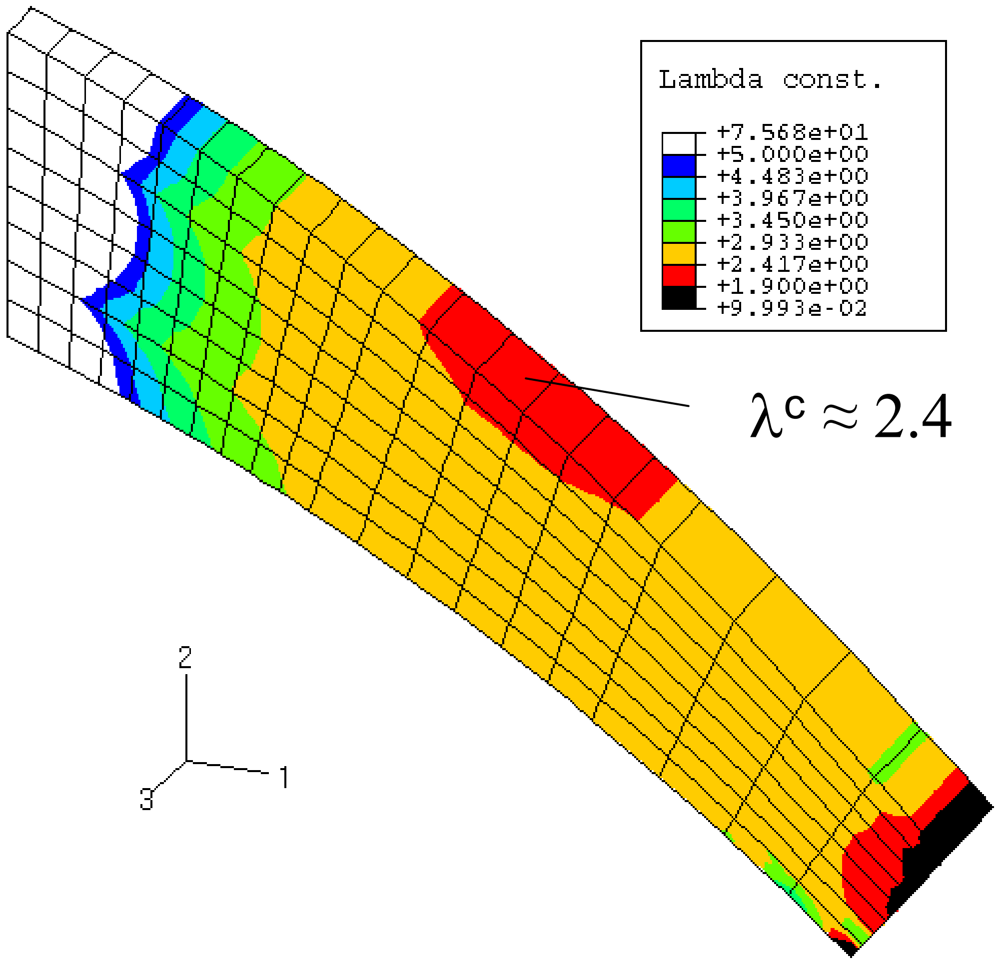
Example Problem - Results

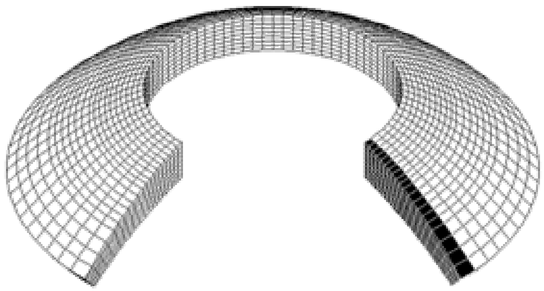
residual stress →const. risk parameter



Example Problem - Results

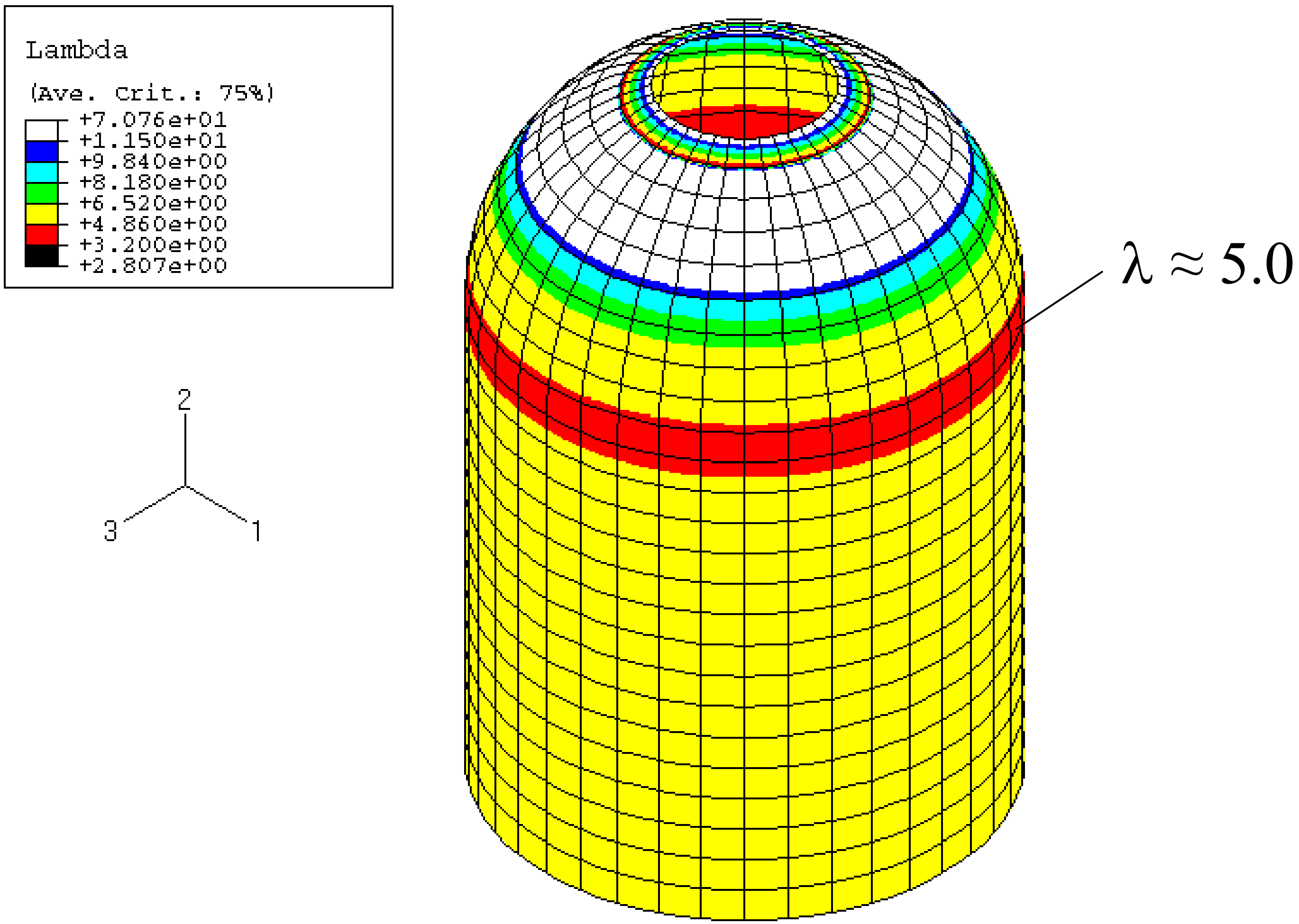
residual stress →const. risk parameter





