Procedure to Calibrate Composite Materials by Serial/Parallel Mixing Theory

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Invited Session: Lightweight Composite Materials in Shipbuilding

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BRIEF DESCRIPTION

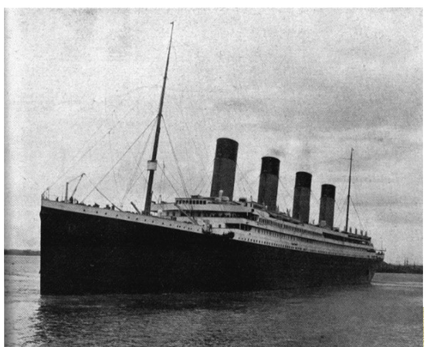
- **INTRODUCTION**
  - Composite materials on naval industry.
  - Analysis of composite structures and challenges.
- **FORMULATION: SERIAL/PARALLEL MIXING THEORY**
  - **S/P Mixing Theory (S/P RoM) as a constitutive law manager.**
- **CALIBRATION PROCEDURE**
  - **Tests and methodology.**
- **RESULTS & CONCUSIONS**
  - **Failure modes and load-position graphs.**

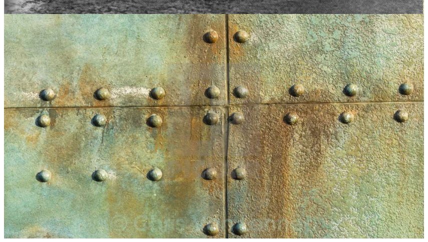
INTRODUCTION. Use of composite materials on naval industry

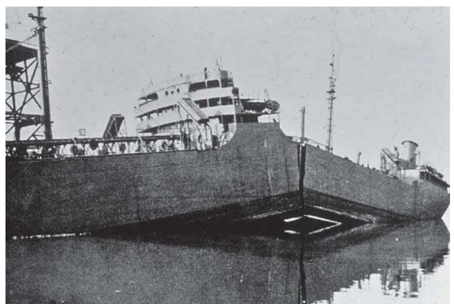
SOLUTIONS ON NAVAL INDUSTRY ARE BECOMING MORE SPECIFIC, AS WELL AS THE MATERIALS USED TO DEAL WITH ARE BECOMING MORE COMPLEX.
COMPLEX SOLUTIONS REQUIRE SPECIFIC TOOLS

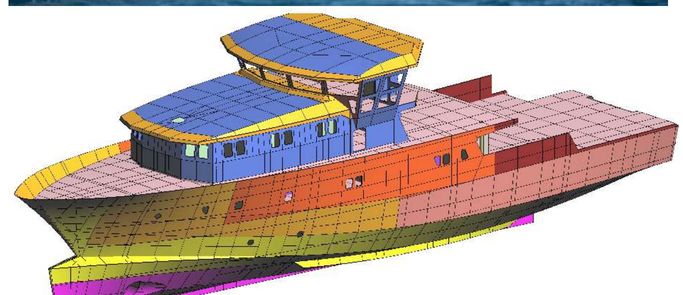
USE OF NUMERICAL MODELS

TO RESOLVE THE PERFORMANCE OF COMPLEX MATERIALS AND COMPLEX STRUCTURES





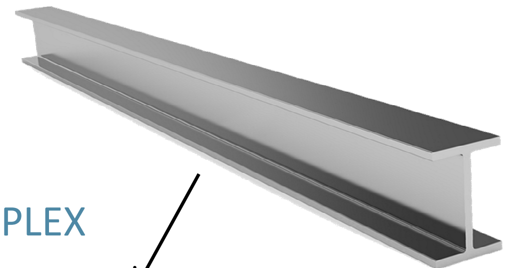




INTRODUCTION. Analysis of composite structures.

Limitations of usual models for composite materials

- Usually, composites are treated as orthotropic elastic materials.
- Failure analysis by means of failure criteria (maximum strain or stress, Tsai-Hill, Tsai-Wu,…).
- Ad hoc formulations require huge testing campaigns.
- Final collapse of the structure is hard to obtain by failure criteria.



NO CHANCE TO OBTAIN POST-FAILURE PERFORMANCE NOR MATERIALS WITH COMPLEX MICRO-STRUCTURES

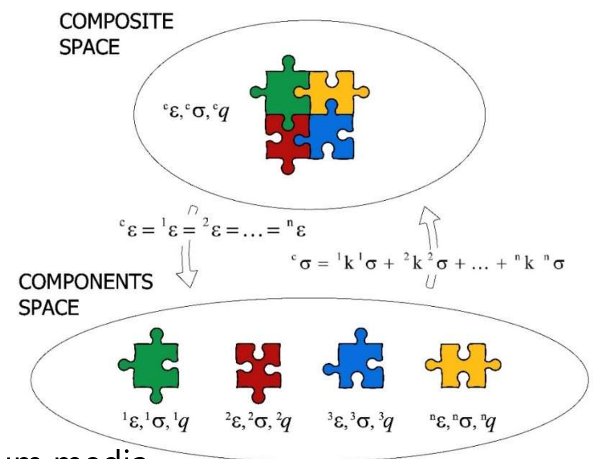
$$f_1(\sigma_1) + f_2(\sigma_2) + f_{11}(\sigma_1)^2 + f_{22}(\sigma_2)^2 + 2f_{12}(\sigma_1\sigma_2) + f_3(\tau_{12})^2 = 1$$

Elastic analysis:

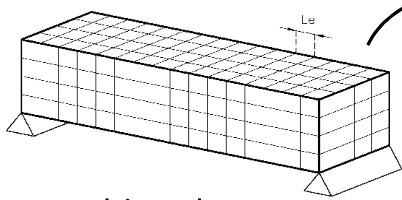
$E_1, E_2, E_3, \nu_{12}, \nu_{23}, \nu_{31}$

One step beyond.

- A good model should be able to obtain the composite stresses and the evolution of the internal variables from the strains calculated by the FEM model.



