Welsh
Composites
Centre

Computational Analysis for Composites

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Swansea University

Ariennir gan Llywodraeth Cynulliad Cymru
Funded by Welsh Assembly Government

ERDF
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Welsh Assembly Government
Ewrop & Chymru: Buddsoddi yn eich Dyfodol
Cronfa Datblygu Rhanbarthol Ewrop
Europe & Wales: Investing in your Future
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OUTLINE

The topics covered include:

- Overview of composites and their applications
- Micromechanics theory for analysis of composites
- Properties (elastic properties, strength properties and hygrothermal properties) in (i) unidirectional composites and (ii) particulate and short fibre composites
- Macromechanical behaviour of composites
- Definition of composite laminates and sandwich structures; vibration and buckling analysis of laminated plates
- Laminate damage and failure criteria in composites
- Finite Element (FE) analysis for composites; Bending and vibration of Composites Shells
- Numerical simulation of composites using commercial FE softwares

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Overview of Composites

- **Composites are hybrid materials in which two or more substances with very different physical and chemical properties, are combined to achieve a new superior material.**

Heterogeneous Composition

Unlimited possibilities

Any characteristic material behaviour

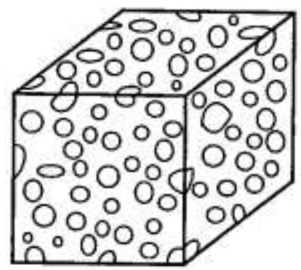
Why we use them?

- High specific strength
- Increased toughness
- Material can be tailored
- Excellent chemical and weather resistance
- Modified electric, thermal, optical and magnetic behaviour.
- Cost effectiveness
- repairability
- etc

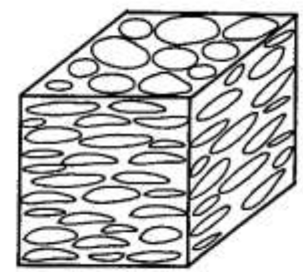
Types of Composites

- **Natural Composites:** Wood, bones, stones etc

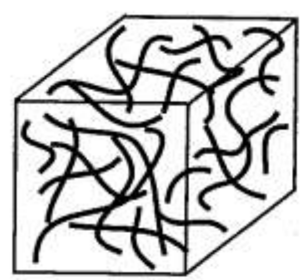
- **Man-made Composites:**
- Fibre reinforced composites, particle reinforced composites (particulate composites). Example: CFRP, GFRP
- polymer matrix composites (or polymer composites), metal matrix composites and ceramic matrix composites
- Laminated composites, sandwich Structures



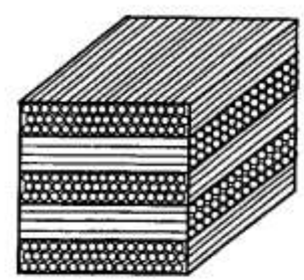
Particulate composite



Flake composite



Fiber reinforced composite



Laminated composite

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Applications of Composites

- should have low density and, at the same time, should be very stiff and strong

Aerospace Applications

Structural

Marine and Mechanical

Sports

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Micromechanics vs. Macromechanics

Micromechanics

Predicting mechanical behaviour of a composite material in terms of its constituent materials

Macromechanics

Predicting mechanical behaviour of a composite material considering it to be a homogenized material

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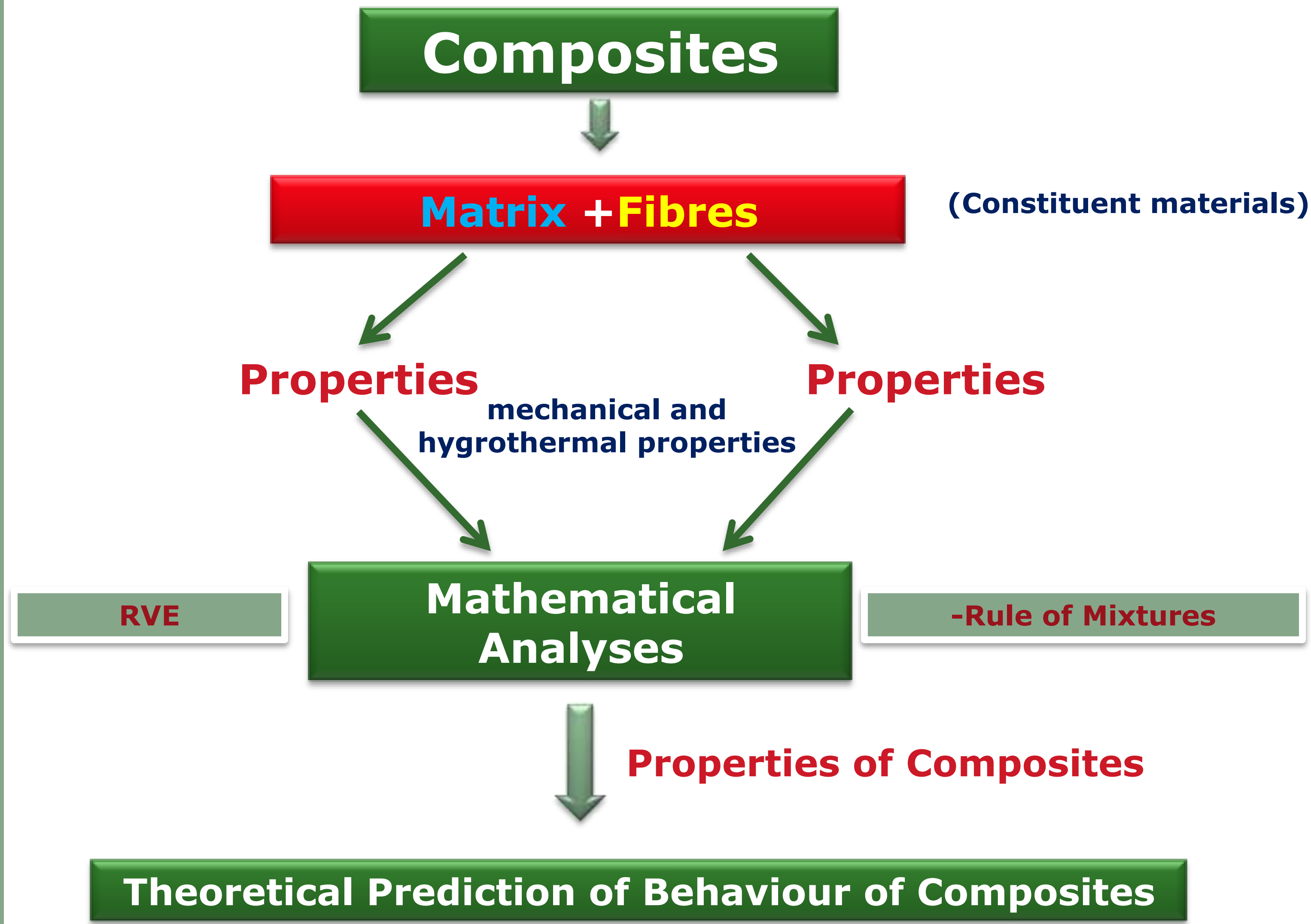
Micromechanics Theory



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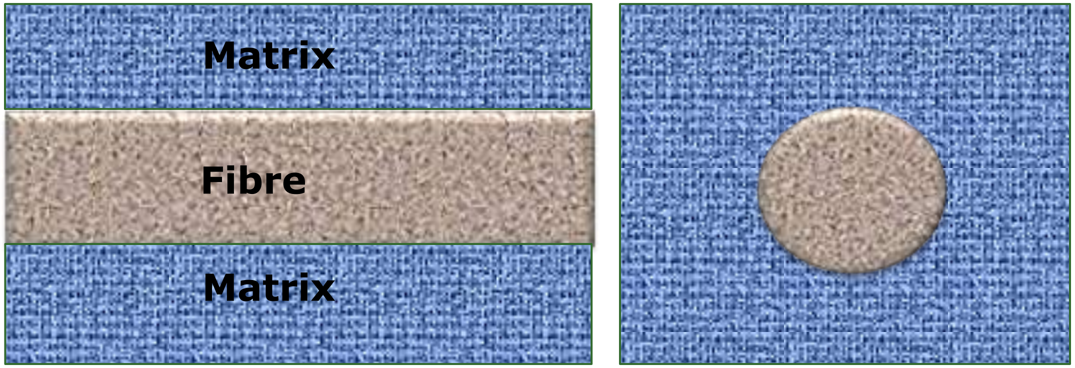
Properties of Composites
(Micromechanics Theory)

General properties of **Unidirectional Composites**

- Longitudinal modulus , E_1
- Major Poisson's ratio, ν_{12}
- Transverse modulus, E_2
- Shear modulus, G_{12}
- Coefficients of thermal expansion (CTE)
- Moisture Expansion (MTE)



Constituent Materials:

Fiber (Graphite, boron, Silicon): E_f , ν_{12} , G_f, and V_f

Matrix (Resin): E_m , ν_m , G_m ,V_m

Assumptions in Micromechanics of Composites ?

