Procedure to Calibrate Composite Materials by Serial/Parallel Mixing Theory

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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 & CONCLUSIONS
- Failure modes and load-position graphs.

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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

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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:
\[ E_1, E_2, E_3, \nu_{12}, \nu_{23}, \nu_{31} \]
INTRODUCTION. Analysis of composite structures.

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.

Models based on multi-scale procedures:

3. Numerical homogenization

Models based on continuum media mechanics:

1. Constitutive equations.

2. Phenomenological homogenization (Rule of Mixtures)

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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

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Composites mechanical performance is obtained from components.

Hypothesis of RoM:

I) Each infinitesimal volume 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 volume.

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).

\[ \varepsilon_{\sigma} = \frac{\partial \Psi}{\partial \varepsilon} = \sum_{i=1}^{n} i_k \frac{\partial \Psi_i}{\partial \varepsilon_i} = \sum_{i=1}^{n} i_k \cdot i_{\sigma} \]
This formulation is a constitutive equations manager that provides the response of the composite by coupling the constitutive equations of its components.

Compatibility equations

\[
\begin{align*}
\varepsilon_p^c &= m_{kc} \varepsilon_p^c + f K_{fc} \varepsilon_f^c \\
\sigma_p^c &= m_{kc} \sigma_p^c + f K_{fc} \sigma_f^c
\end{align*}
\]

Check for convergence:

\[
[\Delta \sigma_S]^k = [m \sigma_S]^k - [f \sigma_S]^k \approx 0
\]
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 $\varepsilon^m$.
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:
$$[\Delta \sigma_S] = \begin{bmatrix} \sigma_S^k \\ \sigma_S^k \end{bmatrix} - \begin{bmatrix} \sigma_S^{k+1} \\ \sigma_S^{k+1} \end{bmatrix} \leq \text{toler}$$
7. If no convergence is achieved, initial prediction of matrix strains is modified by an iterative process of Newton-Raphson.
ADVANTAGES OF USING S/P MIXING THEORY

• Any stacking 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. $\epsilon = \frac{\sigma_1}{E_1} = \cdots = \frac{\sigma_i}{E_i} = \cdots = \frac{\sigma_n}{E_n}$

• SP RoM is applied inside each ply. $\epsilon_i = \sigma_i$

• Stress on the whole composite is obtained applying classic RoM. $^C\sigma = \sum_{i=p_1}^{n} (^i k ^i\sigma)$
S/P MIXING THEORY. Constitutive laws for materials.

Elastic law

Visco-plastic law

Damage law

\[
\sigma = (1 - d) \cdot \sigma_0 \rightarrow C_5 : \varepsilon = (1 - d) \cdot C_0 : \varepsilon
\]
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.

3-POINT BENDING TEST (3PB)  TENSILE TEST  SHORT BEAM SHEAR TEST (SBS)

Göteborg, 13th May 2019
CALIBRATION PROCEDURE

WHICH PARAMETERS ARE REQUIRED?

• Composite architecture \(\rightarrow\) 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 \(\rightarrow\) We know how SP RoM works.
# CALIBRATION PROCEDURE

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Method to obtain</th>
</tr>
</thead>
<tbody>
<tr>
<td>FIBRE ORIENTATION</td>
<td>DEFINED BY DESIGN</td>
</tr>
<tr>
<td>FIBRE AND PLY VOLUME PARTICIPATION</td>
<td>BURN OFF TEST. VERIFIED BY LONGITUDINAL AND TRANSVERSE TENSILE TESTS</td>
</tr>
<tr>
<td>FIBRE YOUNG MODULUS</td>
<td>DATASHEET PRODUCT. VERIFIED BY LONGITUDINAL TENSILE TESTS</td>
</tr>
<tr>
<td>MATRIX YOUNG MODULUS</td>
<td>DATASHEET PRODUCT. VERIFIED BY TRANSVERSE TENSILE TESTS</td>
</tr>
<tr>
<td>POISSON COEFFICIENT</td>
<td>LITERATURE</td>
</tr>
<tr>
<td>SHEAR MODULUS</td>
<td>SHORT BEAM SHEAR TEST (SBS).</td>
</tr>
<tr>
<td>FIBRE TENSILE STRENGTH</td>
<td>LONGITUDINAL TENSILE TEST.</td>
</tr>
<tr>
<td>FIBRE COMRESSIVE STRENGTH</td>
<td>LONGITUDINAL 3 POINT BENDING TEST (3PB).</td>
</tr>
<tr>
<td>MATRIX TENSILE STRENGTH</td>
<td>TRANSVERSE TENSILE STRENGTH</td>
</tr>
<tr>
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<td>TRANSVERSE 3PB TEST.</td>
</tr>
<tr>
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<td>SBS TEST.</td>
</tr>
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<td>FIBRE FRACTURE ENERGY</td>
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</tr>
</tbody>
</table>
## MODELS GEOMETRY

### Tensile Test Model
- **Test:** Tensile
- **Elements nº:** 20.250
- **Nodes nº:** 28.184
- **Element type:** Linear hexahedral
- **Dimensions:** 135 x 12.5 x 1.5 mm

### Flexure Test Model
- **Test:** Flexure
- **Elements nº:** 10.000
- **Nodes nº:** 12.636
- **Element type:** Linear hexahedral
- **Dimensions:** 40 x 12.5 x 3 mm

### Shear Test Model
- **Test:** Shear
- **Elements nº:** 3.200
- **Nodes nº:** 3.969
- **Element type:** Linear hexahedral
- **Dimensions:** 7.5 x 7.5 x 3 mm

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RESULTS. Load-position curves

LONGITUDINAL TENSILE TEST

Stiffness of the laminate is obtained

TRANSVERSE TENSILE TEST

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

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RESULTS. Load-position curves

LONGITUDINAL FLEXURE TEST

TRANSVERSAL FLEXURE TEST

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

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RESULTS. Load-position curves

SHEAR TEST

Delamination
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 performance 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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