ε

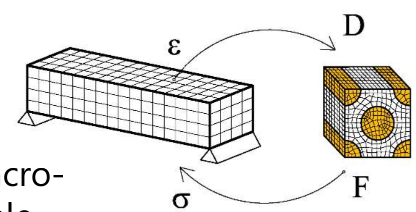


Material Model

σ, q

Models based on multi-scale procedures:

3. Numerical homogenization



Micro-Scale

Macro-Scale

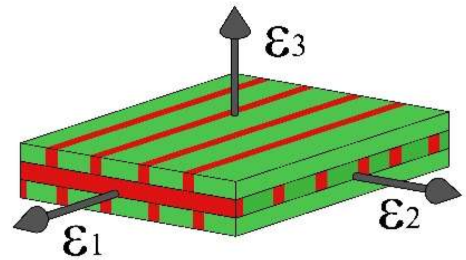
Models based on continuum media mechanics:

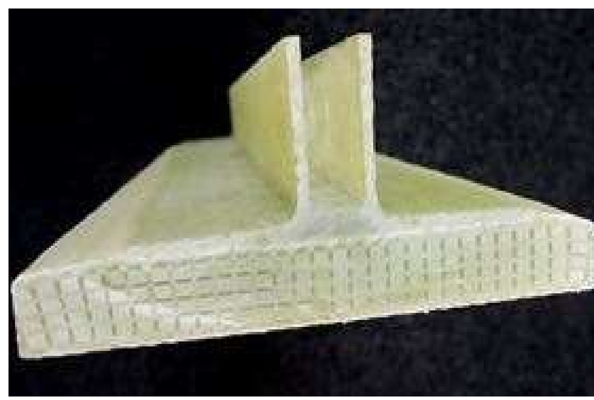
1. Constitutive equations.
2. **Phenomenological homogenization (Rule of Mixtures)**

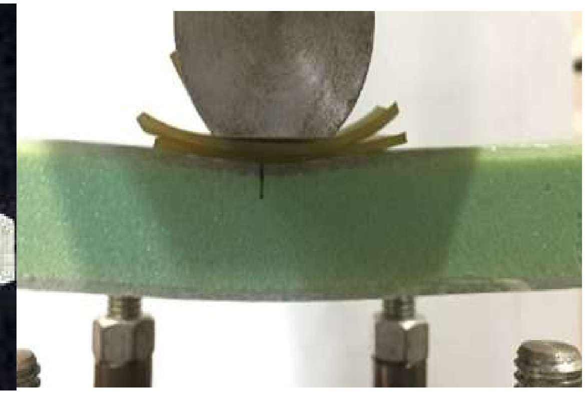
INTRODUCTION. Challenges with composites

INTRODUCTION. Challenges with composites

- Anisotropic behavior: material properties are orientation-dependent.
- Different failure modes (delamination, matrix cracking, fiber breakage,…)
- Lack of experimental data compared with other materials.







HOW TO DEAL WITH THESE CHALLENGES?

⇩

Standardization of tests and calibration methods

SERIAL/PARALLEL MIXING THEORY. Hypothesis of RoM.

Composites mechanical performance is obtained from components.
Hypothesis of RoM:

I) Each infitesimal volumen of the composite contains a finite number of component materials.

II) The contribution of each component is proportional to its volumetric participation.

III) The volume of each component is minor than the composite volumen.

IV) Iso-strain condition on parallel direction (fiber direction).

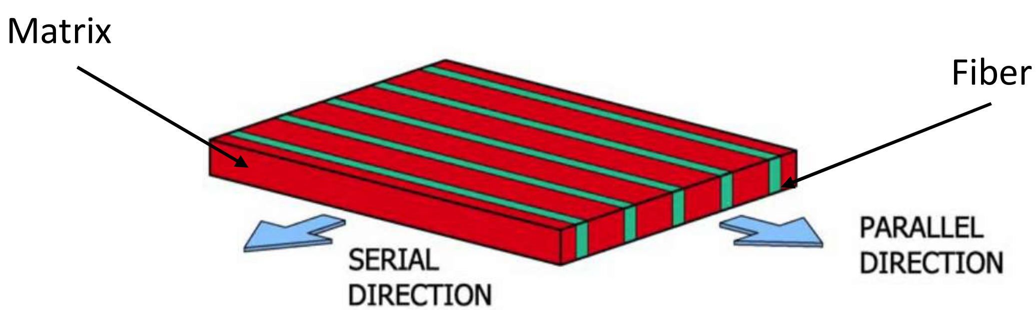
V) Iso-stress condition on directions different than fiber direction.

Composite stress is obtained by solving each constitutive equation for each component (constitutive law manager).

$$ {}^{c}\sigma = \frac{\partial \Psi}{\partial \varepsilon} = \sum_{i=1}^{n} {}^{i}k \frac{\partial \Psi^{i}}{\partial \varepsilon^{i}} = \sum_{i=1}^{n} {}^{i}k \cdot {}^{i}\sigma $$

SERIAL/PARALLEL MIXING THEORY

This formulation is a constitutive equations manager that provides the response of the composite by coupling the constitutive equations of its components.



Compatibility equations

Parallel behavior

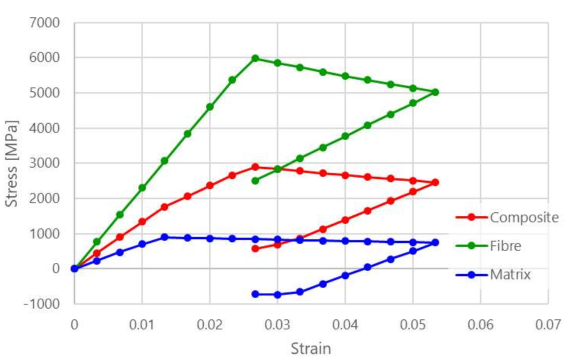
$$\begin{cases} {}^{c}\varepsilon_P = {}^{m}\varepsilon_P = {}^{f}\varepsilon_P \\ {}^{c}\sigma_P = {}^{m}k\,{}^{m}\sigma_P + {}^{f}k\,{}^{f}\sigma_P \end{cases}$$

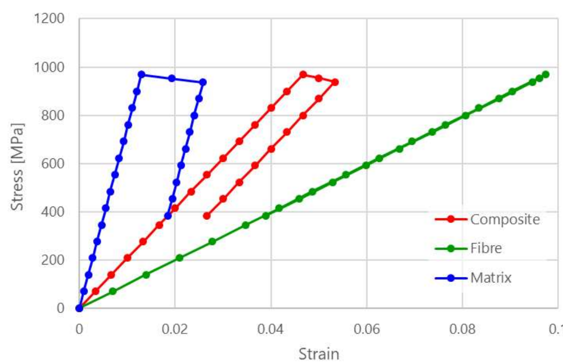
Serial behavior

$$\begin{cases} {}^{c}\varepsilon_S = {}^{m}k\,{}^{m}\varepsilon_S + {}^{f}k\,{}^{f}\varepsilon_S \\ {}^{c}\sigma_S = {}^{m}\sigma_S = {}^{f}\sigma_S \end{cases}$$

Check for convergence:

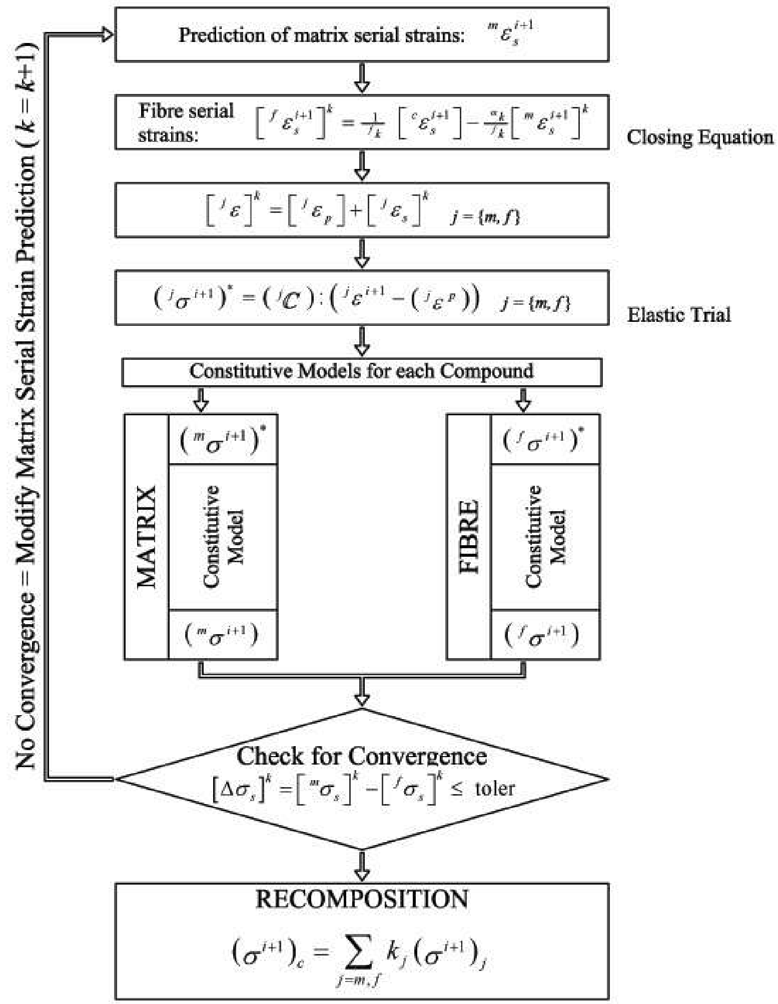
$$[\Delta\sigma_S]^k = [{}^{m}\sigma_S]^k - [{}^{f}\sigma_S]^k \approx 0$$





SERIAL/PARALLEL MIXING THEORY

1. F.E. model gives composite strains.
2. Composite strains are decomposed on serial and parallel.
3. It is given a prediction of matrix serial strains ${}^{m}\varepsilon_{S}$.
4. Then, matrix and fiber strain is obtained.
5. At this point, constitutive models for each component are applied, obtaining the stresses for the fiber and matrix.
6. Convergence is checked as:
$$[\Delta\sigma_S] = [{}^{m}\sigma_S] - [{}^{f}\sigma_S] \leq toler$$
7. If no convergence is achieved, initial prediction of matrix strains is modified by a iterative process of Newton-Raphson.



SERIAL/PARALLEL MIXING THEORY

ADVANTAGES OF USING S/P MIXING THEORY

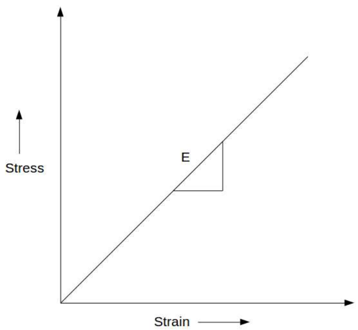
- **Any staking sequence, no matter fiber orientation or fiber volume fraction.**
- **Formulation is able to couple different fiber/matrix systems, different constitutive laws.**
- **Non-linear performance of the composite can be defined from its constituents.**

HOW DO SP RoM **WORKS** AT COMPOSITE LEVEL?

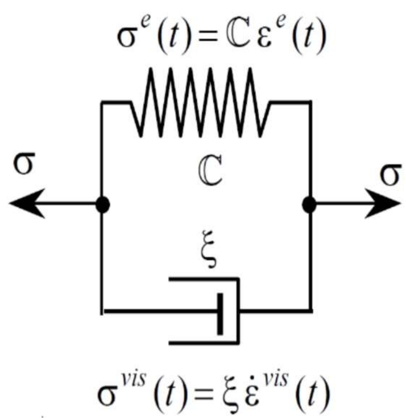
- **Classic RoM is applied between plies in the same GP.** → ${}^{c}\boldsymbol{\varepsilon} = {}^{p1}\boldsymbol{\varepsilon} = \cdots = {}^{pi}\boldsymbol{\varepsilon} = \cdots = {}^{pn}\boldsymbol{\varepsilon}$
- **SP RoM is applied inside each ply.** $\boldsymbol{\varepsilon_i} = \boldsymbol{\sigma_i}$
- **Stress on the whole composite is obtained applying classic RoM.** ${}^{c}\boldsymbol{\sigma} = \sum_{i=p1}^{n} ({}^{i}\boldsymbol{k} \; {}^{i}\boldsymbol{\sigma})$

S/P MIXING THEORY. Constitutive laws for materials.