Properties of Composites
(Micromechanics Theory)

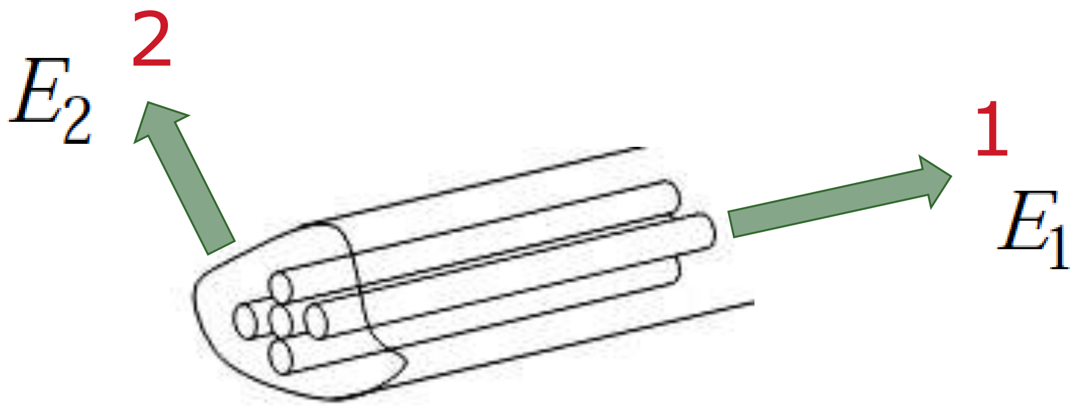
What we know…
(properties of individual **fibres** and **matrix**)

Elastic Modulus

E_f E_m

Volume fractions

V_f V_m



What is the elastic modulus of the composite?

E_1 E_2

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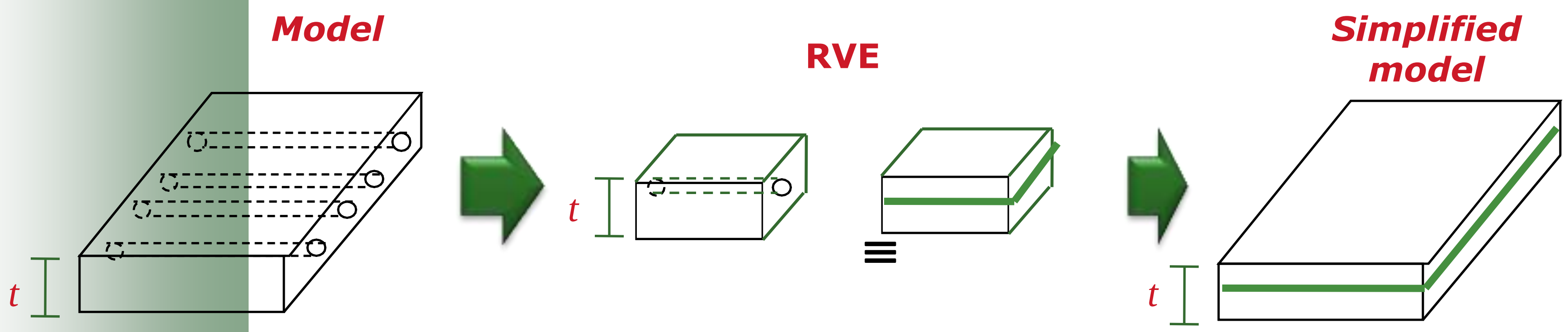
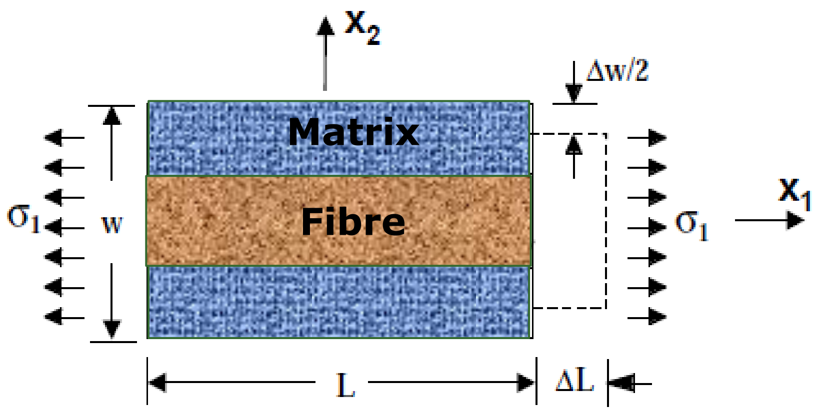
Representative volume element (RVE):

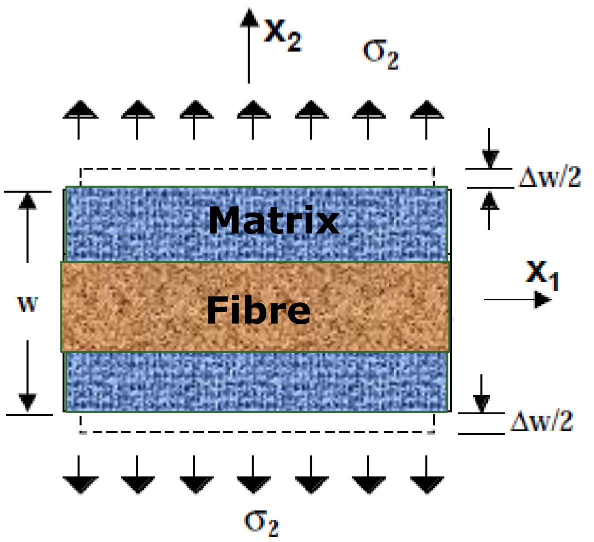


$$1 = V_f + V_m$$

V_f , V_m : fiber and matrix volume fraction

Properties of Composites





Strain in the composite $\varepsilon_1 = \dfrac{\Delta L}{L} = \varepsilon_f = \varepsilon_m$

Total force in composite $\sigma_1 A_c = \sigma_f A_f + \sigma_m A_m$

Stress in the composite $\sigma_1 = \sigma_f \dfrac{A_f}{A_c} + \sigma_m \dfrac{A_m}{A_c} = \sigma_f V_f + \sigma_m V_m$

$$\varepsilon_1 E_1 = \varepsilon_1 E_f V_f + \varepsilon_1 E_m V_m$$

$$E_1 = V_f E_f + V_m E_m$$

$$\nu_{12} = V_f \nu_f + V_m \nu_m$$

$$\Delta W = \varepsilon_2 W = \frac{\sigma_2}{E_f} W_f + \frac{\sigma_2}{E_m} W_m$$

$$\frac{\sigma_2}{E_2} = \sigma_2 \frac{W_f}{E_f W} + \sigma_2 \frac{W_m}{E_m W}$$

Rule of Mixtures

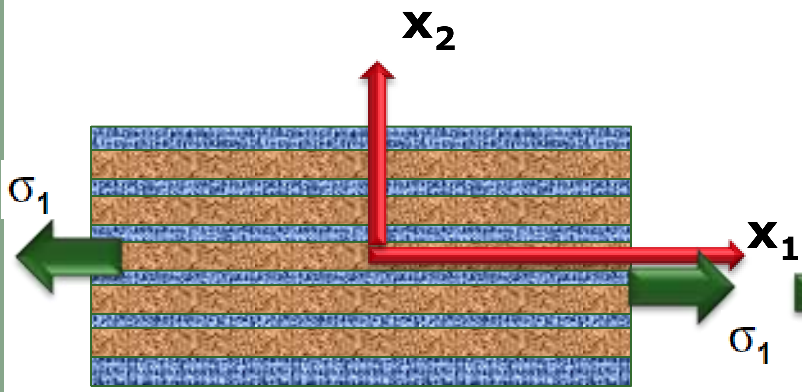
$$\frac{1}{E_2} = \frac{V_f}{E_f} + \frac{V_m}{E_m}$$