Example Problem - Results

combined stresses → risk parameter



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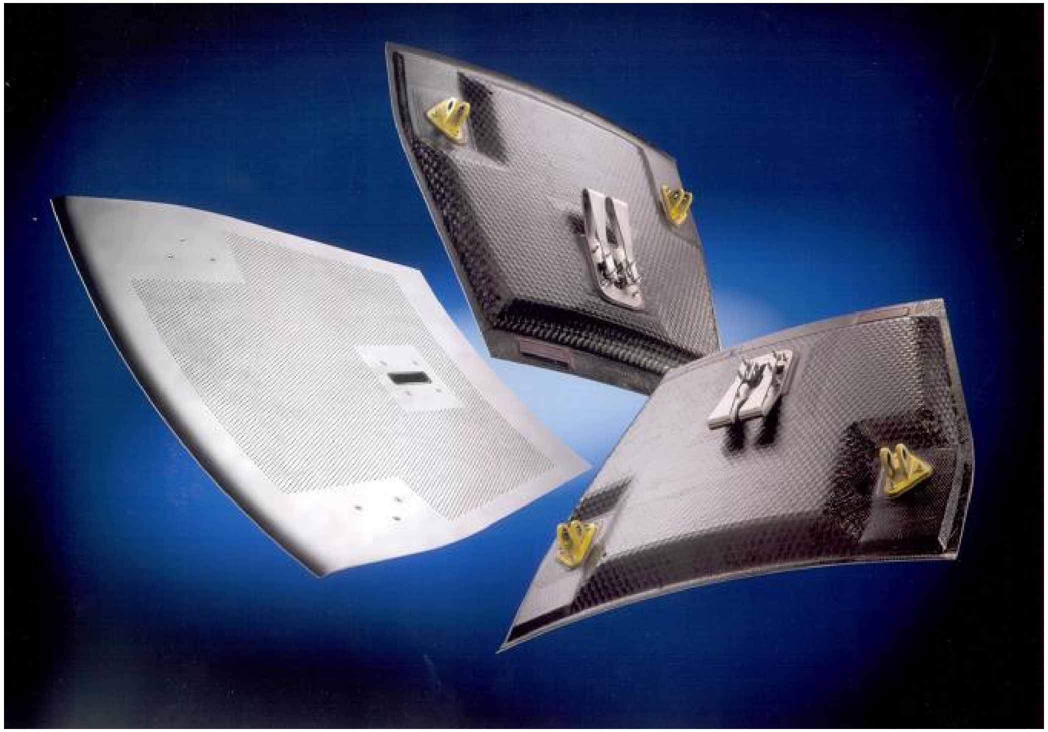
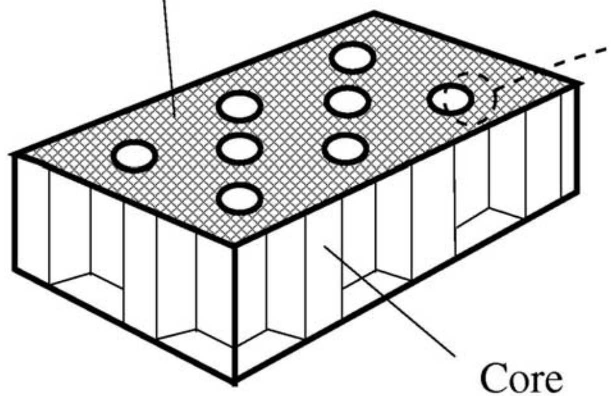
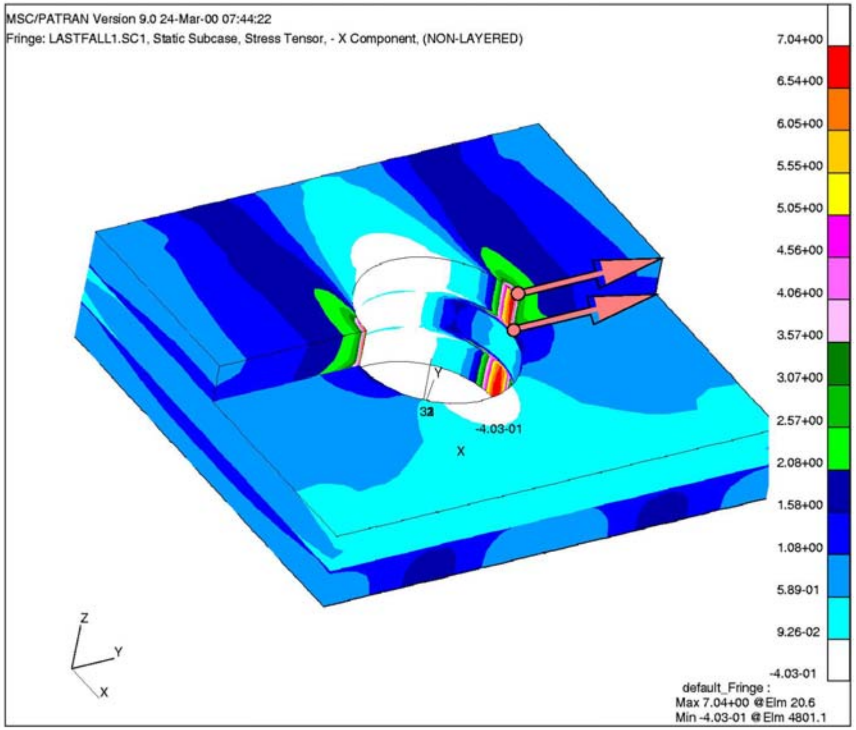
HIERARCHICAL MODEL