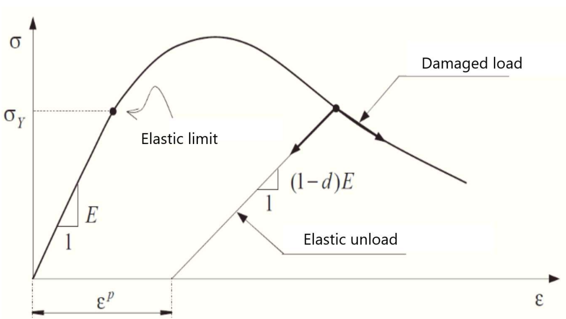
Elastic law



Visco-plastic law

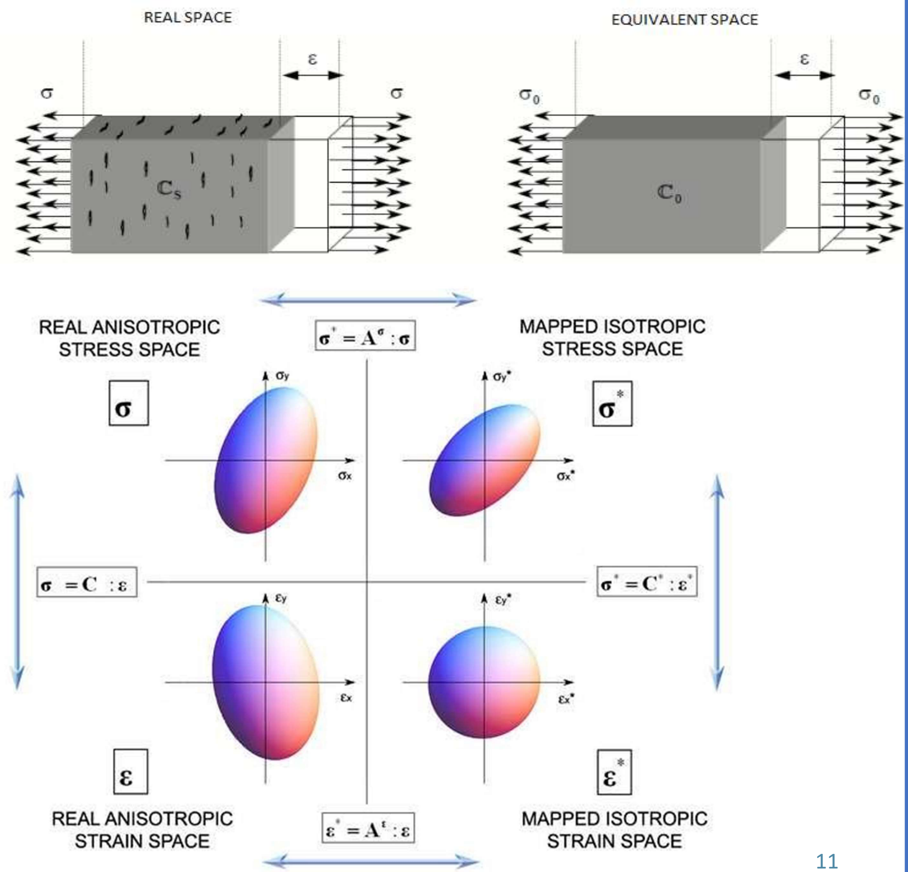


Damage-plastic law



Damage law

$$\sigma = (1-\mathrm{d})\cdot\sigma_0 \rightarrow C_s\!:\varepsilon = (1-d)\cdot C_0\!:\varepsilon$$



EXPERIMENTAL CAMPAIGN

- Two systems were selected: LEO System and Sicomin system.
  - LEO System: Vinylester matrix reinforced with fiber glass.
  - Sicomin System: Epoxy matrix reinforced with fiber glass.

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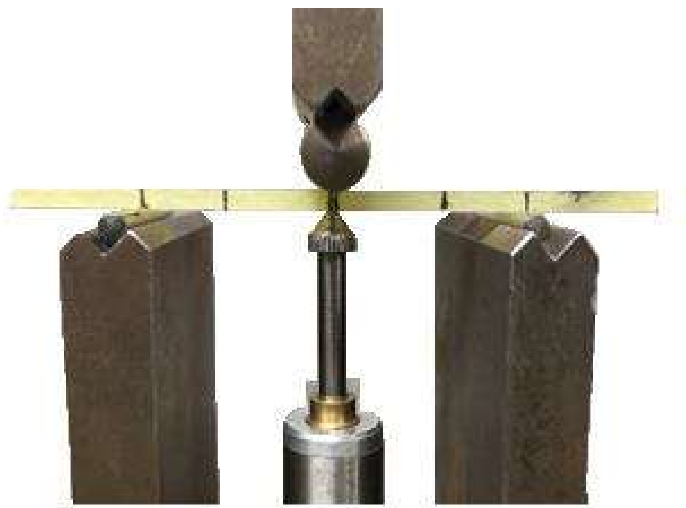
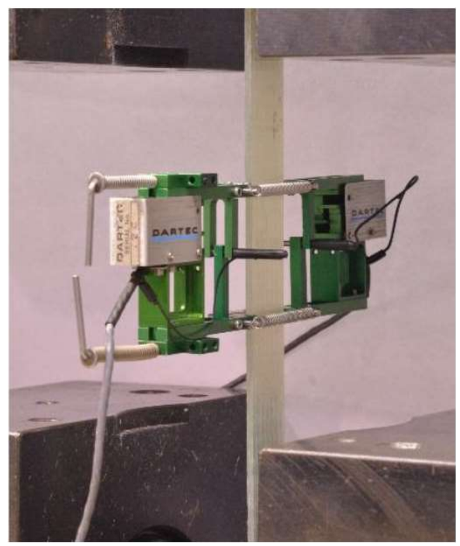
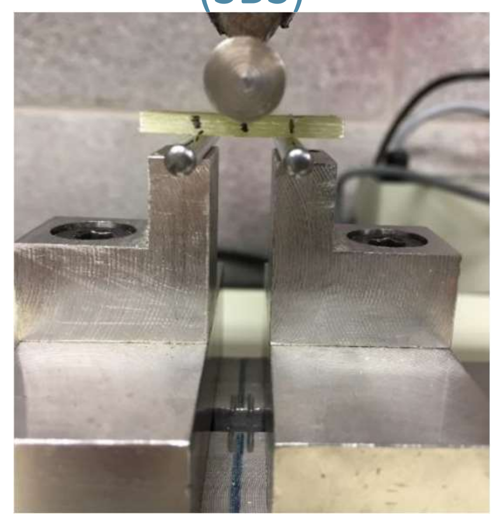
3-POINT BENDING TEST (3PB)



TENSILE TEST



SHORT BEAM SHEAR TEST (SBS)



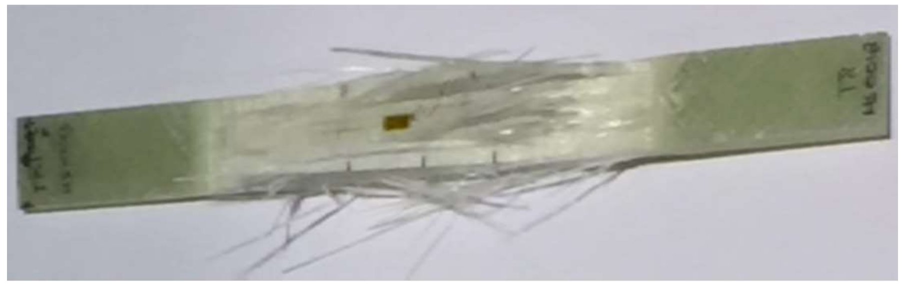
CALIBRATION PROCEDURE

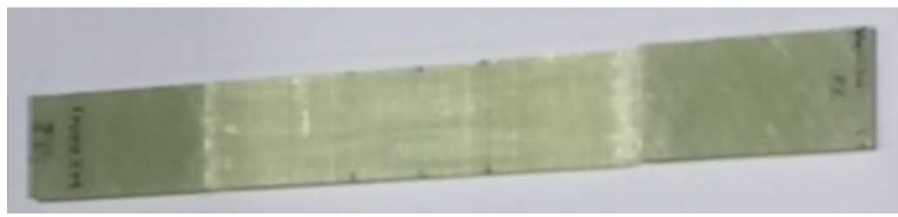
WHICH PARAMETERS ARE REQUIRED?