$$\frac{1}{G_{12}} = \frac{V_f}{G_f} + \frac{V_m}{G_m}$$

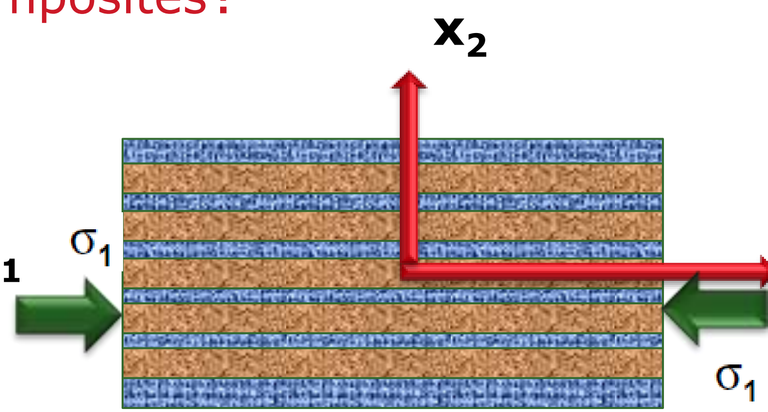
Strength Properties of Composites

- level of stress at which failure occurs
- material constant

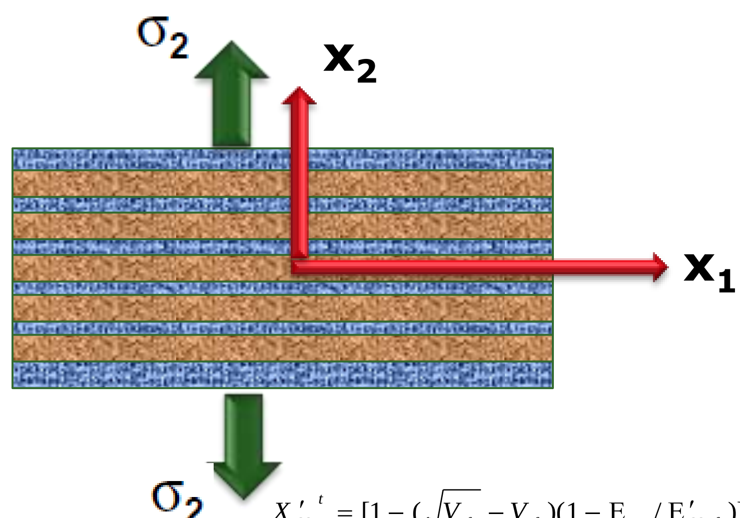
We know strength properties of fibres and matrix. What about the composites?



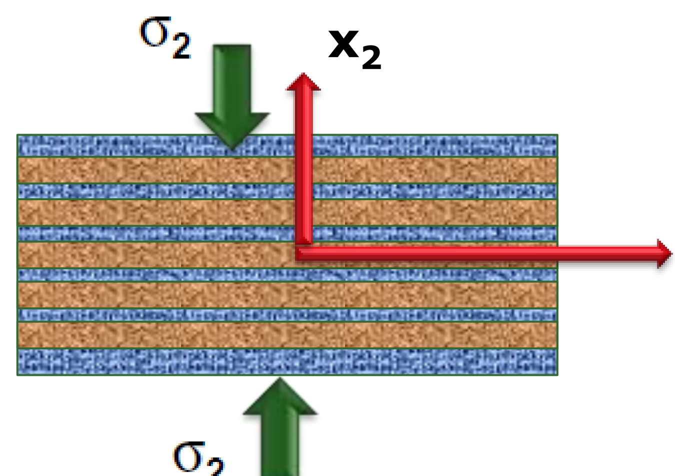
$$X'^{t}_{11} = X'_{11f} V_f + X'_{11m} V_m$$



$$X'^{c}_{11} = 2(V_f + V_m E_m / E_f)(V_f E_f E_m / 3V_m)^{1/2}$$



$$X'^{t}_{22} = [1 - (\sqrt{V_f} - V_f)(1 - E_m / E'_{22f})] X^{t}_{m}$$



$$X'^{c}_{22} = [1 - (\sqrt{V_f} - V_f)(1 - E_m / E'_{22f})] X^{c}_{m}$$

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Hygrothermal Properties

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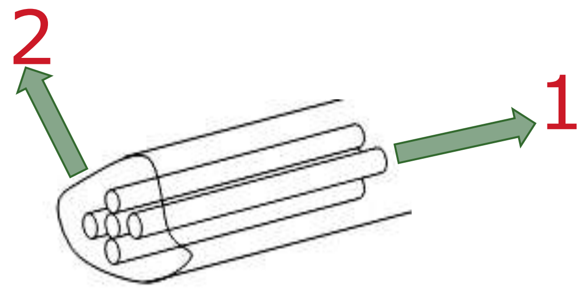
The change in properties due to moisture absorption and temperature change



We know hygrothermal properties of fibres and matrix. What about the composites?

Longitudinal moisture diffusion coefficient of the composite

$$d'_{11} = d'_{11f}\, V_f + d'_{11m}\, V_m$$

Transverse moisture diffusion coefficient of the composite

$$d'_{22} = d'_{22m} \frac{[(d'_{22f} + d'_{22m}) + (d'_{22f} - d'_{22m})V_f]}{[(d'_{22f} + d'_{22m}) - (d'_{22f} - d'_{22m})V_f]}$$

Thermal expansion coefficients

$$\alpha'_{11} = \frac{\alpha'_{11f} E'_{11f} V_f + \alpha'_{11m} E'_{11m} V_m}{E'_{11f} V_f + E'_{11m} V_m}$$

$$\alpha'_{22} = \alpha'_{33} = [\nu'_{12f} V_f + \nu'_{12m} V_m]\left[\frac{\alpha'_{11f} E'_{11f} V_f + \alpha'_{11m} E'_{11m} V_m}{E'_{11f} V_f + E'_{11m} V_m}\right]$$

Particulate and Short fibre composites

Micromechanics Theory ?

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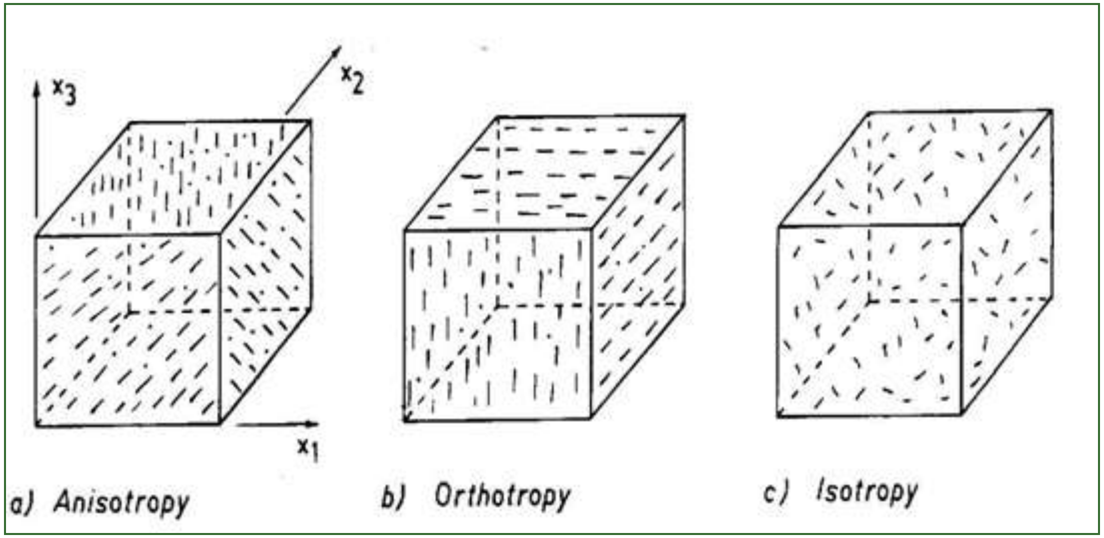
Macromechanical behaviour of composites

Predicting mechanical behaviour of a composite material considering it to be a homogenized material

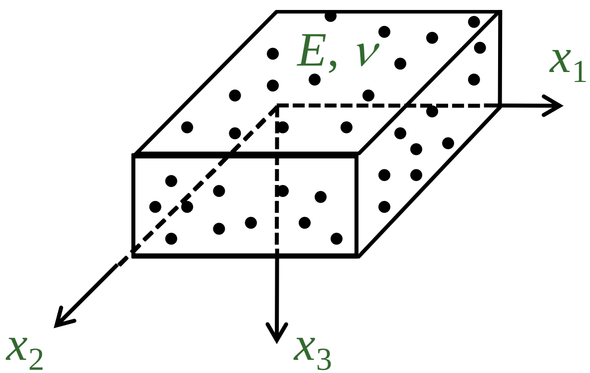
Design of Composites !