Blockerdoor

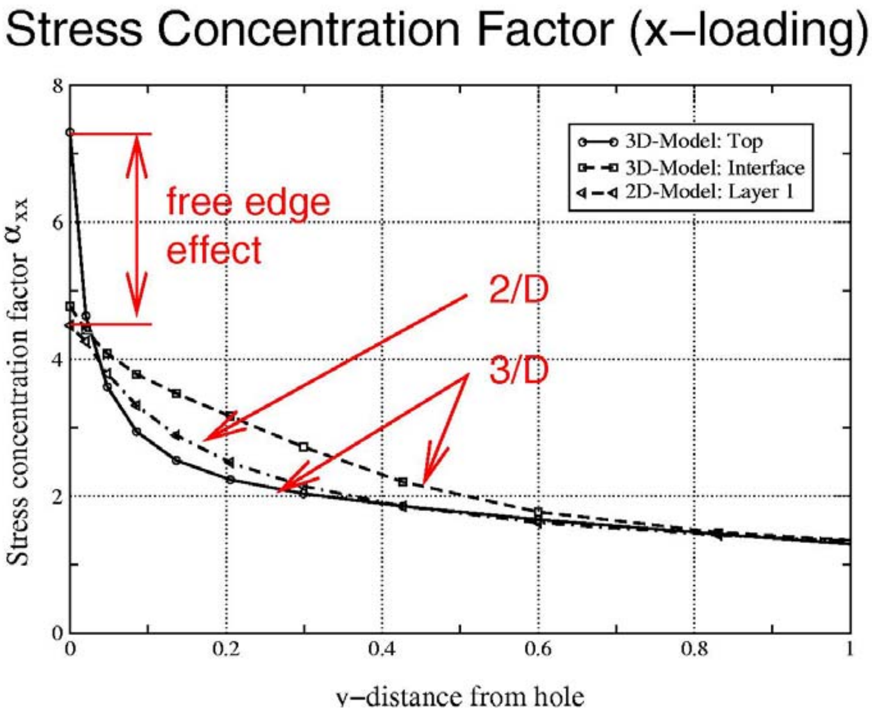




HIERARCHICAL MODEL



UC-model to derive homogenized material behavior
→ global FEM-analysis



Predicted stress distributions in acoustic laminate: free edge effect

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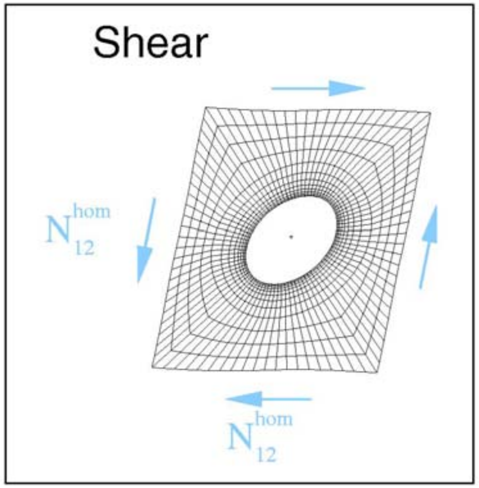
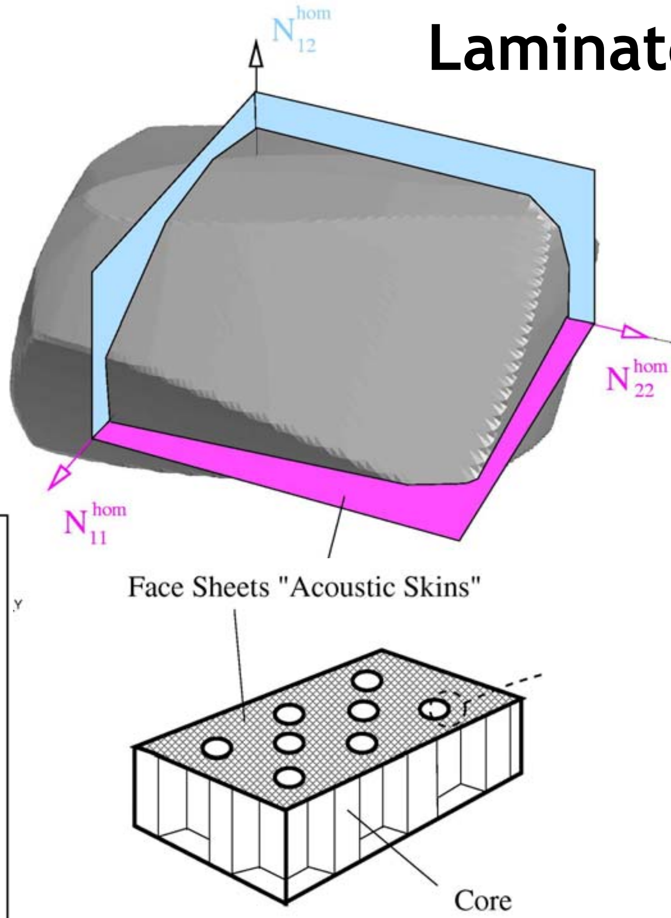
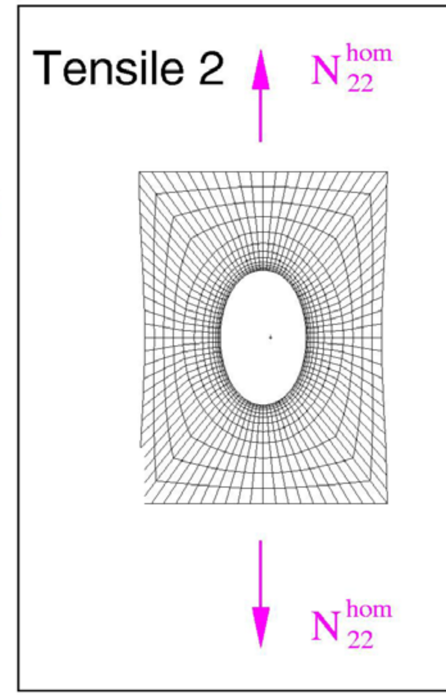
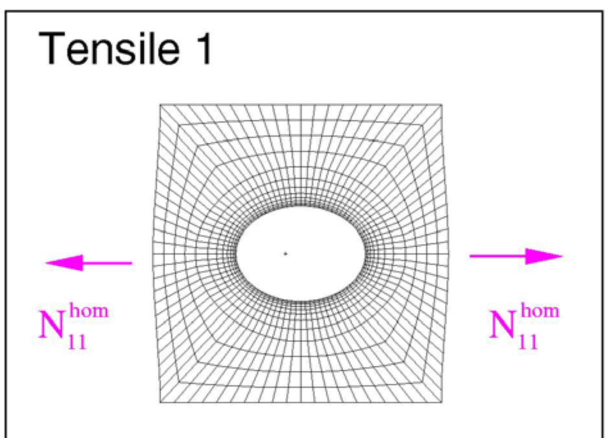
HIERARCHICAL MODEL