- **Composite architecture → Fiber/Matrix system, ply orientations, participation of each ply on the whole laminate.**
- **Elastic properties of the constituents and non-linear properties of the constituents (fiber and matrix) (SP RoM AS A CONSTITUTIVE LAW MANAGER!)**
- **We have proposed a procedure for material calibration. An experimental campaign have been conducted to characterize FibreShip materials.**

HOW DO WE OBTAIN CONSTITUENT PARAMETERS FROM LAMINATE TESTING?

- Longitudinal UD is fibre-driven (parallel behavior).
  - **Fibre parameters from longitudinal tests.**
- Transverse UD shear performance are matrix-driven (serial behavior).
  - **Matrix parameters from transverse and shear tests.**
- Reverse engineering → We know how SP RoM works.



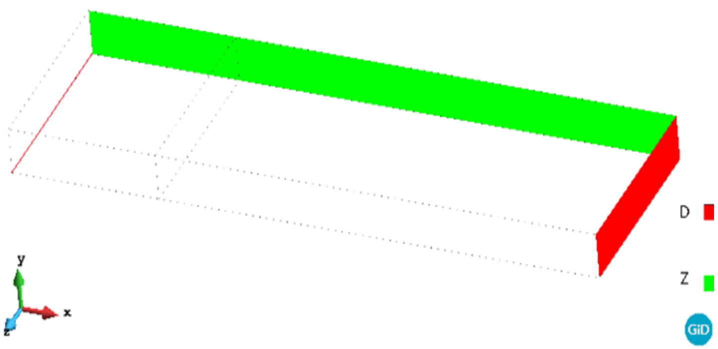


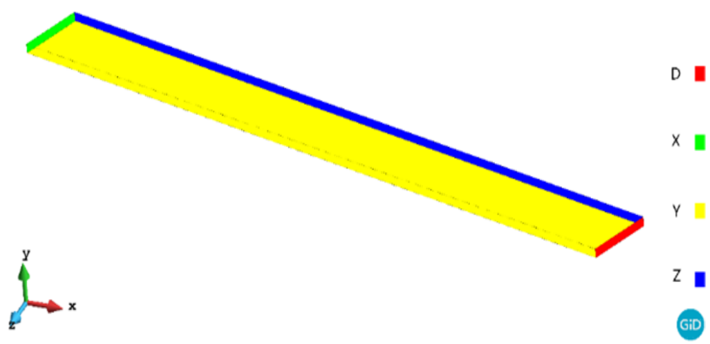
CALIBRATION PROCEDURE

Parameter	Method to obtain
FIBRE ORIENTATION	DEFINED BY DESIGN
FIBRE AND PLY VOLUME PARTICIPATION	BURN OFF TEST. VERIFIED BY LONGITUDINAL AND TRASNSVERSE TENSILE TESTS
FIBRE YOUNG MODULUS	DATASHEET PRODUCT. VERIFIED BY LONGITUDINAL TENSILE TESTS
MATRIX YOUNG MODULUS	DATASHEET PRODUCT. VERIFIED BY TRANSVERSE TENSILE TESTS
POISSON COEFFICIENT	LITERATURE
SHEAR MODULUS	SHORT BEAM SHEAR TEST (SBS).
FIBRE TENSILE STRENGTH	LONGITUDINAL TENSILE TEST.
FIBRE COMPRESSIVE STRENGTH	LONGITUDINAL 3 POINT BENDING TEST (3PB).
MATRIX TENSILE STRENGTH	TRANSVERSE TENSILE STRENGTH
MATRIX COMPRESSIVE STRENGTH	TRANSVERSE 3PB TEST.
MATRIX SHEAR STRENGTH	SBS TEST.
FIBRE FRACTURE ENERGY	LONGITUDINAL TENSILE TEST
MATRIX FRACTURE ENERGY	SBS TEST.

MODELS GEOMETRY

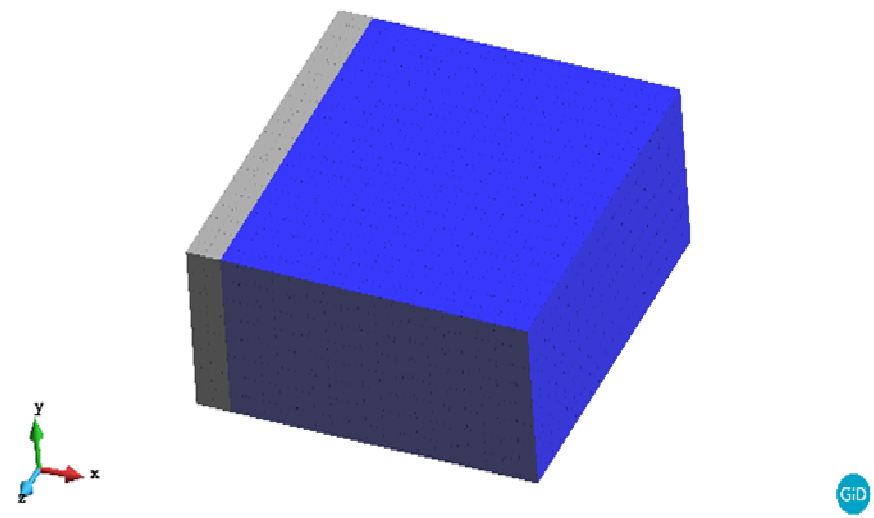
3PB BC





Tensile test model

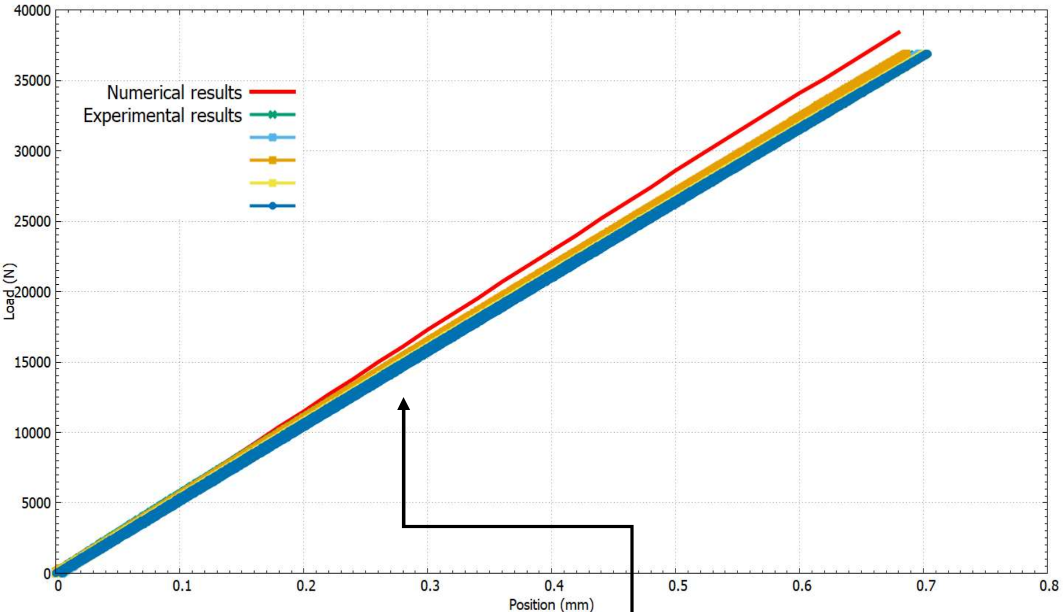
Test	Elements nº	Nodes nº	Element type	Dimensions
Tensile	20.250	28.184	Linear hexahedral	135 x 12.5 x 1.5 mm
Flexure	10.000	12.636	Linear hexahedral	40 x 12.5 x 3 mm
Shear	3.200	3.969	Linear hexahedral	7.5 x 7.5 x 3 mm



