Composite Space Structures Modelling and Analysis Software

Final Presentation of the COSSMAS project

November 22, 2016, ESTEC, Nederlands

Samtech s.a., Airbus Safran Launchers, Open engineering
Scope of the presentation

- Project overview (goals, partnership,...)
- Design process of composite structure
- Main improvement of our modeling tools
- Multi-physics analyses and applications
- Space applications
Goals of the project

• Develop a professional computer-aided engineering software environment for the design and the verification of composite space structures

• Develop new functionalities in pre-existing software:
  - Mechanical analysis (SAMCEF)
  - Multi-physic analyses (OOFELIE::Multiphysics)
  - GUI (NX CAE – now SIMCENTER)

• Targets
  - Gain of time in the design of composite solutions
  - Innovative designs with composites
Participants

• Consortium
  • SAMTECH s.a. (A Siemens Company)

• Open Engineering

• Airbus Safran Launchers

• Luxembourg Institute of Science and Technology
Description of work

Milestone 1 - COSSMAS system specification

WP 1 - Technological and IT specifications

Milestone 2 - Standalone prototypes and revised specifications

WP 2 - Mechanical solvers
WP 3 - Multi-Physic Multi-Layer Composite Shell
WP 4 - Graphical User Interface for Composite pre/post-processing

Milestone 3 - Validated standalone software modules

WP 5 - Space composite case studies for software validation

Milestone 4 - Integrated software for modelling and the analysis of composite space structures

WP 6 - Project management
Design methodology of composite structure

Requirements

Design and pre-sizing based on analytical methodology

Global FE model:
- global mechanical validation of the structure (global behavior, sizing of regular areas...)
- Identification of critical local areas → Singularities

Tests with representative subcomponent

Local FE analysis

Scale 1 tests

Specific tools and methodologies developed and validated for each structure family

Qualification with dedicated Specimen or Protoflight
Main achievement (Local analysis of composites)

- Detailed FEM in SAMCEF with
  - Modeling of damage in plies and interfaces
  - Prediction of failures in plies

- COSSMAS contribution
  - New non-local interface continuum damage law (ENS-Cachan)
    - Depends on crack densities and fibers orientations in the adjacent plies
    - Interface is fully damage once maximal crack density is reached in a ply
  - NASA LaRC04 composite failure criterion (6 failure modes)
    - Matrix tensile and compression (axial & bi-axial)
    - Fiber tensile and compression (axial & bi-axial)
    - Available for multi-layer and volume elements
Main achievement (Composite mechanical simulation)

- Shell element with ZIG-ZAG functions

Murakami supposes the zigzag slope depends only on the thickness of individual layers:

\[
\phi_{x}^{(k)} = (-1)^{k} \xi^{(k)}
\]

\[
\xi^{(k)} = \frac{z - z_{m}^{(k)}}{h^{(k)}},
\]

Nasa supposes the zigzag slope depends not only on the thickness of individual layers but also on their shear modulus:

\[
Slope^{(1)} = \frac{G_{xz}^{(1)} - G}{G_{xz}^{(1)}},
\]

\[
Slope^{(2)} = \frac{G_{xz}^{(2)} - G}{G_{xz}^{(2)}},
\]

\[
Slope^{(3)} = \frac{G_{xz}^{(3)} - G}{G_{xz}^{(3)}}.
\]

\[
\frac{2h}{G} = \frac{2h^{(1)}}{G_{xz}^{(1)}} + \frac{2h^{(2)}}{G_{xz}^{(2)}} + \frac{2h^{(3)}}{G_{xz}^{(3)}}
\]
Main achievement (Composite mechanical simulation)

• Sub-modeling technologies

1) Structural Zoom
   • Chaining between global and local models
   • Apply boundary conditions from the global to the local model by means of interpolations
   • Merging results for post-processing

2) Co-simulation
   • Global and local models are strongly coupled within a co-simulation scheme at iteration level
   • Gluing is used to connect shell and volume meshes

Figure 9: recombined co-simulation model
Main achievement (Composite mechanical simulation)

- Simcenter for Composite in SAMCEF

- NX Laminates features are supported including
  - Laminate modeler, draping (UD), link to Fibersim
  - Mesh inflation

- Samcef supported multi layer elements
  - composite volumes, solid shells, Mindlin shells and membranes

- Dedicated material laws
  - The Samcef Damage Interface material
  - The Ply Damage material models (UF Ply Dam., WF Ply Dam., UF Ply Enhanced Dam.) are also available as orthotropic material properties.
  - The non-local behavior of 3D elements can be activated to reflect the mutual effects of ply and interface damages.