Laminate Failure Surface

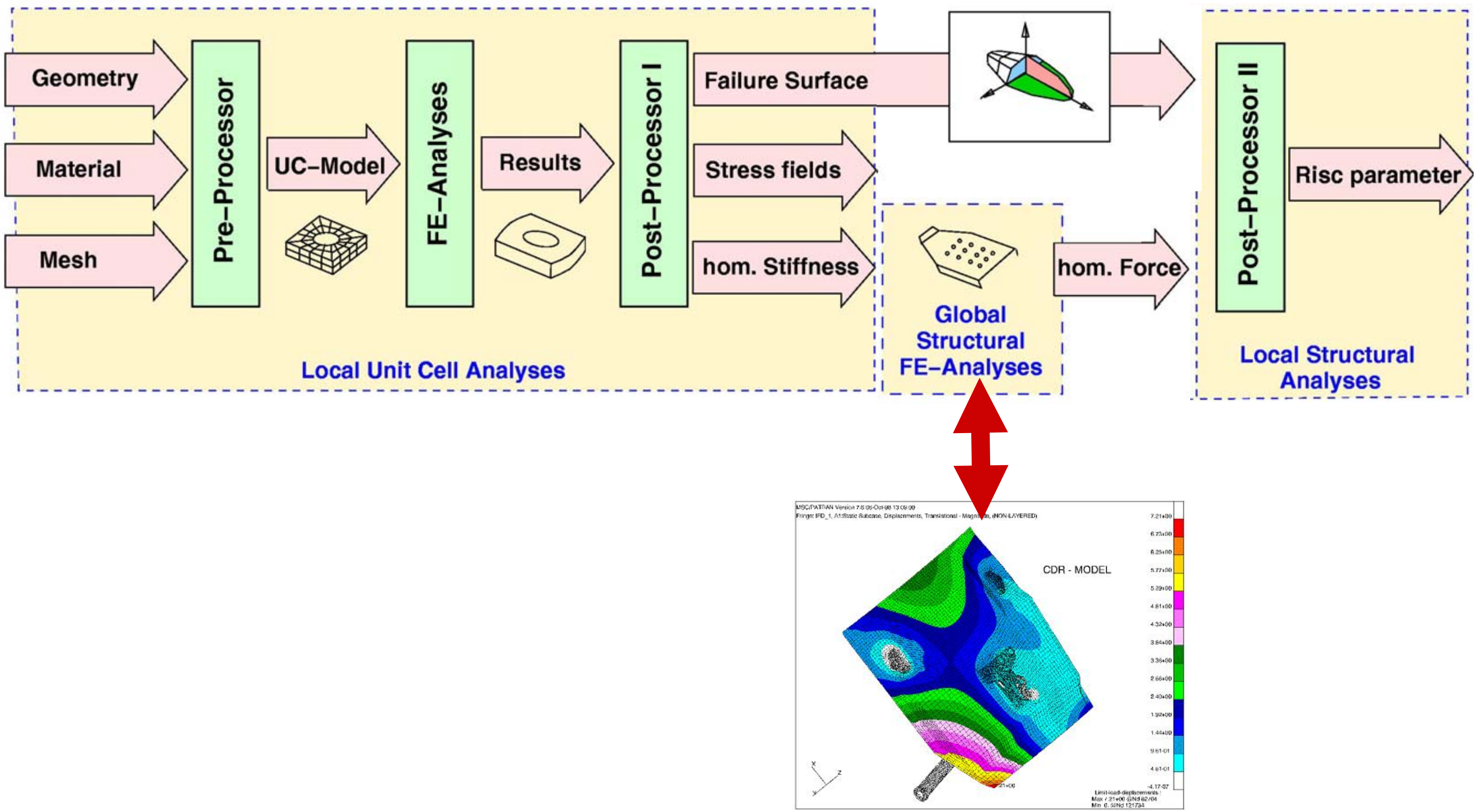






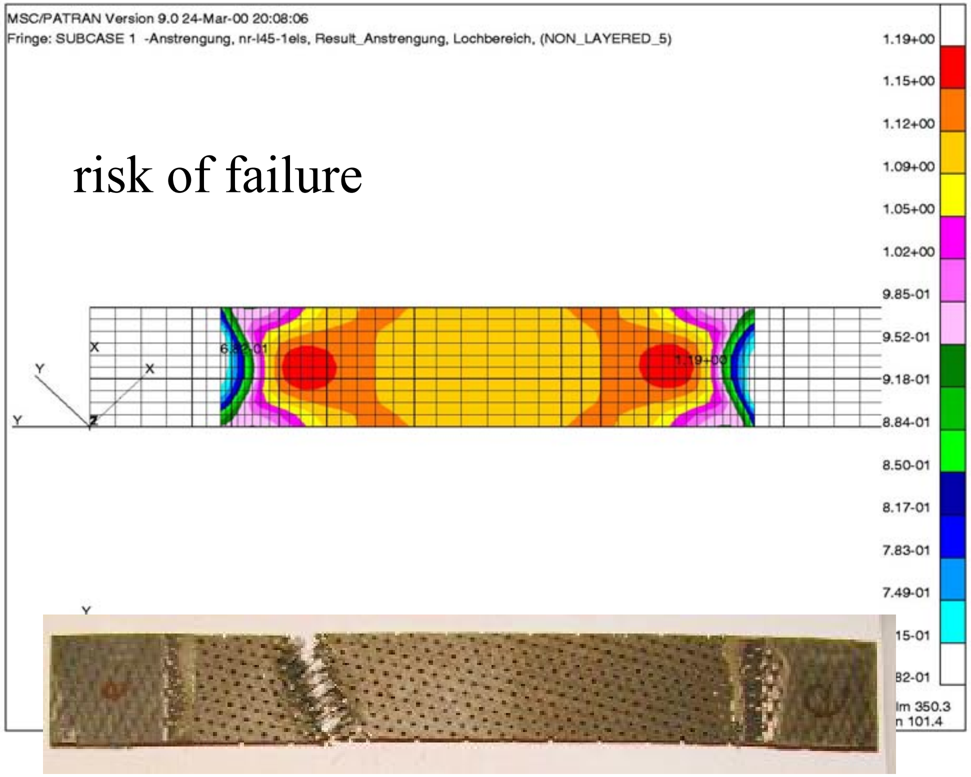


HIERARCHICAL MODEL

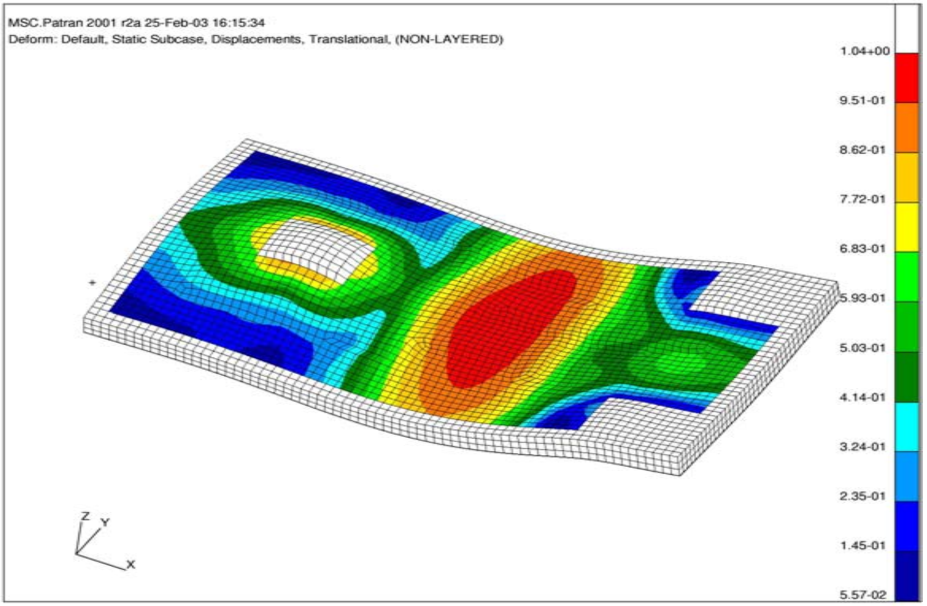


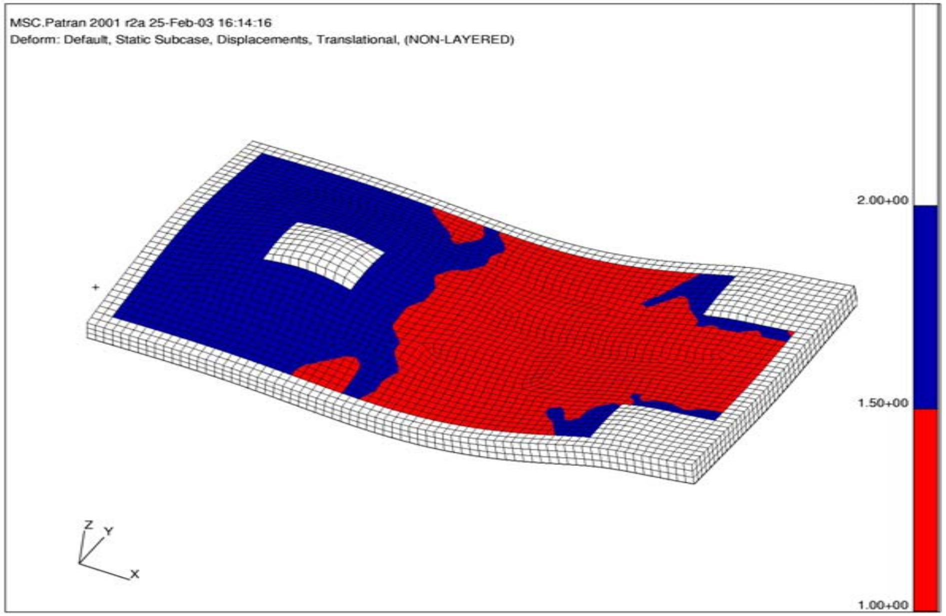
HIERARCHICAL MODEL

Comparison: FE-Computations - Test



HIERARCHICAL MODEL





- Additional results to standard FE are:
  - Risk parameter of perforated regions
  - Failure modes of perforated regions