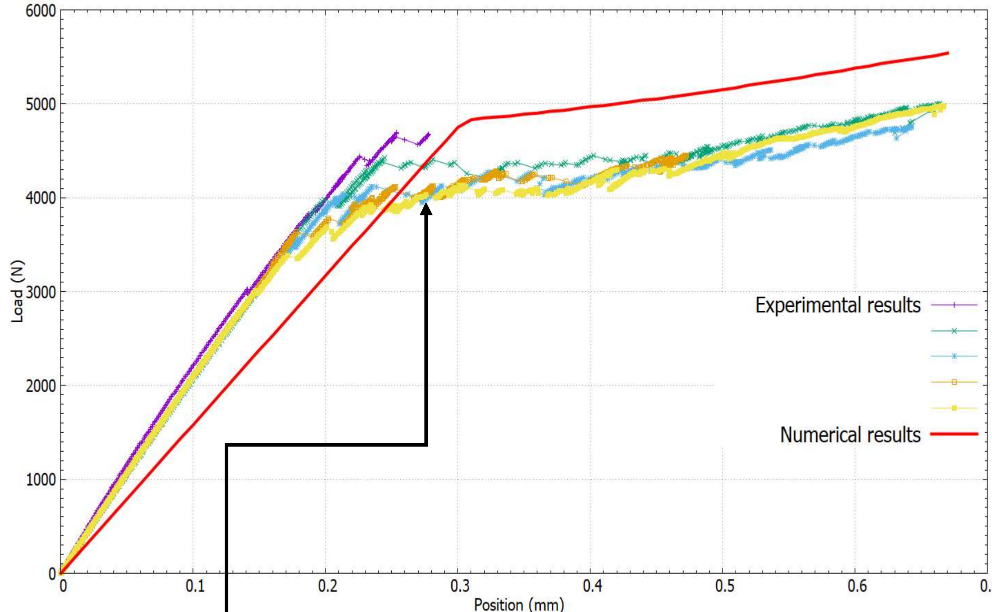
Shear test model

RESULTS. Load-position curves

LONGITUDINAL TENSILE TEST



TRANSVERSE TENSILE TEST

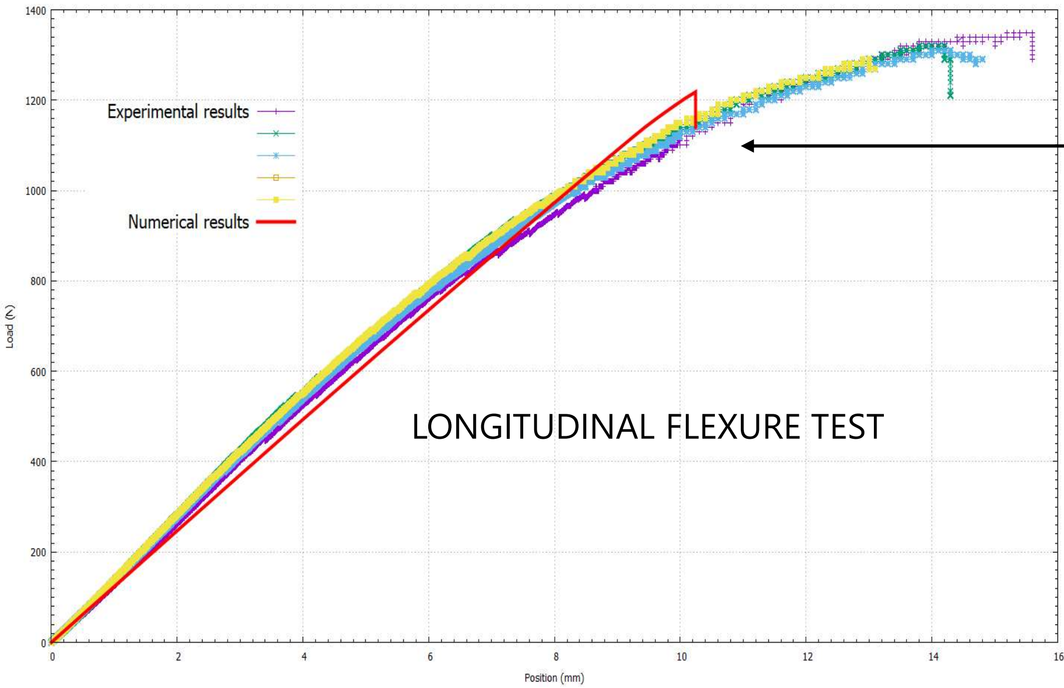


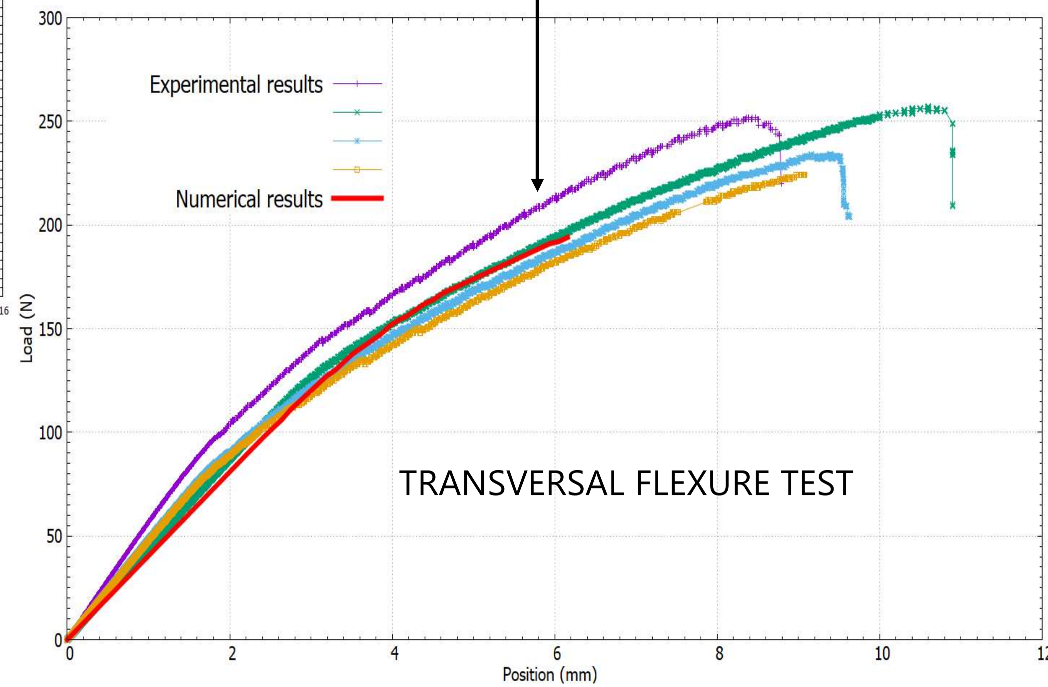
Stiffness of the laminate is obtained

Once matrix fails, only appear the stiffness of transverse (now longitudinal) fibres.