Constitutive Relations:



Isotropic composites

- **Example:** particle composite layer
- **Characteristic:** same material properties in all directions



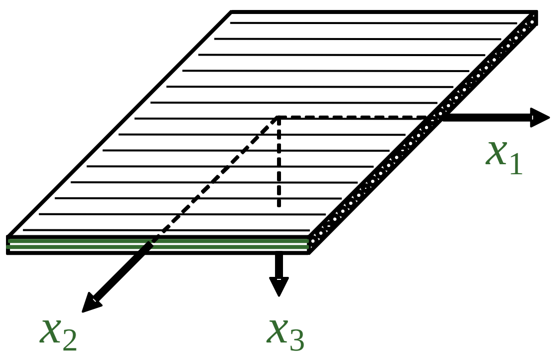
$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{Bmatrix} = \frac{E}{1-\nu^2} \begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & \frac{1}{2}(1-\nu) \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{Bmatrix}$$

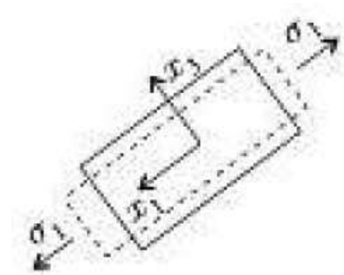
- **Effective properties:**
  - Elastic: E, ν
  - Thermal expansion coefficient: α
  - Strength value: σ^u , τ^u

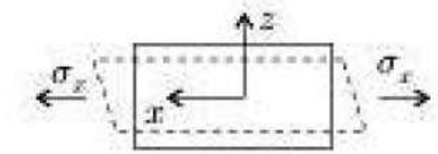
Orthotropic composites

- **Example**: unidirectional fiber composite layer

⇒ The fibers are oriented in two mutually perpendicular directions







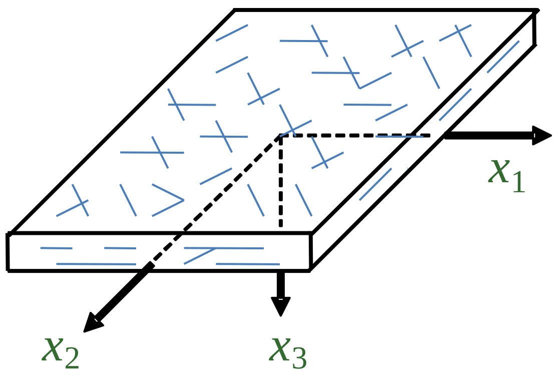
$$\begin{Bmatrix}\sigma_1\\ \sigma_2\\ \tau_{12}\end{Bmatrix}=\frac{E}{1-\nu^2}\begin{bmatrix}\dfrac{E_1}{1-(\nu_{12})^2} & \dfrac{\nu_{12}E_1}{1-(\nu_{12})^2} & 0\\ \nu\dfrac{\nu_{12}E_2}{1-(\nu_{12})^2} & \nu\dfrac{\nu_{12}E_2}{1-(\nu_{12})^2} & 0\\ 0 & 0 & G_{12}\end{bmatrix}\begin{Bmatrix}\varepsilon_1\\ \varepsilon_2\\ \gamma_{12}\end{Bmatrix}$$

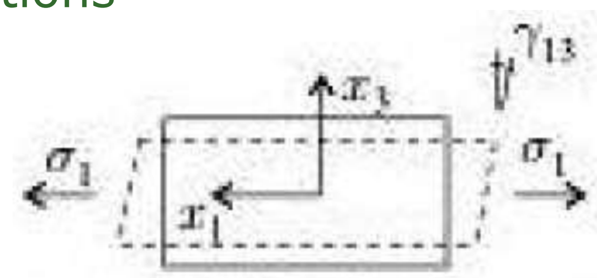
- **Effective properties** (plane stress):
  - Elastic: E_1, E_2, G_{12} , ν_{12}
  - Thermal expansion coefficient: α_1, α_2
  - Strength value: $\sigma^u{}_1$, $\sigma^u{}_2$, $\tau^u{}_{12}$

Anisotropic composites

- **Example:** short fibre composite layer,

$\Rightarrow$ The fibres are oriented randomly or aligned in two non-orthogonal directions





$$\begin{Bmatrix}\sigma_1\\ \sigma_2\\ \tau_{12}\end{Bmatrix} = \begin{bmatrix} D_{11} & D_{12} & D_{13}\\ D_{12} & D_{22} & D_{23}\\ D_{13} & D_{23} & D_{33}\end{bmatrix}\begin{Bmatrix}\varepsilon_1\\ \varepsilon_2\\ \gamma_{12}\end{Bmatrix}$$

- **Effective properties** (plane stress):
  - Elastic: : $D_{11}, D_{22}, D_{33}, D_{12}, D_{13}, D_{23}$
  - Thermal expansion coefficient: $\alpha_1, \alpha_2, \alpha_{12}$
  - Strength value: $\sigma^u_1, \sigma^u_2, \tau^u_{12}$

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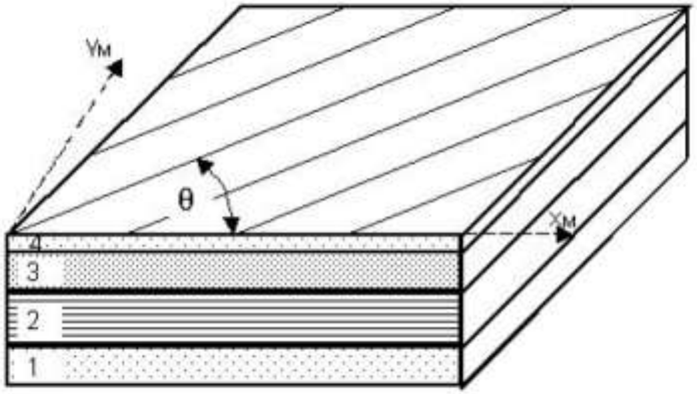
Composite Laminate:
DEFINITION

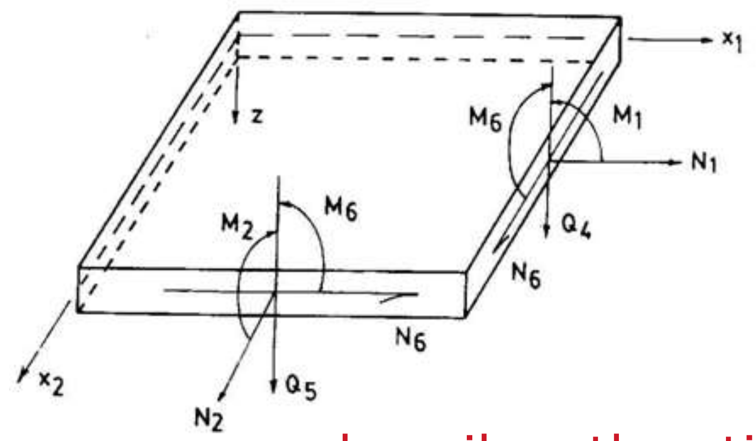
- A fibre composite laminate consists of thin, parallel, unidirectionally reinforced layers, which are firmly bounded together
- Each layer is usually represented as homogeneous anisotropic with effective properties of unidirectional material
- Composite Laminates are typically defined using: **nr of layers, thickness, fibre orientation and layer material**

⇒ Heterogeneity is produced by the different orientations of the layers



Fibres are no longer aligned with the applied stress!!!

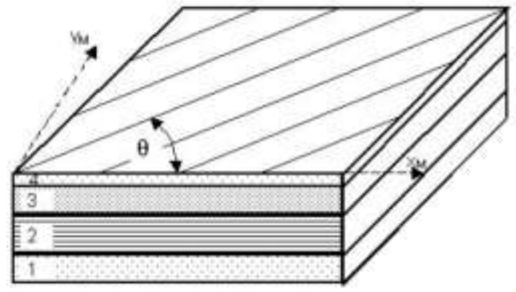
GENERAL LAMINATES



Constitutive Equation

describes the stiffness matrix of a laminate

$$\begin{Bmatrix} N_1 \\ N_2 \\ N_6 \\ M_1 \\ M_2 \\ M_6 \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} \\ A_{12} & A_{22} & A_{26} & B_{12} & B_{22} & B_{26} \\ A_{16} & A_{26} & A_{66} & B_{16} & B_{26} & B_{66} \\ B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} \\ B_{12} & B_{22} & B_{26} & D_{12} & D_{22} & D_{26} \\ B_{16} & B_{26} & B_{66} & D_{16} & D_{26} & D_{66} \end{bmatrix} \begin{Bmatrix} \in_1^0 \\ \in_2^0 \\ \in_6^0 \\ k_1 \\ k_2 \\ k_6 \end{Bmatrix}$$