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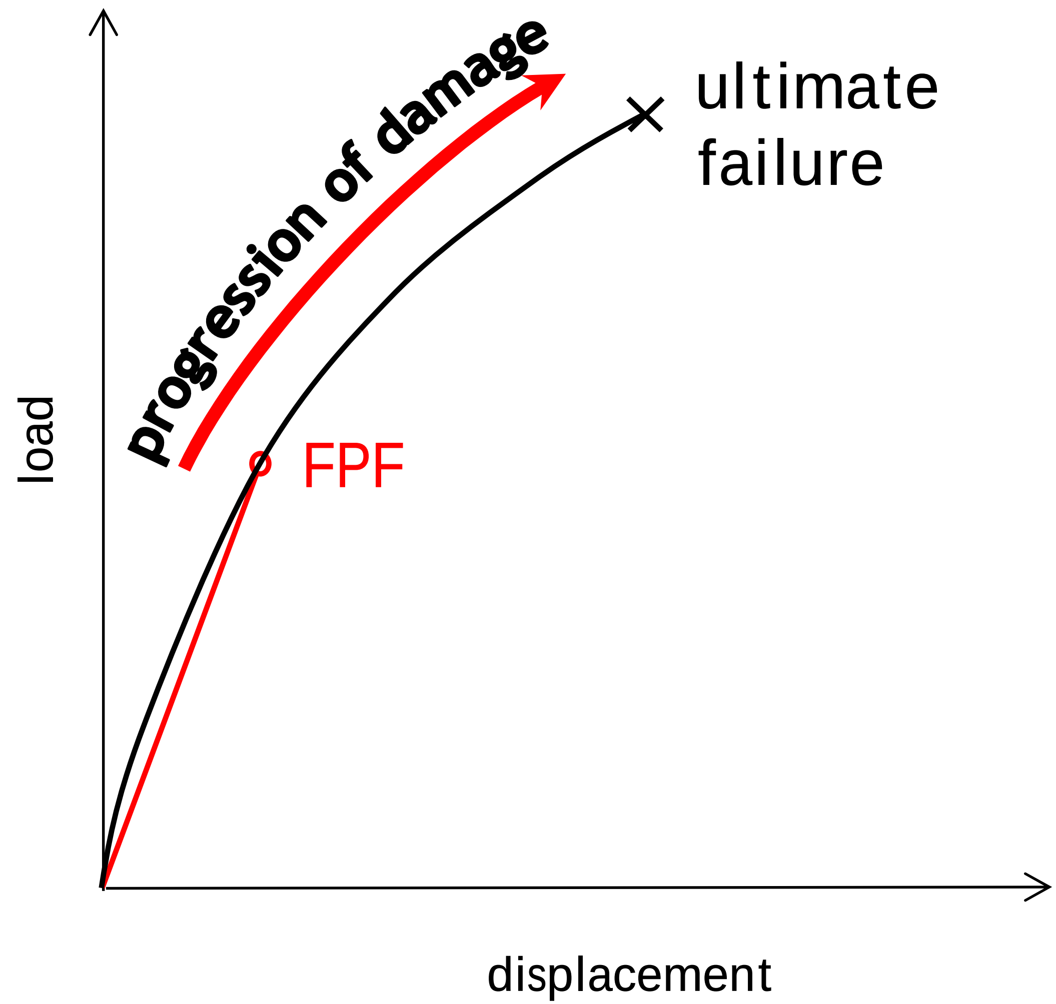
Motivation

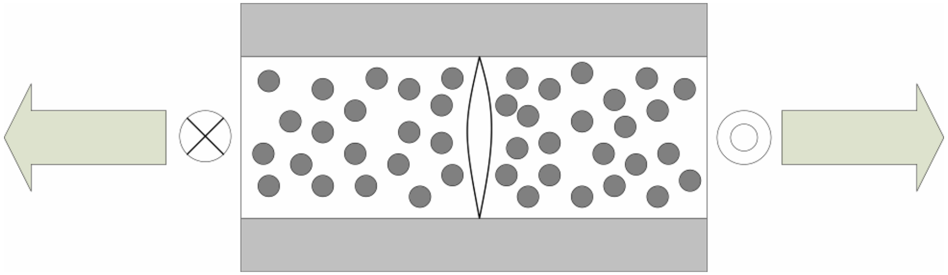
- Failure analysis
  - First Ply Failure
  - linear elastic
- Actual material behavior
  - non-linear due to damage
  - high margin to ultimate failure

→ damage modeling



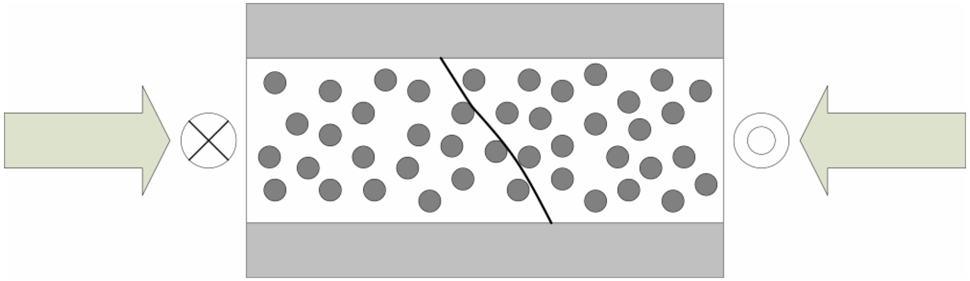
Ply material behavior

effect of damage dependent on stress state



tension / shear

open transverse crack



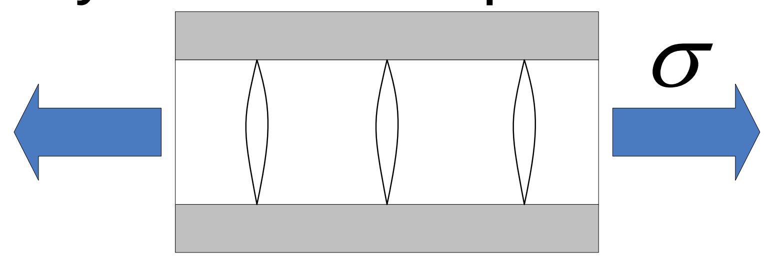
compression / shear

fracture plane angle 0 - 53°
additionally friction
→ ‘stiffness recovery’