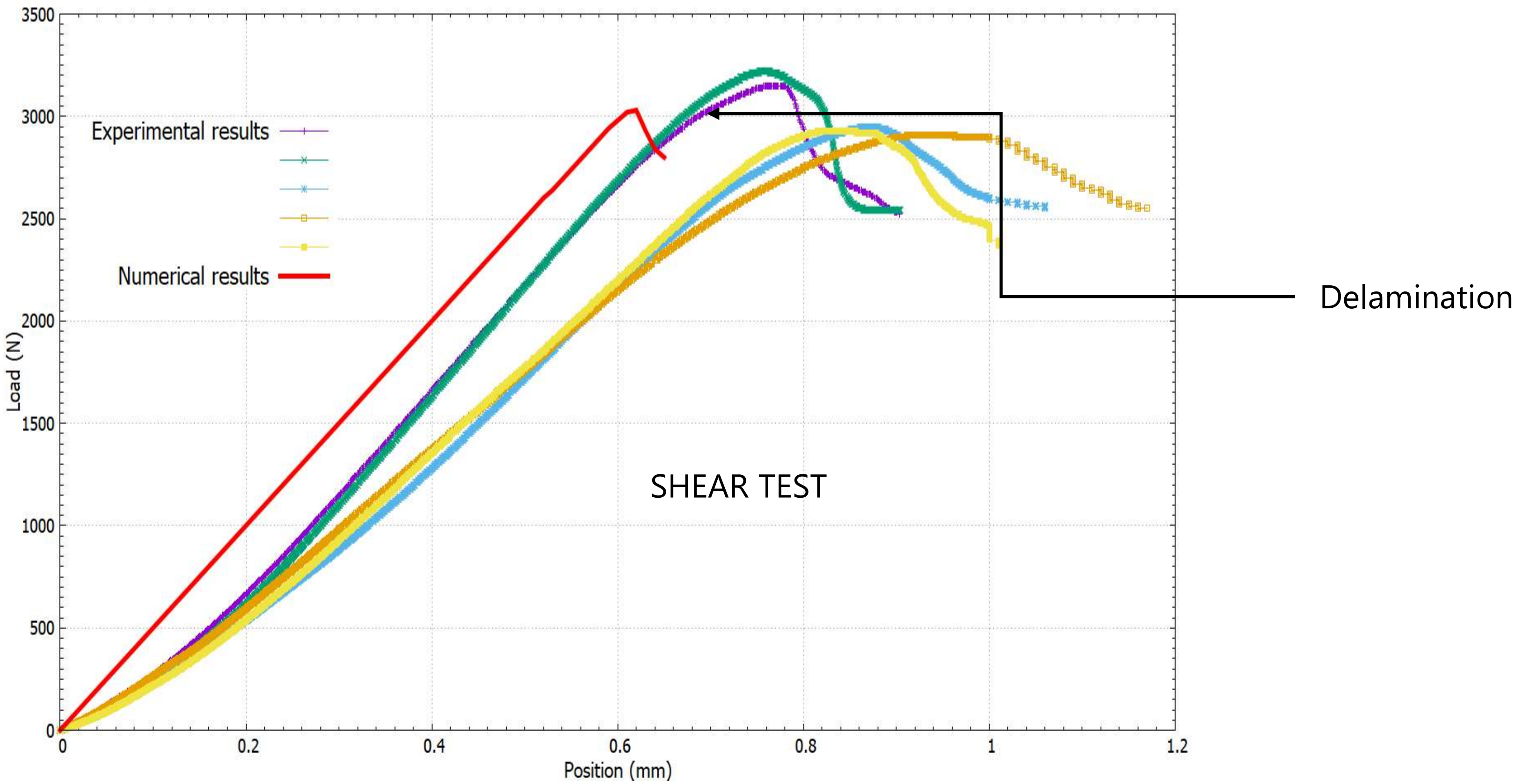
RESULTS. Load-position curves

Stiffness obtained, but not failure load (still conservative).