inplane, extension bending coupling and bending stiffness

$$A_{ij} = \sum_{k=1}^{n} (Q_{ij})_k (z_k - z_{k-1})$$

$$B_{ij} = \frac{1}{2} \sum_{k=1}^{n} (Q_{ij})_k (z_k^2 - z_{k-1}^2)$$

$$D_{ij} = \frac{1}{3} \sum_{k=1}^{n} (Q_{ij})_k (z_k^3 - z_{k-1}^3)$$

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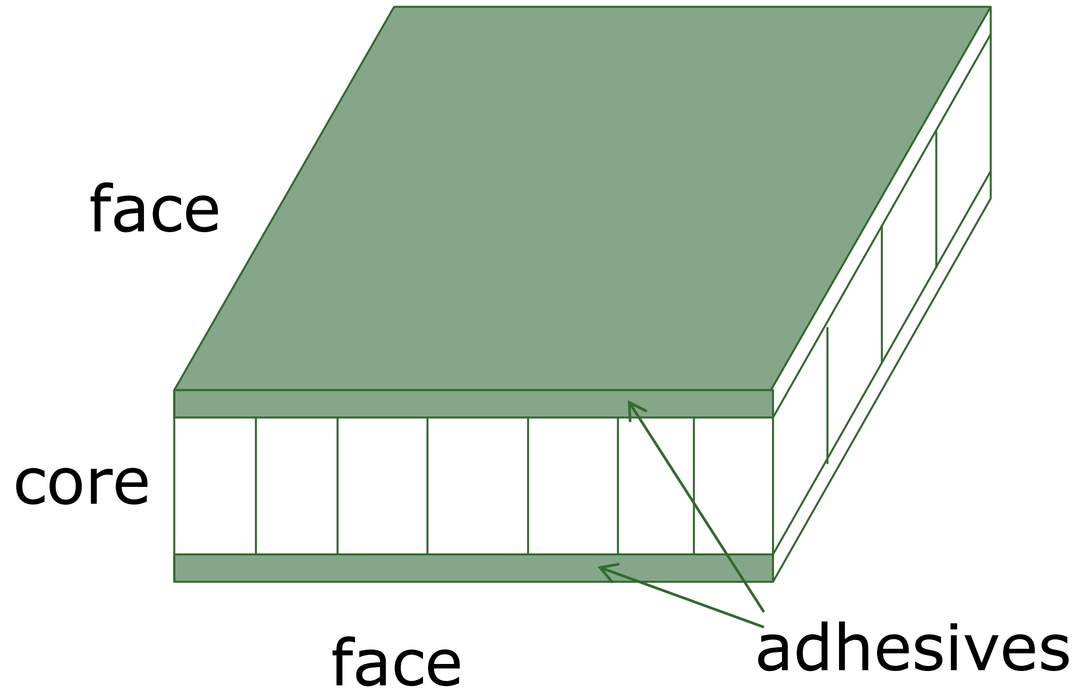
SANDWICH STRUCTURE:

A composite construction, where a relatively thick core layer of low strength, stiffness and density is sandwiched between two thin, face layers of strong and dense materials



Vibration and buckling analysis of laminated plates

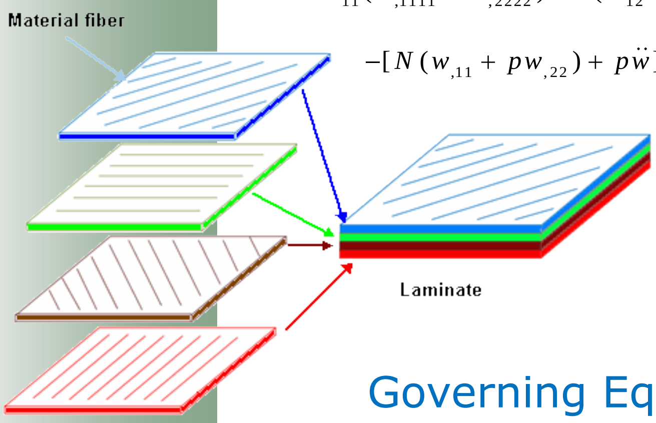
Cross-ply laminations of stacking sequence $[0/90]_n$

(7.65)

$$A_{11}\,u^0_{1,11} + A_{66}\,u^0_{1,22} + (A_{12} + A_{66})\,u^0_{2,12} - B_{11}\,w_{,111} = 0$$

$$(A_{12} + A_{66})\,u^0_{1,12} + A_{66}\,u^0_{2,11} + A_{22}\,u^0_{2,22} + B_{11}\,w_{,222} = 0$$

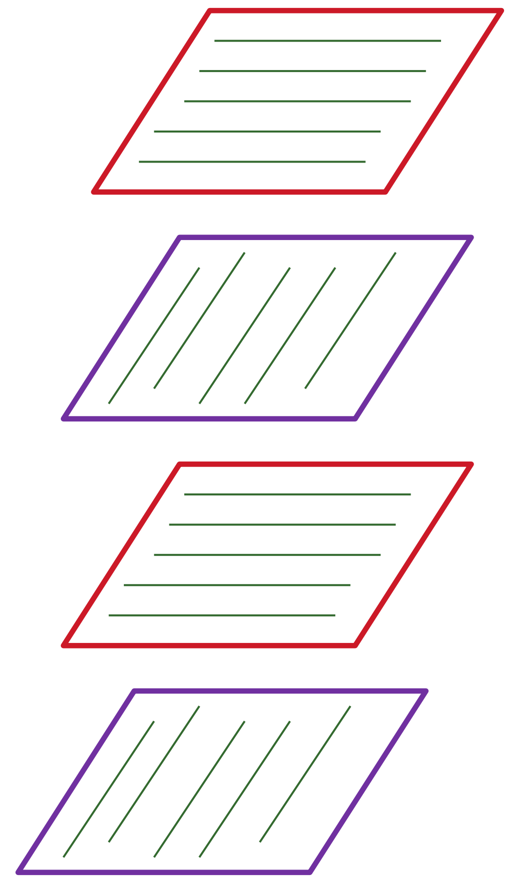
$$D_{11}(w_{,1111} + w_{,2222}) + 2(D_{12} + 2D_{66})\,w_{,1122} - B_{11}(u^0_{1,111} - u^0_{2,222}) = q$$
$$-[N(w_{,11} + p\,w_{,22}) + p\ddot{w}]$$



$$u^0_1 = A_{mn}\cos\frac{m\pi x_1}{a}\sin\frac{n\pi x_2}{b}e^{i\omega_{mn}t}$$

$$u^0_2 = B_{mn}\sin\frac{m\pi x_1}{a}\cos\frac{n\pi x_2}{b}e^{i\omega_{mn}t}$$

$$w = W_{mn}\sin\frac{m\pi x_1}{a}\sin\frac{n\pi x_2}{b}e^{i\omega_{mn}t}$$

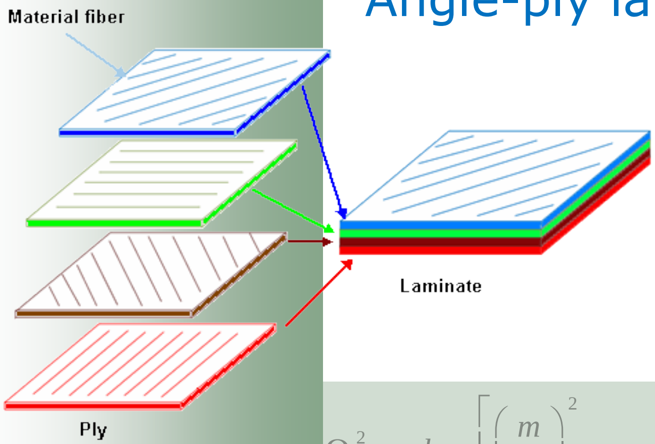


Governing Equations

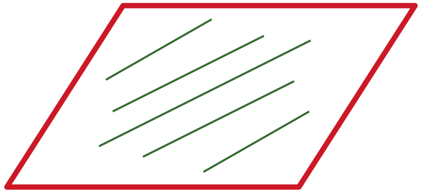
$$\Omega^2_{mn} + k_{mn}\left[\left(\frac{m}{\eta}\right)^2 + pn^2\right] = \frac{D_{11}}{D_{22}}\left(\frac{m^4}{\eta^4} + n^4\right) + 2\left(\frac{D_{12}}{D_{22}} + 2\frac{D_{66}}{D_{22}}\right)\frac{m^2n^2}{\eta^2}$$
$$-\left(\frac{B_{11}^2}{D_{22}}\right)\left(\frac{m^6H_{mn} + 2m^3n^3\eta^3F_{mn} + n^6\eta^6E_{mn}}{\eta^4(E_{mn}H_{mn} - F_{mn}^2)}\right)$$

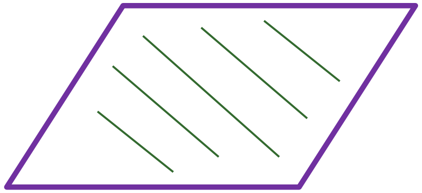
$$\eta = \frac{a}{b} \qquad \Omega_{mn}^2 = \frac{p\,\omega_{mn}^2 b^4}{\pi^4 D_{22}} \qquad k_{mn} = \frac{Nb^2}{\pi^2 D_{22}},$$