- Cohesive element definition through the Layup Modeler or from manual sweeping

- Specific post-processing
Main achievement (Composite mechanical simulation)

- Simcenter for Composites in SAMCEF allows

**Strength / Stiffness Analysis**
- Displacement
- Stress
- Strain
- Frequencies

**Buckling and Post Buckling analysis (implicit solver)**
- Nonlinear with large displacements/rotations, large strains & various types of contact and gluing conditions
- Dedicated algorithm for buckling, post-buckling

**Progressive damage simulation**
- Classic Failure criteria computed directly by FE solver (performance): critical ply, value, load case
- Progressive damage simulation for inter- or intra-laminar damage modeling
Main achievement (Composite mechanical simulation)

- NX OPEN extension to manage multi-harmonic analyses

NEW ITEM: multiharmonic

Create 5 new UDOs

Edit UDOs – Write Epilog Bank File
Before the project (Multi-physic shell)

- 3D elements available in OOFELIE::Multiphysics for
  - Mechanical, Thermal & Electrical fields
  - ... and related couplings (thermo-mechanical, piezoelectrical, ...)

- Kirchhoff & MITC shell elements available in OOFELIE
  - Only purely mechanical shells (with Isotropic material)

- Most of MEMS applications exhibit large aspect ratio
  - Shell FE are more suitable that 3D FE for efficient simulation
  - Multi-physics aspects are important in MEMS
  - BUT no multi-physic shell element is available in OOFELIE

Main objective: development of multi-layer multi-physic shell elements in OOFELIE::Multiphysics

www.open-engineering.com
Main challenges and tasks (Multi-physic shell)

• In-depth reworking of OOFELIE kernel to support
  • Variable number of dofs by elements
  • Dofs at layer level
  • Storage of results at layer level (DB reworking)
• Connections of shell with 3D elements
  • Shell to Solid Mechanical gluing
• 3D assemblies of multi-layer shell
  • Extension of MechanicalGluing (rotation transfer capabilities)
  • Reworking of ScalarGluings
• Reworking of boundary conditions
  • Constraint and loads
• User interface
  • First prototype of « OOFELIE Link to NX CAE »
Main achievements (Multi-physic shell)

• MITC multi-layer multi-physic shell element implemented inside OOFELIE

• Single physic layer support
  • Purely mechanical (K & M contributions)
  • Purely dielectric layer (K contribution)
  • Purely thermal layer (K & C contributions)
  • Purely electrokinetic layer (K contribution)

• Multi-physic layer support
  • Piezoelectric layer (K contribution)
  • Thermomechanical layer (K & C contributions)
  • Electro-thermal layer (Joule effect contribution)
  • Electro-thermomechanical layer

• Successful validation on “unit” test cases
  • Shell results vs 3D results (fine meshes)

• Main actual limitations:
  • Non linear geometric effects are not supported, Simple material orientation
  • Raytracing algorithm does not support yet the multi-physic shells, ...
Validation (micro-bolometer, IR sensor pixel)

- **Principle**
  - Cell made of a resistive material with temperature dependent conductivity (TCR = - 2 % /K)
  - The temperature of the cell is influenced by the incoming IR power
  - The measure of the resistance of the cell is related to the incoming IR power

- 3D results vs MP shell results

The new MP shell elements are suitable for efficient micro-bolometer modelling inside OOFELIE::Multiphysics
Validation (MEMS piezoelectric energy harvester)

- **Principle**
  - A cantilever plate with
    - An added mass
    - A piezoelectric layer
  - The harvester is located in a vibrating environment and is able to deliver some power (to remote sensor for example)

- **3D results vs MP shell results**
  - Eigen frequencies and related shapes fit very well

Max 1% relative error for the 20 first eigen frequencies

The new MP shell elements are suitable for efficient piezoelectric energy harvester modelling inside OOFELIE::Multiphysics.
Composite space applications

• **Case studies are space applications dealing with launcher structures:**
  - Technological specimens or a full scale structure
  - For damage models and fracture mechanics aspects, tests cases with existing experimental data have been favoured (but no experimental study made in the frame of COSSMAS)

• **Equipment support:**

  Steel support ≈ Equipment support

  Quasi-isotropic composite plate (monolithic)

  Loading : bending

- Bending loading (with very local indentation)
- 3D stress state, with area in compression and in tension
- Highly complex damage kinetics
- Available experimental data