Continuum damage modeling

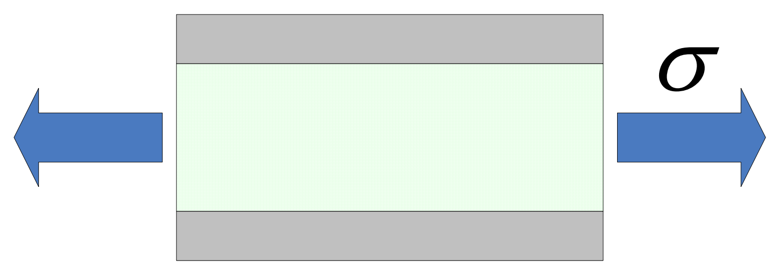
uniaxial tension:

layer with multiple cracks



equivalent

effective material

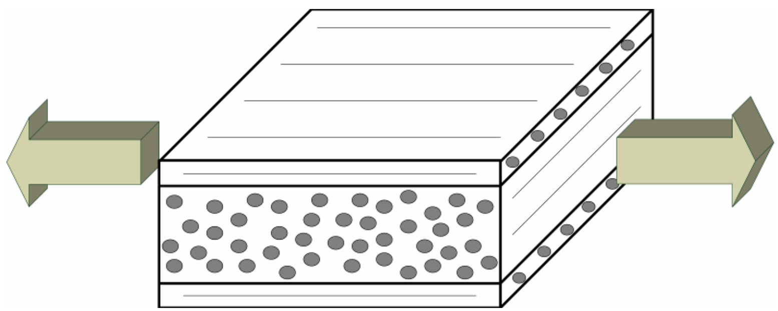


$$E_2^d = E_2^0 (1 - d_2)$$

d_2 ... damage variable

Continuum damage modeling

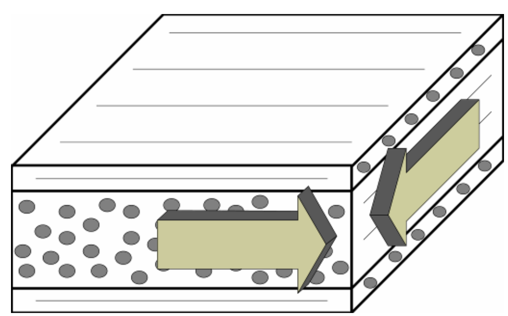
- Simple model
  based on experimental curve fits



σ_{22} →

$$E_2^d = E_2^0 (1 - d_2)$$

↕ **interaction?**



σ_{12} →

$$G_{12}^d = G_{12}^0 (1 - d_{12})$$

Continuum damage modeling

- In general

$$\mathbf{E}^d = \mathbf{E}^0 \, \mathbf{F}(\mathbf{D})$$

$\mathbf{E}^d$, $\mathbf{E}^0$ ... elasticity tensors

$\mathbf{D} = \mathbf{D}(d_1, d_2, \ldots, d_n)$ ... 4th order damage tensor

$\mathbf{F}(\mathbf{D})$ ... tensorial function

$\mathbf{F}(\mathbf{D})^{init} = \mathbf{I}$

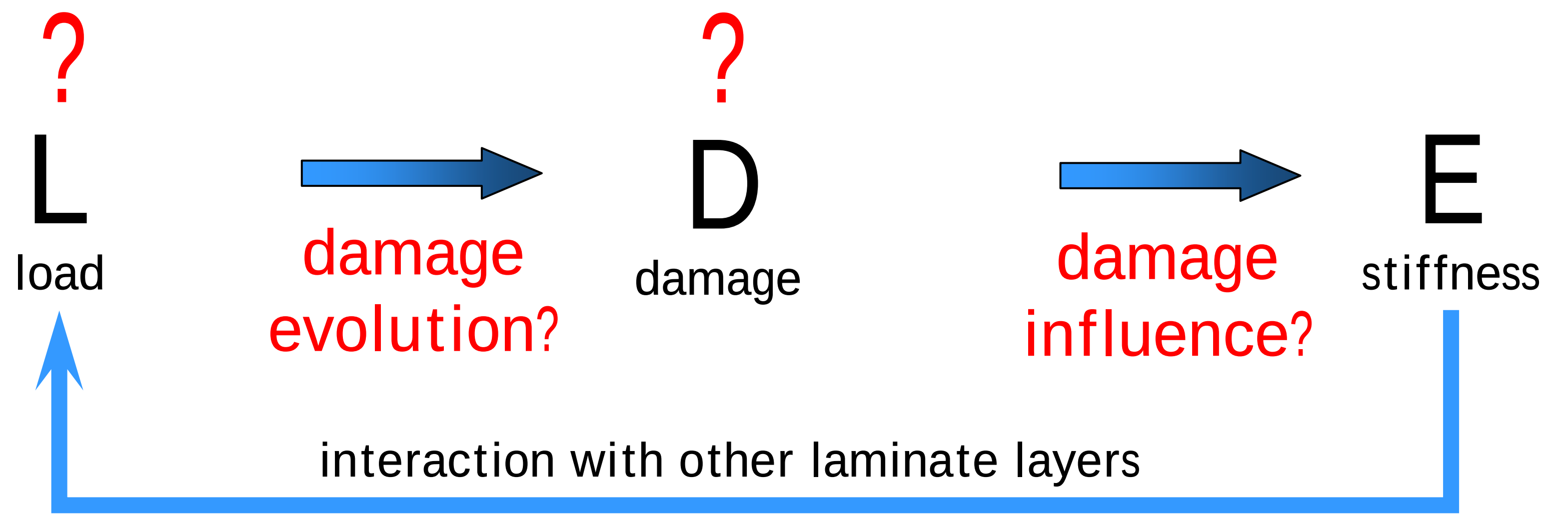
Model objectives

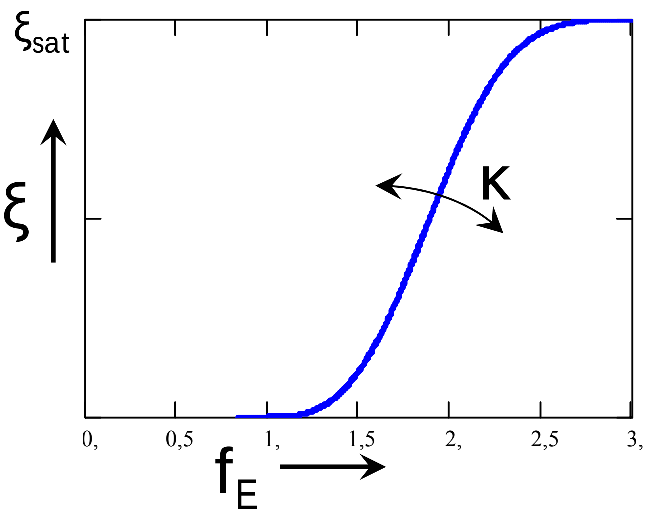
- thermodynamically consistent
- physically realistic
- concept that can capture
  - inclined cracks
  - closed cracks (stiffness recovery)
  - (3-axial stress states → delamination)