Vibration and buckling analysis of laminated plates



Angle-ply laminations





Governing Equations

$$\Omega_{mn}^2 + k_{mn}\left[\left(\frac{m}{\eta}\right)^2 + pn^2\right] = \frac{D_{11}}{D_{22}}\frac{m^4}{\eta^4} + 2\left(\frac{D_{12}}{D_{22}} + 2\frac{D_{66}}{D_{22}}\right)\frac{m^2n^2}{\eta^2} + n^4$$

$$-\frac{1}{N_{mn}}\left[\frac{m^2}{\eta^2}\left(B_{16}\frac{m^2}{\eta^2} + 3B_{26}n^2\right)\frac{L_{mn}}{D_{22}} + n^2\left(3B_{16}\frac{m^2}{\eta^2} + B_{26}n^2\right)\frac{M_{mn}}{D_{22}}\right]$$

$$k_{mn} = \frac{Nb^2}{\pi^2 D_{22}},$$

$$\Omega_{mn}^2 = \frac{p\,\omega_{mn}^2 b^4}{\pi^4 D_{22}}$$

$$\eta = \frac{a}{b}$$

$$L_{mn} = (A_{11}m^2 + A_{66}n^2\eta^2)(B_{16}m^2 + 3B_{26}n^2\eta^2) - n^2\eta^2(A_{12} + A_{66})(3B_{16}m^2 + B_{26}n^2\eta^2)$$

$$M_{mn} = (A_{66}m^2 + A_{22}n^2\eta^2)(3B_{16}m^2 + B_{26}n^2\eta^2) - m^2(A_{12} + A_{66})(B_{16}m^2 + 3B_{26}n^2\eta^2)$$

$$N_{mn} = E_{mn}H_{mn} - F_{mn}^2$$

OUTLINE

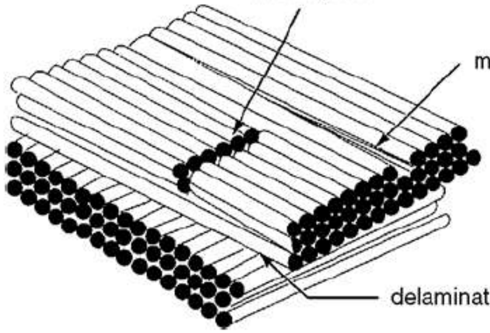
The topics covered include:

- Overview of composites and their applications
- Micromechanics theory for analysis of composites
- Properties (elastic properties, strength properties and hygrothermal properties) in (i) unidirectional composites and (ii) particulate and short fibre composites
- Macromechanical behaviour of composites
- Definition of composite laminates and sandwich structures; vibration and buckling analysis of laminated plates
- **Laminate damage and failure criteria in composites**
- Finite Element (FE) analysis for composites; Bending and vibration of Composites Shells
- Numerical simulation of composites using commercial FE softwares

Laminates damage

- Laminate composite structure develop

- Matrix cracks
- Fibre-matrix debonds
- Fibre fractures
- Delaminations



loss of stiffness and strength of the material!

Once the mechanical properties of the layers are known, the initial failure of a layers within a laminate or structure can be predicted by applying an appropiate failure criterion

- Failure criterion is used only to check whether allowables are exceeded

Composite (anisotropic) failure criterion

- **Layer failure index (F>1)**

Maximum stress criterion

$$F = \max\left(\left|\frac{\sigma_1}{X}\right|, \left|\frac{\sigma_2}{Y}\right|, \left|\frac{\sigma_{12}}{S}\right|\right)$$

Maximum strain criterion

$$F = \max\left(\left|\frac{\varepsilon_1}{\tilde{X}}\right|, \left|\frac{\varepsilon_2}{\tilde{Y}}\right|, \left|\frac{\gamma_{12}}{\tilde{S}}\right|\right)$$

Tsai-Hill anisotropic criterion:

$$F = \frac{\sigma_1^2}{X^2} - \frac{\sigma_1 \sigma_2}{X^2} + \frac{\sigma_2^2}{Y^2} + \frac{\tau_{12}^2}{S^2}$$

- **Bonding failure index**

$$FB = \frac{\max(|\tau_{1z}|, |\tau_{2z}|)}{SB}$$

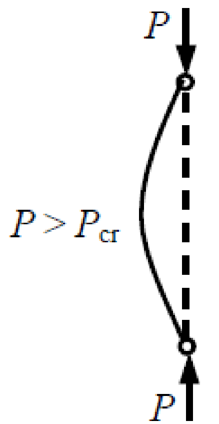
- **Global final failure index for composite element**

  Maximum of all computed layer and bonding failure indices

Buckling

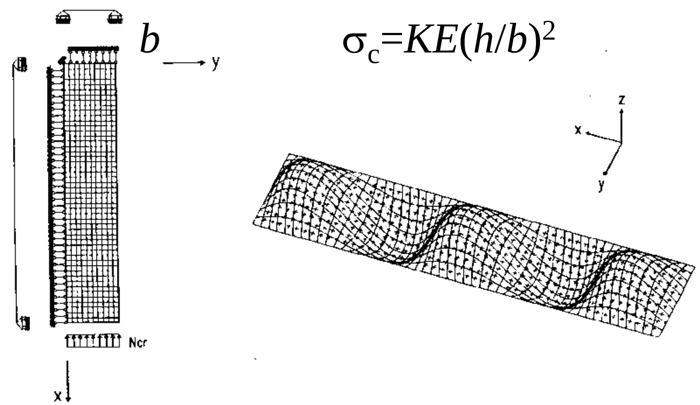
- Sudden large out-of-plane displacements occur when the critical value of the load is reached.

Compressed bar



$$P_{cr} = \frac{\pi^2 EI}{l^2}$$

Compressed isotropic plate



$$\sigma_c = KE(h/b)^2$$

Linear Buckling Analysis

$$(\mathbf{K} - \lambda \mathbf{K}_G)U = 0$$

λ: smallest positive eigenvalue is associated with buckling, λ_{cr}.

K: Stiffness matrix, $\mathbf{K}_G$: geometric stiffness matrix

$$P_{cr} = \lambda_{cr} P_{ref}$$ *Critical or buckling load*

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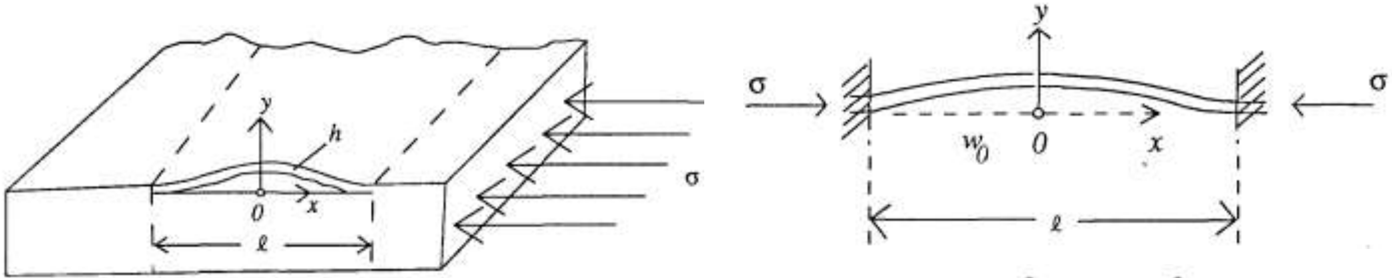
Delamination buckling

- Local delamination can be seen as a crack in the bond.
- Laminated plastic material possess fairly low bonding

→ low velocity impacts and defects in manufacturing lead to local delamination



$$\sigma_c = \frac{\pi^2 E}{3(1-\nu^2)}\left(\frac{h}{\ell}\right)^2 ,$$

Delamination buckling can be considered as a classical linear problem of buckling of a strip with fixed ends

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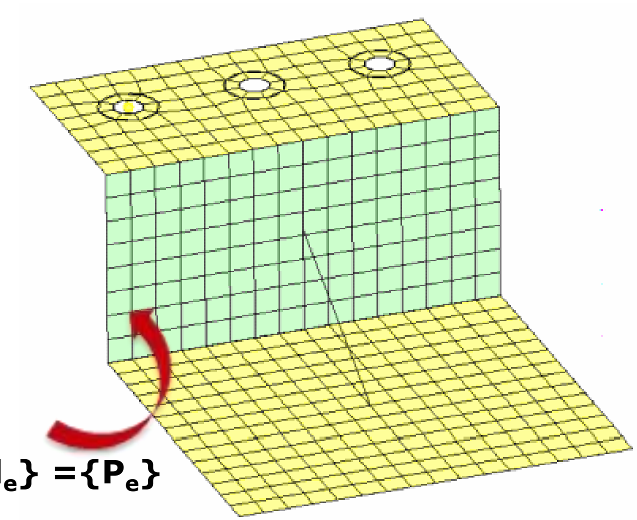
Finite Element (FE) Analysis

Consider: an arbitrary plate geometry with complicated loading and boundary conditions