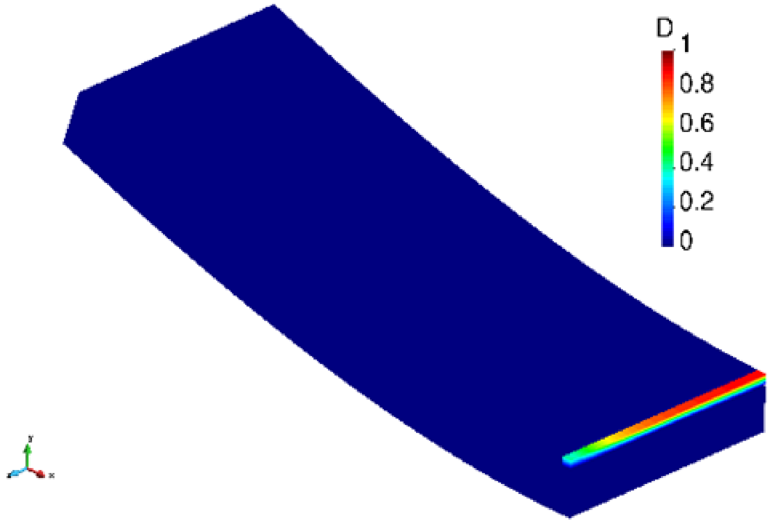




RESULTS. Load-position curves

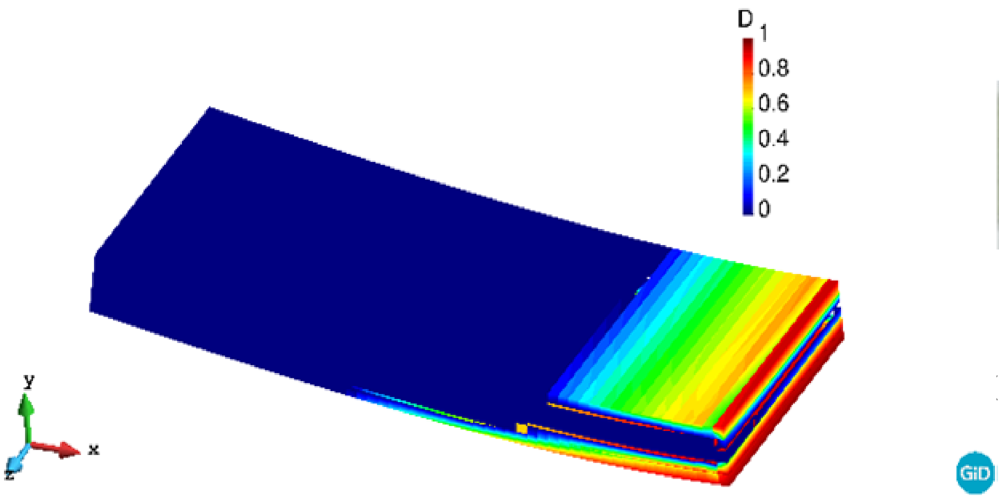


RESULTS FEM MODELS. Failure modes



FIBER DAMAGE FOR LONGITUDINAL FLEXURE TEST

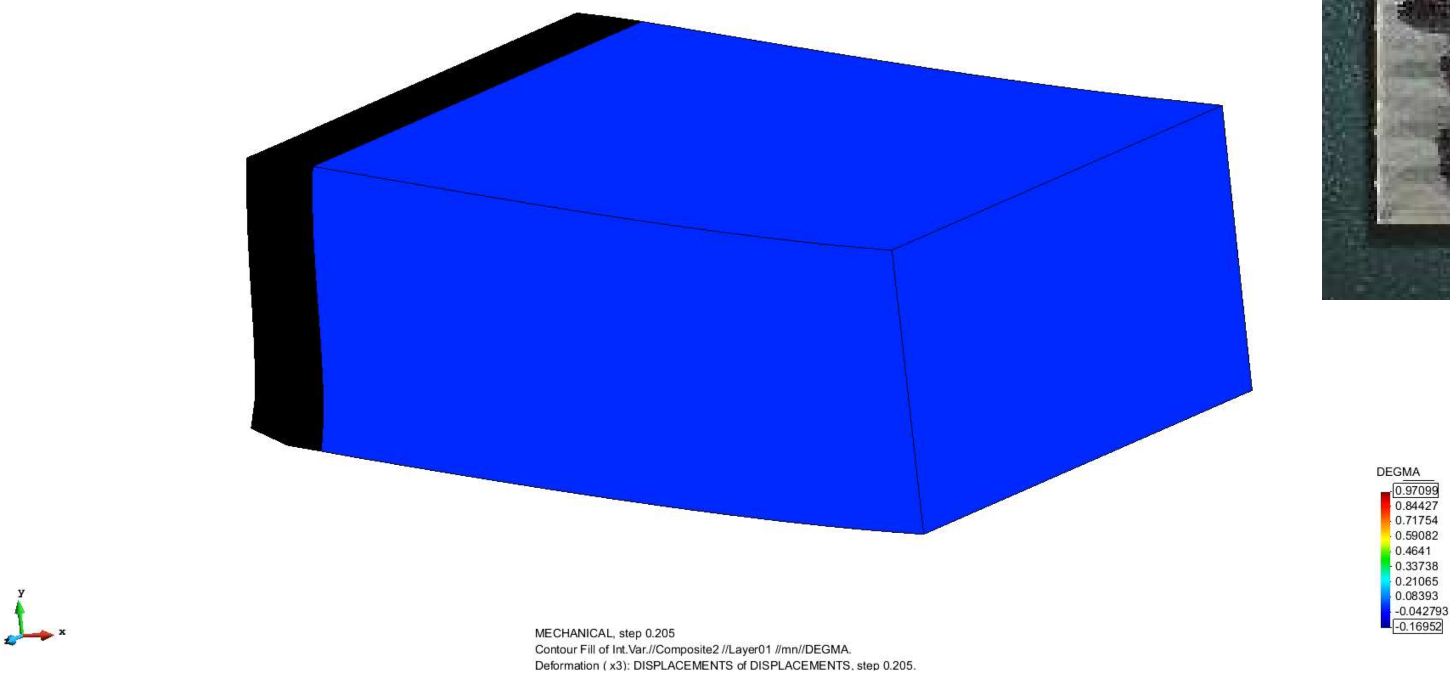
RESULTS FEM MODELS. Failure modes



DAMAGE FOR TRANSVERSAL FLEXURE TEST

RESULTS FEM MODELS. Failure modes

MATRIX DAMAGE FOR SHEAR TEST



CONCLUSIONS

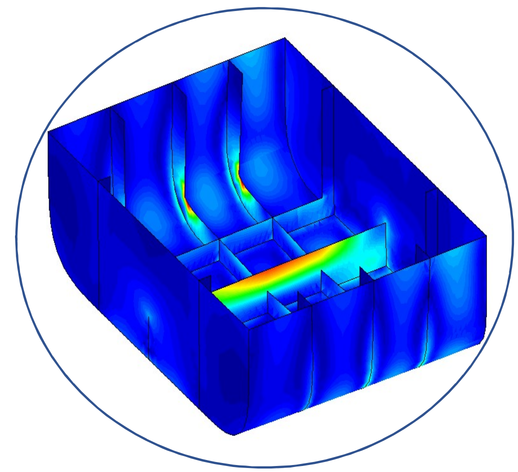
RELEVANT ASPECTS

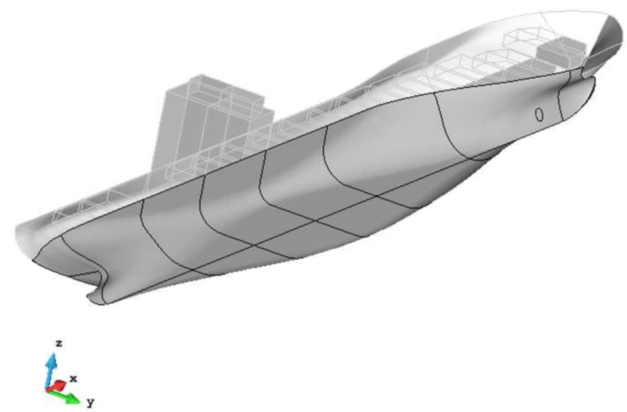
- Composite perfromance is obtained by means of fiber and matrix behavior, regardless fiber orientation or fiber participation, what reduces number of tests to be done.

- A procedure to calibrate the S/P Mixing Theory is built.

- Failure modes of the composite can be obtained.

- S/P Mixing Theory is compatible with known failure criteria (Tsai-Hill, first ply failure, etc).





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THANK YOU

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