  ➔ New behaviour law for the interface

  ➔ LaRC04 criterion

  ➔ Shape functions through the thickness of composite FE

Visible failure on the face in tension
Composite space applications

- Equipment support: Validation of damage model improvements (1/2)

**Metallic part:**
- Mindlin shell,
- Elastic, isotropic

**« Global » zone:**
- Composite brick elements,
- 1 multi-layer element through thickness,
- Elastic

**« Transition » zones:**
- Composite brick elements,
- 5 multi-layer elements through thickness,
- Elastic

**« Interest » zone:**
- Composite brick elements,
- 5 multi-layer elements through thickness,
- 4 interface elements through thickness,
- Damage behaviour (for plies and interfaces)

- ½ model
- Degree 2
- Metallic part « glued » to composite plate
- Load: displacement imposed through rigid body element
- BC: infinite support
Composite space applications

• Equipment support: Validation of damage model improvements (2/2)

3 models compared to experimental data
No coupling between damage in plies and in interfaces
Previous coupled law
Abisset’s formulation

Higher delamination with Abisset’s formulation

damage kinetics observed using the implemented model is in agreement with enhancement brought in the LMT Cachan mesomodel.

damage mechanisms seem better represented using Abisset’s formulation, even if no major deviations have been observed for this specific test case.
Composite space applications

• **Equipment support : Validation of the LaRC04 criterion**

  1. Hashin Matrix Tension Mode
  2. LaRC04 #2 (Matrix Compression)
  3. LaRC04 #6 (Fibre Compression)
  4. LaRC04 #4 (Fibre Compression)
  5. Hashin Matrix Compression Mode
  6. LaRC04 #1 (Matrix Tension)
  7. Hashin Fibre Tension Mode
  8. LaRC04 #5 (Matrix Compression)
  9. Hashin Fibre Compressive Mode
  10. LaRC04 #3 (Fibre Tension)

Results fit with the expected physical behaviour

Conservative approach and criteria (indentation area very local, high stress gradients, FPF...)

More failure mechanisms with LaRC04 (kink-bands)
Composite space applications

- **Equipment support**: Validation of shape function through thickness of composite elements (Zigzag)

<table>
<thead>
<tr>
<th>3 models compared in terms of element types</th>
<th>“Zigzag” model restrictions</th>
<th>“Mindlin” model adjustment</th>
<th>“Volume” model adjustment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composite <strong>volume</strong> elements</td>
<td>All in plane rotations are fixed</td>
<td>All in plane rotations are fixed</td>
<td>No DOF associated to rotations</td>
</tr>
<tr>
<td>Composite <strong>mindlin shell</strong> elements</td>
<td><strong>Eccentricity not taken into account</strong></td>
<td>the mid-plane has been adapted in order to avoid eccentricity</td>
<td>No need for eccentricity definition</td>
</tr>
<tr>
<td>Composite <strong>zigzag shell</strong> elements</td>
<td>No mid-side node available ➔ degree 1</td>
<td>Degree 1 instead of 2</td>
<td>Degree 1 instead of 2</td>
</tr>
<tr>
<td></td>
<td>Geometric non linearity not taken into account</td>
<td>Linear computation</td>
<td>Linear computation</td>
</tr>
</tbody>
</table>

- **Displacement fields are very close**
- **For an industrial use in the case of structure analysis, there is a need to minimize the restrictions that exist concerning the use of the zigzag hypothesis.**
- **The more penalizing restriction**: Local equilibrium is not verified for stresses/strains computation ➔ no post-processing of stresses/strains (development in progress in an other frame)

*e.g. Displacement field (Uy)*
Composite space applications

- SYLDA access holes:

SYLDA: the dual launch system of Ariane 5

- Cylinder: length 4.7m / diameter 4.5m

- 4 sandwich panels (core: aluminum honeycomb / face sheets: lay-ups of UD carbon prepreg) glued by longitudinal composite doublers (“lashings”)

- To access to the lower payload: circular hole at the bottom of the cylinder of the SYLDA. Hole reinforced locally by monolithic layers on inner and outer faces.