~~Analytical Technique~~

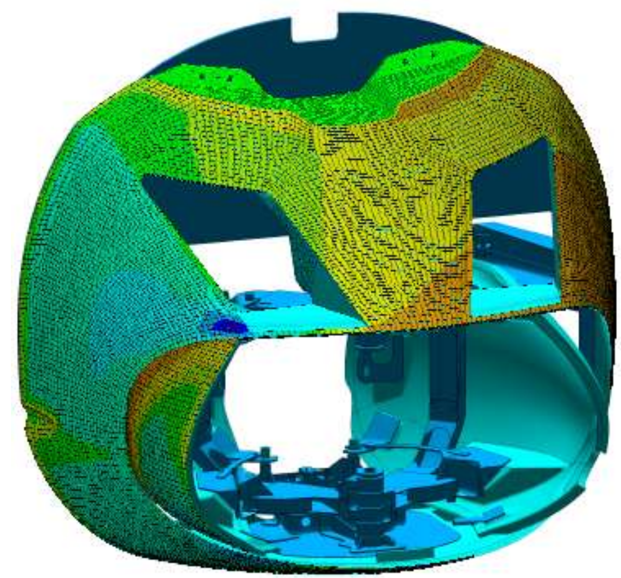
Numerical analysis technique

Finite Element Method



$[K_e]\{d_e\} = \{P_e\}$

Meshing of joint plates

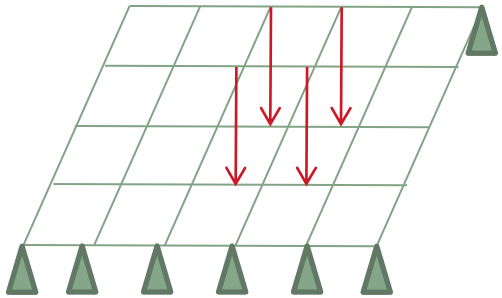


FE of train nose section

Overview - Example

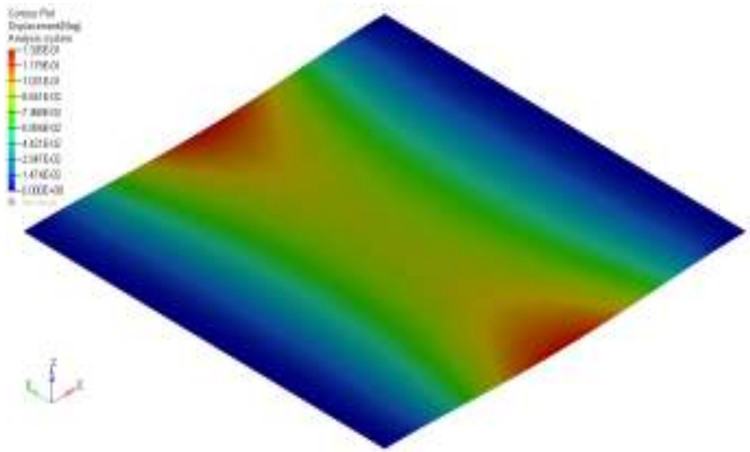
What do we know:

- We have a plate
- We know how it is supported
- We know what composite material it is made of
- We know what the loading is



What would we like to know?

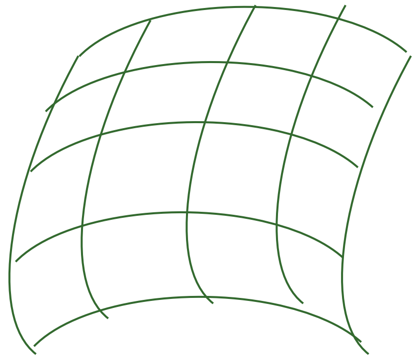
- Displacements
- Strains
- Stresses
- Delamination
- Fracture



Bending and vibration of Composites Shells Finite Elements Approach

The stress resultants on a composite shell

$$\begin{Bmatrix} N_1 \\ N_2 \\ N_6 \\ M_1 \\ M_2 \\ M_6 \\ Q_4 \\ Q_5 \end{Bmatrix} = \begin{bmatrix} A_{ij} & B_{ij} & 0 \\ B_{ij} & D_{ij} & 0 \\ 0 & 0 & K_{ij} S_{ij} \end{bmatrix} \begin{Bmatrix} \in_1^0 \\ \in_2^0 \\ \in_6^0 \\ K_1 \\ K_2 \\ K_6 \\ \in_4^0 \\ \in_5^0 \end{Bmatrix}$$



$$\{P_e\} = \iint [N]^T \{q\} dx_1 dx_2$$ **: Element load vector**

$$[M_e] = \iint [N]^T [P][N] dx_1 dx_2$$ **: Element mass matrix**

$$[K_e] = \iint [B]^T [D][B] dx_1 dx_2$$ **: Element stiffness matrix**

Vibration Equation

$$\left| [K] - \omega_{mn}^2 [M] \right| = 0$$

Bending Equation

$$[K]\{d\} = \{P\}$$

Finite Element (FE) softwares used for Composites Analysis

ABAQUS, ALTAIR HYPERWORKS, ANSYS and NASTRAN

Common characteristics:
FE solvers for solids, fluids, thermal, acoustic, electromagnetic and/or multiphysics problems

Robust and reliable meshing tools

Several optimization methods: topological, size and shape

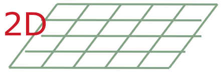
Combination of performance data management, process automation and good data exchange facilities for the solution of large scale optimization problems

Steps in a FE software

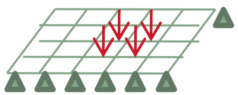
- Geometry definition:

  CAD, drawing facilities

- Element definition & FE mesh construction



- Application of constraints and loads



- Selection of the type of Material

- Element properties definition

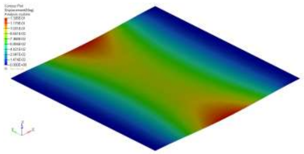
- Type of problem:

  Static, dynamic

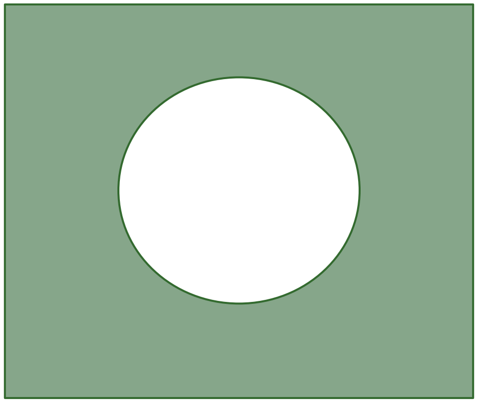
- Run the program

- Analysis of results:

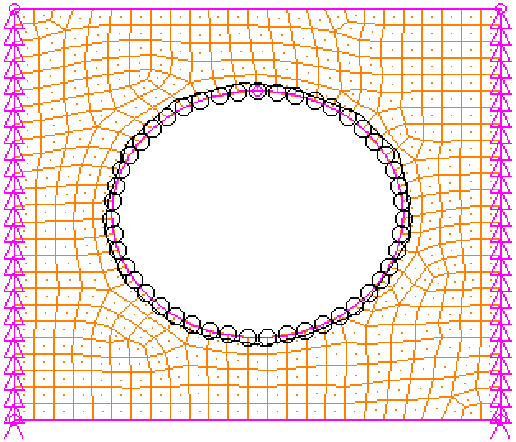
  Displacements, stresses, etc



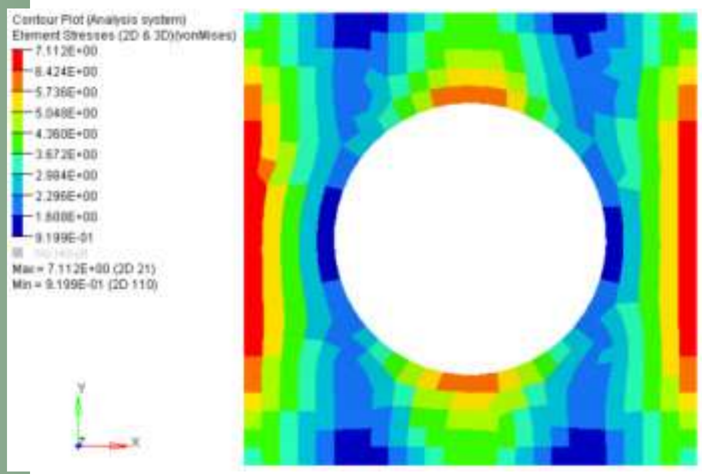
Analysis Steps in Hyperworks



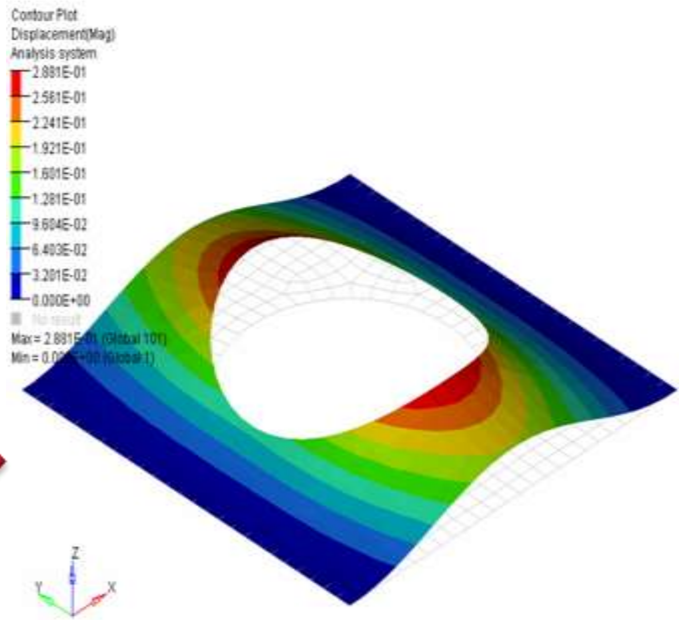
Geometrical Model



Finite Element Model



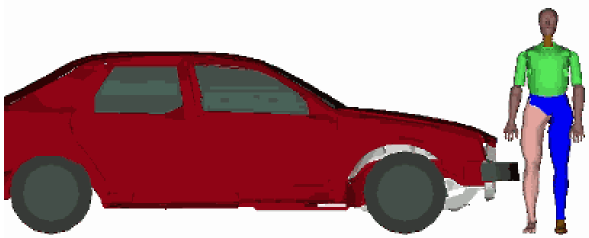
Post Analysis Model

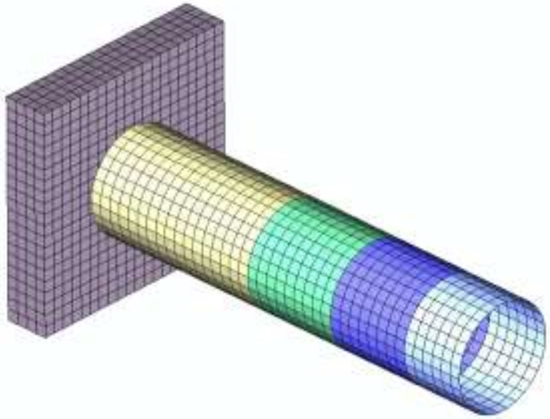


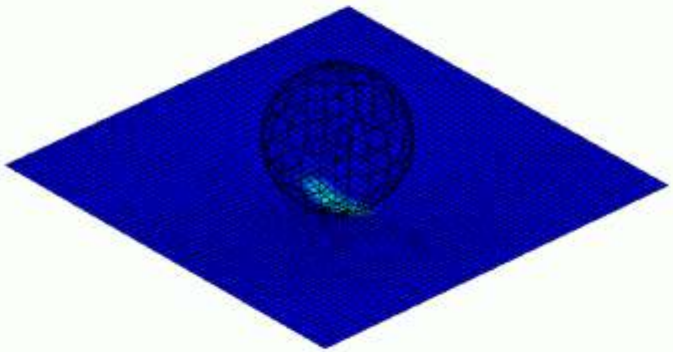
Deformation in Hyperview

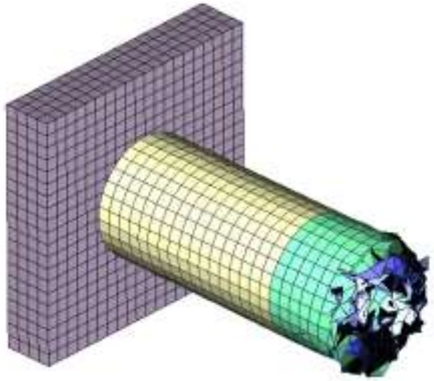
courtesy Altair Engineering

FE Solver
&
DYNAMIC (CRUSH) ANALYSIS









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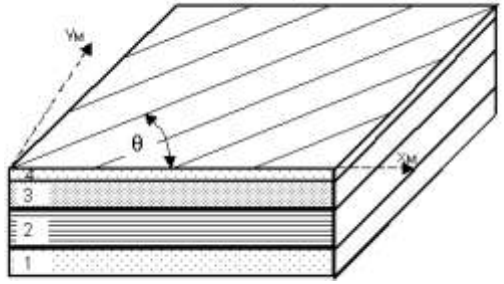
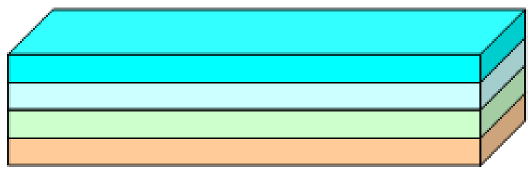
Topology Optimisation of Composites

-PCOMP

-HyperLaminate



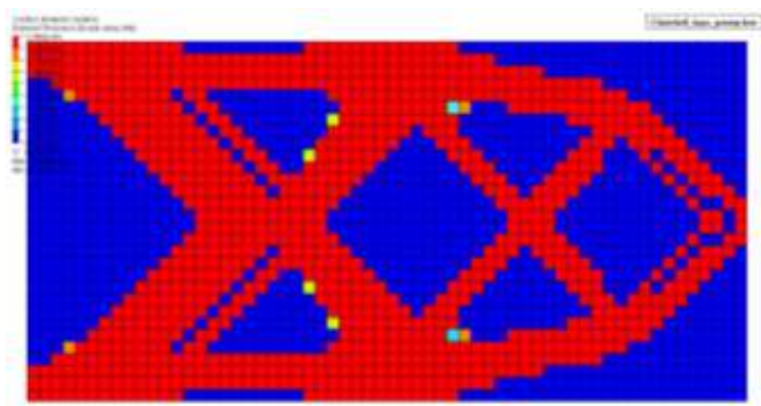
Composite Cantilever Plate



PCOMP

90
45
-45
0

Symmetry & membrane property [SYMEM]



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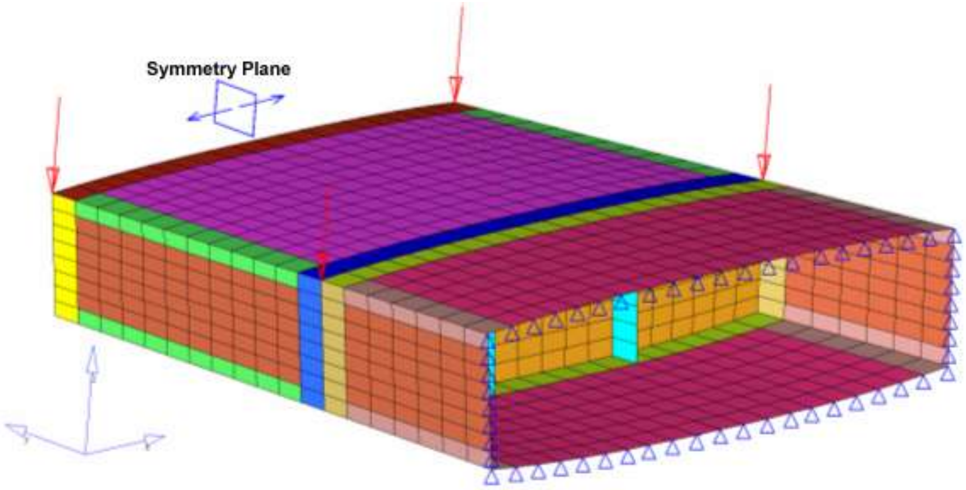
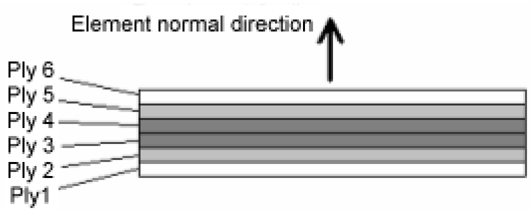
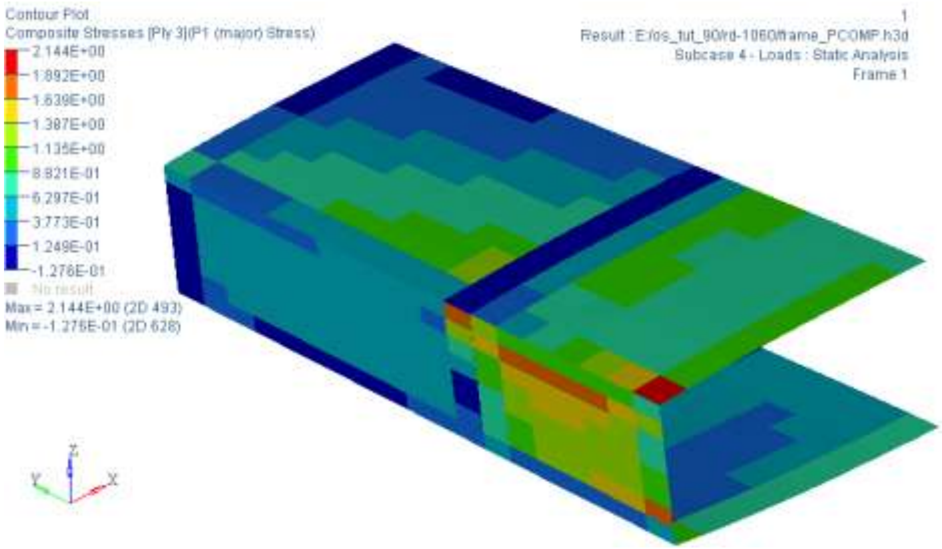
Composite Aircraft Structure FE Model







courtesy Altair Engineering

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