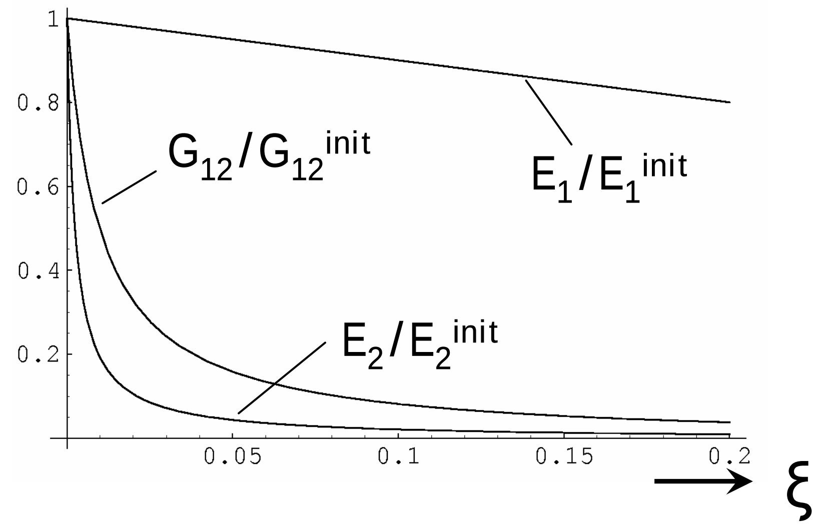
- few parameters

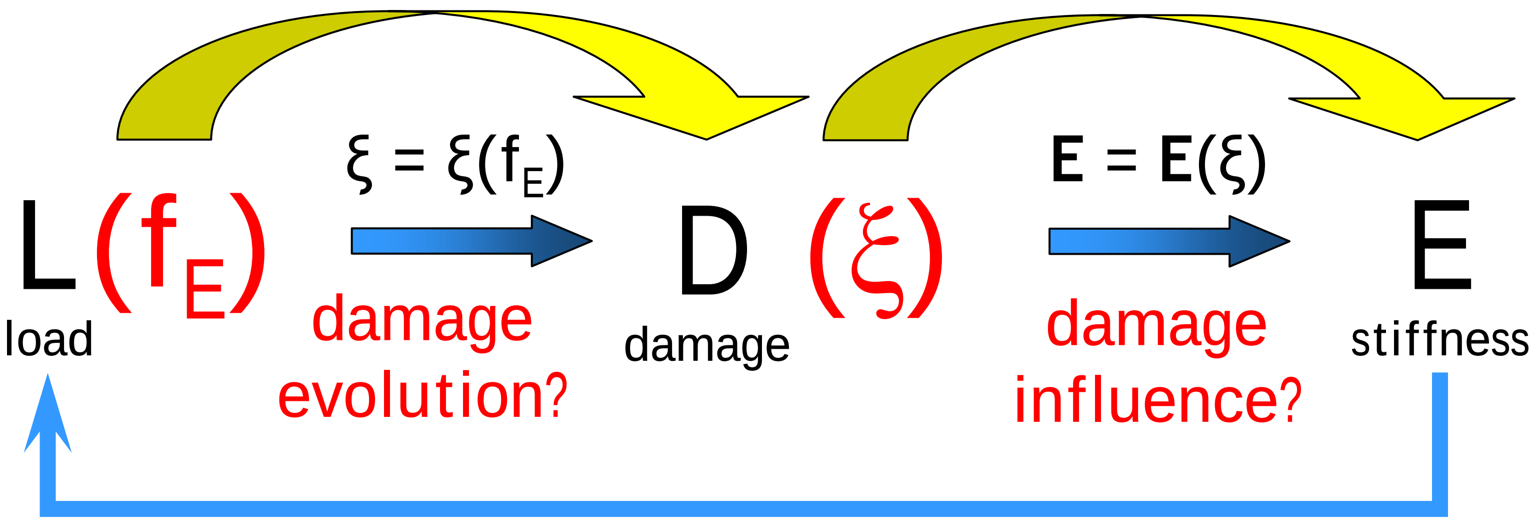
Problem definition

- choice of damage variable(s)
- definition of "load"
- damage evolution law
- influence of damage on stiffness