Hole’s size <<< SYLDA’s size ➔ sub-modelling technics
Composite space applications

- **SYLDA access holes: Validation of sub-modelling methods (1/4)**

**GLOBAL FEM:**
- 360° 3D shell model
- BC/Loads: representation of some adjacent structures, fully clamped at the bottom, loads at the top normal compression load, transverse load and flexural moment load → maximize the compression flux at the azimuth of the hole

**LOCAL FEM:**
- Refined 3D volume patch around the hole

**COUPLING CURRENTLY USED IN ASL:**
- Kinematic conditions to “glue” meshes with different refinements
- Reference for the comparison with other sub-modelling techniques
Composite space applications

• SYLDA access holes: Validation of sub-modelling methods (2/4)

**.ZOOM Command :**
- 1st step: Computation of the master model
- 2nd step: Computation of the slave model using imposed displacement of the master model

**CO-SIMULATION**
- At iteration level:

  - Master
  - Slave

  **Displacement field Through .ZOOM border**

  **Global FEM (3D shell)**

  **WEAK COUPLING**

  **Local FEM (volume)**

  **Global FEM (3D shell)**

  **STRONG COUPLING**

  **AIRBUS SAFRAN LAUNCHERS**

  **Position Variation Vector**

  **Condensed Iteration Matrix + Condensed Residual Vector Through COSI element**

  **Slaves**
Composite space applications

• SYLDA access holes: Validation of sub-modelling methods (3/4)

- Compared to the .ZOOM command, displacement fields and values are closer to the ones obtained with .APS in the interest area (i.e. volume patch) using the co-simulation method (< 3%)

- Strong coupling leads to better results than weak coupling in terms of displacements even if deviations remain low using .ZOOM command

- Compared to the .ZOOM command, stress fields and values are closer to the ones obtained with .APS in the interest area (i.e. volume patch) using the co-simulation method even if maximum deviations on the stresses in fibre direction are quite important (36% locally observed; would need further investigations).

- Strong coupling leads to better results than weak coupling in terms of stresses
Composite space applications

- SYLDA access holes: Validation of sub-modelling methods (4/4)

<table>
<thead>
<tr>
<th></th>
<th>.APS (currently used in ASL)</th>
<th>.ZOOM</th>
<th>CO-SIMULATION</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Strong coupling</strong></td>
<td>Good representation of the local area behaviour since the detailed model interacts with the global one.</td>
<td>Low computation time</td>
<td>Strong coupling</td>
</tr>
<tr>
<td><strong>High computation time</strong></td>
<td>19h with 8 processors used in parallel.</td>
<td>Weak coupling</td>
<td>High computation time for this test case and this configuration</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No influence of the detailed model on the global one.</td>
<td>22h with 8 processors used in parallel (need of an optimal use of the processors)</td>
</tr>
</tbody>
</table>

- Here: weak coupling method (.ZOOM) seems to be the more convenient for displacement assessment: lowest computation time and satisfying results (quite close to those obtained with the .APS command)

- But: more accurate stresses assessment with co-simulation

- Co-simulation may be more adapted in other cases: important influence of the detailed patch on the global one, lot of slaves... If the proper parallel configuration is used.
Composite space applications

• **Motor Case Skirt**
  - Cylindrical composite structure integrated on a motor case vessel by the use of bonded junctions
  - Makes the link between the pressurized vessel and launcher inter-stage structure, allowing the transmission of loads from one stage to another one
  - Studied skirt: reduced scale skirt (Ø450) made of 2D woven fabrics

- Axi-symmetrical structure linked to a 3D structure → FE model: skirt (2D multi-harmonic elements) + adjacent structure (3D brick elements)

→ **Pre- and Post-processing of multi-harmonic models using NX Open** (including connection between multi-harmonic model and 3D model)
Composite space applications

- **Motor Case Skirt**: Validation of pre- and post-processing of multi-harmonic models with NX Open
  
  - Use of UDOs for the pre-processing: instinctive and simple
  - Associated epilog well written
  - No problem when launching the computation

Displacements magnitude
(3D existing mesh and 2D mesh on 0° meridian)

Displacements magnitude
(3D built from multiharmonics - Harmonic 10)

- Need to visualize elements created to link a 3D model to a 2D multi-harmonic model in NX pre-processing (and not only in NX post-processing)
- Need to visualize 3D shape from a recombination of harmonics
Conclusions

• New versions of Simcenter and Samcef provide efficient modeling tools for the design and the verification of composite structures.

• Successful implementation and validation of multi-layer multi-physic shell elements inside OOFELIE::Multiphysics solver.

• Iterative process has been done in collaboration with SAMTECH (through regular exchanges all along the validation phase). It allowed to figure out main issues observed during first evaluations.

• Most of developments performed in the scope of COSSMAS can be used immediately in an industrial way.

• Remaining restrictions will be solved in an other frame (some of them are in progress).