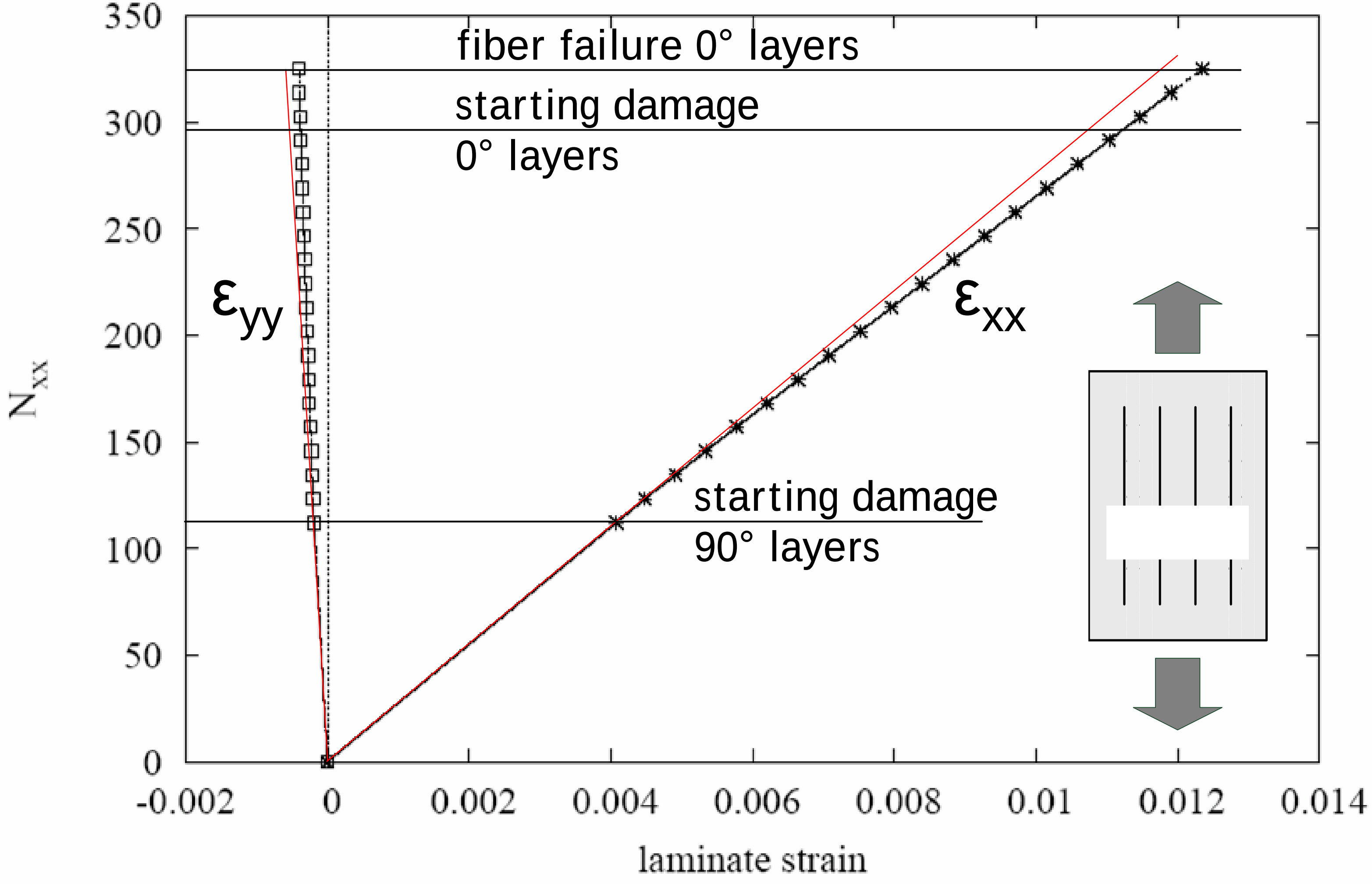



ξsat
ξ
K
0,
0,5
1,
1,5
2,
2,5
3,
fE

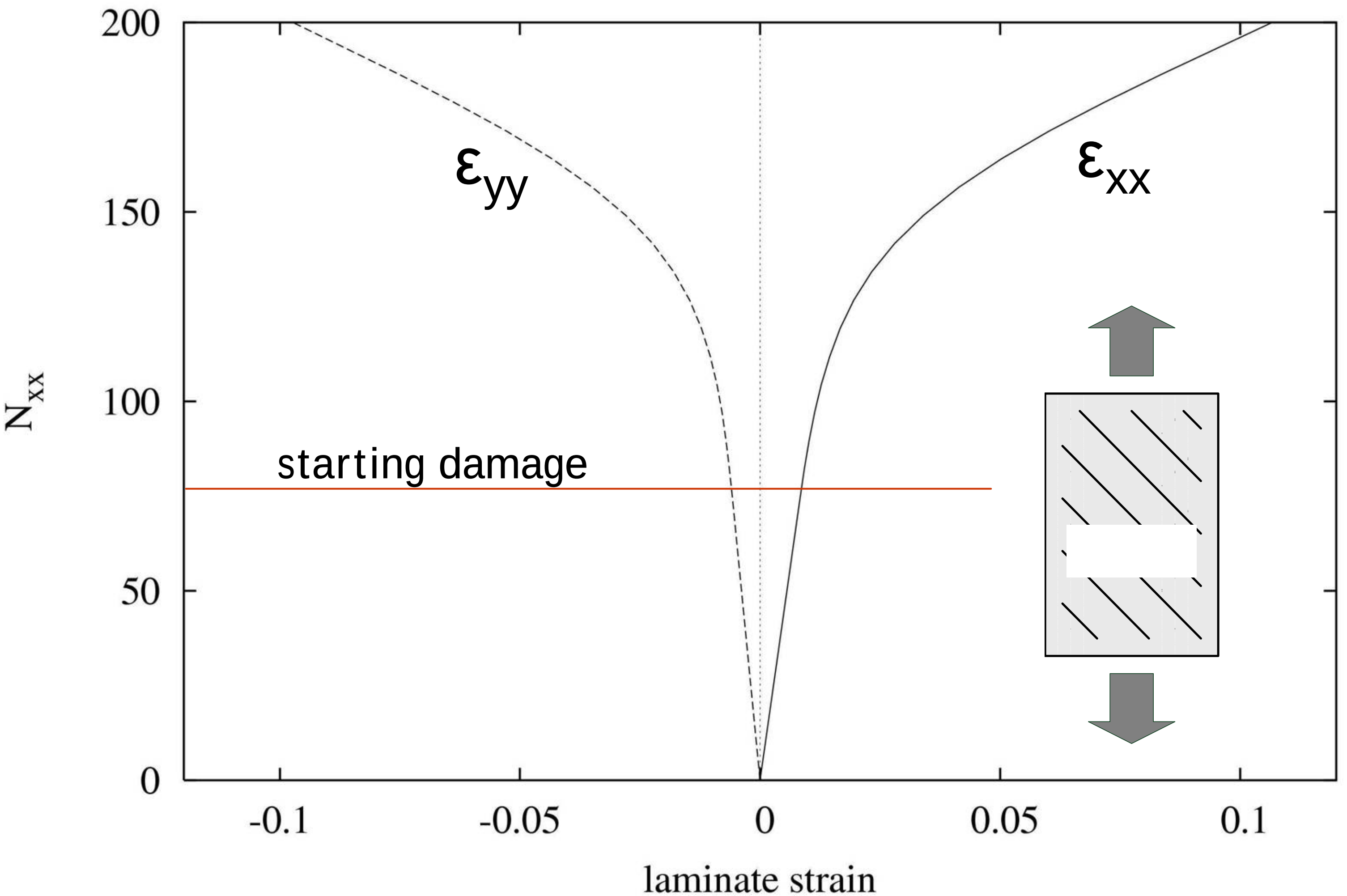

1
0.8
0.6
0.4
0.2
0.05
0.1
0.15
0.2
G12/G12init
E1/E1init
E2/E2init
ξ


ξ = ξ(fE)
E = E(ξ)
L (fE)
load
damage evolution?
D (ξ)
damage
damage influence?
E
stiffness

$(0/90)_s$ Laminate - uniaxial tension



$(\pm 45)_s$ Laminate - uniaxial tension



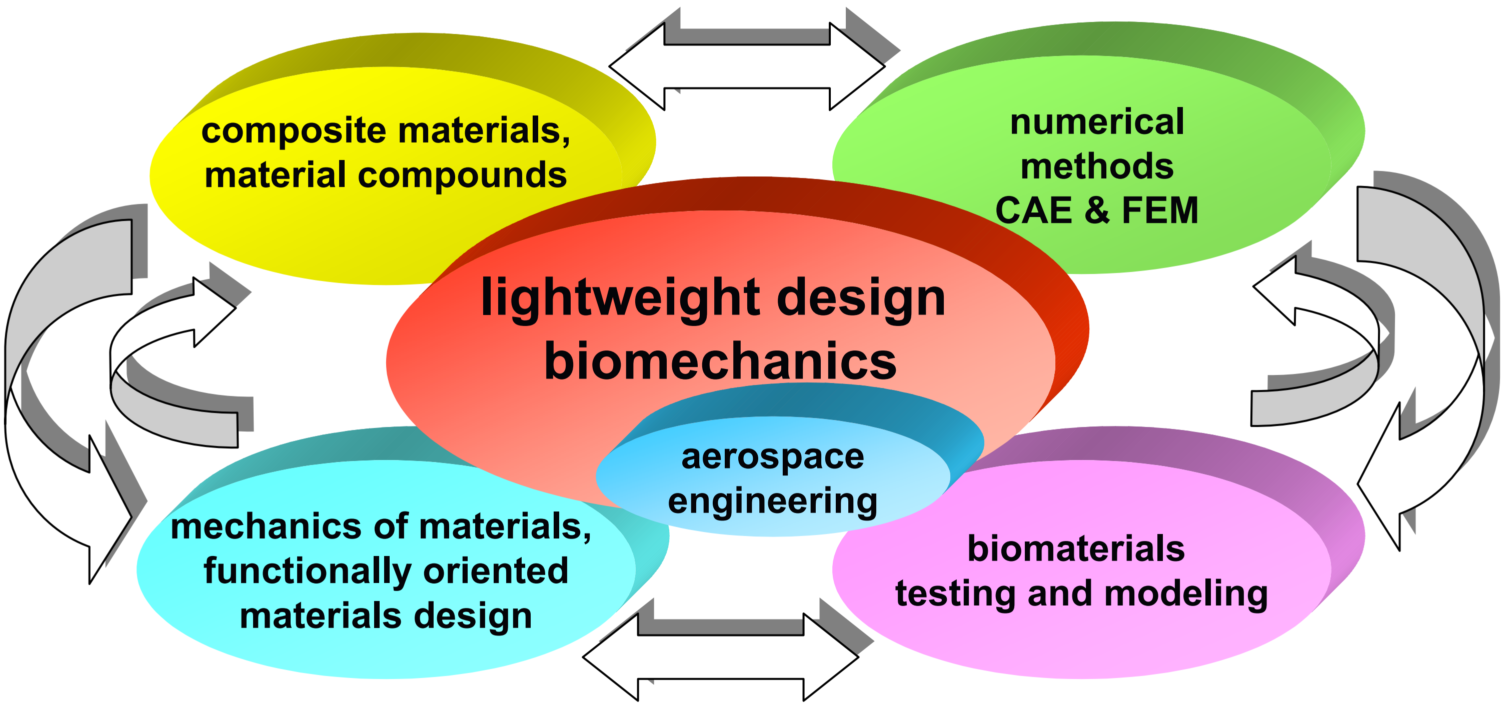
Model capabilities

- Arbitrary loading paths
- Constitutive law for FEM
- Evolution law for fatigue

- Structural analysis of components

Summary

- modeling of the material behavior
  - FPF
  - progressive damage
- ... utilized for structural analyses
  - hierarchical modeling
- improved stress analysis


composite materials,
material compounds
numerical
methods
CAE & FEM
lightweight design
biomechanics
aerospace
engineering
mechanics of materials,
functionally oriented
materials design
biomaterials
testing and modeling