ESI’s Composites Simulation Solution
Integrated solution to simulate the manufacturing of structural composites components

Dr. Xiaoshi Jin
November 2015
ESI’s Composites Simulation Solution

What is it?

**FEA Solution to define and Optimize process parameters**
- Dedicated to composites structural components made of continuous fibers

**Dedicated to automated processes**
- For mass production
- For full control on costs, delays and reproducibility

**Address a wide range of materials**
- Carbon, Glass and natural fibers
- Thermoplastic and thermoset resins
- Including core, inserts
- Woven fabrics, NCF, UD...
- Prepregs or dry textiles
ESI’s Composites Simulation Solution

- Post-cure distortion of a fuselage panel
- Thermoforming of organosheets
- Infusion of a wind blade
- CPD-to-ESI in CATIA V5 XML
- Fibersim XML

PAM-COMPOSITES

PAM-DISTORTION
PAM-FORMING
PAM-RTM

Performance Analysis
ESI’s Composites Simulation Solution

Compensated mold (CATIA RSO)

Temperature history
Degree of cure history

Fiber orientations

PAM-DISTORTION

PAM-FORM

PAM-RTM
# PAM-FORM Simulation

## What for?

### To Simulate

- Preforming
- Draping of thermoset prepregs
- Thermoforming of Organosheet

### To Determine and Optimize process parameters such as:

- Kinematic of the tools
- Temperature cycle
- Pressure cycle
- Clamping conditions
- Clamping forces
- Initial flat pattern

### Through the prediction of

- Wrinkles
- Thicknesses
- Bridging
- Strains (shearing and in fibers)
- Stresses (Shearing and in fibers)
- Fibers orientation
Non-linear elasto-plastic material with damage

- Possible **Temperature**, **Strain rate** and **Curvature** dependency
- Behavior defined through following input:
  - **Tension and Compression deformation** in fiber directions
    - Tension is elastic with damage or plastic (transverse direction of UD)
    - Compression is elastic
  - **In-plane shear** deformation
    - Elastic with damage or plastic
  - **Bending deformation** in fiber directions
  - **Thickness deformation** through normal pressure
Material compressibility

- Whether the material is defined as **incompressible**
  - The volume of each element remains constant during the simulation: \( \epsilon_1 + \epsilon_2 + \epsilon_3 = 0 \)
- Whether the material is defined as **compressible**
  - Thickness is then dependant of the shear deformation and/or pressure
  - Possibility to visualize compaction ratio (=initial volume of element/final volume of element) as an output
Elastic damage behavior

- Damage behavior is **automatically activated after each necking point** detected in the stress-strain curves.
- Computed damage amount **express the broken fiber ratio**.
  - It is approximated as the ratio between the damaged stress amount and the assumed ideal tensile stress when no damage.

\[
\delta = \max \left( \frac{\sigma_{\text{damage}}}{\sigma_{\text{ideal}}} \right)
\]
Thermal phenomena coupled to mechanical analysis

- Interesting when thermal dependency in material properties (prepreg materials)
- The following phenomena can be taken into account:
  - Conductivity in the composites material
  - Conductivity in the tools
  - Heat transfer between composites layers
  - Heat transfer between composites and tools
  - Convection exchanges
  - Radiation exchanges
Thermoplastic forming Application

Flap rib thermoforming

Bridging effect

Fiber Shearing

Rubber pad forming simulation
Thermoplastic forming Application
Wrinkling prediction

Wrinkling prediction
20 plies carbon UD / APC2-AS4
Thermoplastic forming Application

Flat pattern optimization

Initial flat pattern

Optimized flat pattern

Poor part quality

Improved part quality

Flat pattern optimisation
4 plies / thermoplastic matrix

Simulation setup

Upper tool

4 plies

Lower tool

Copyright © ESI Group, 2015. All rights reserved.
Thermoplastic forming Application
Wing box thermoforming

Thickness per ply

Process animation

Laminate thickness
Ultrasonic measurement versus simulation

Thermoplastic forming Application
Wing box thermoforming
Preforming Application

Fiber shearing

Forming – Results of ±45 NCF: Sh. angles

Results of experimental forming for +45/-45 and -45/+45 are symmetric

Wrinkles

Shear Angles
PAM-RTM Simulation

What for?

To Simulate

- RTM
- VARI
- Light RTM
- C-RTM
- Curing

To Determine and Optimize process parameters such as:

- Location of injection gates
- Location of vents
- Position and size of flow media
- Heating of the mold
- Cure cycle

Through the prediction of

- Air traps
- Micro porosity
- Injection time
- Curing time
- Temperature evolution
- Degree of cure evolution
- Pressure in the mold
Darcy’s law

- Darcy’s law:
  \[ \vec{V} = -\frac{K}{\mu} \nabla P \]
  
  - \( K \): permeability tensor
  - \( \mu \): viscosity of the resin
  - \( V \): Darcy’s velocity
  - \( P \): pressure

- Resin mass conservation:
  \[ \nabla \cdot \vec{V} = 0 \]

Boundary conditions required to solve the equation:
- imposed pressure
- or imposed flow rate at the inlet
Temperature of the resin

• Governs the reactivity of the polymerization reaction
• Influences the filling since the viscosity of the resin is temperature dependent

• Temperature field is governed by following equation:

\[
\rho C_p \frac{\partial T}{\partial t} + \rho_r c_{pr} \vec{V} \cdot \nabla T = \nabla \cdot \{k \cdot \nabla T\} - \rho_r \Delta h \frac{D \alpha}{Dt}
\]

where \( T \) denotes the temperature, \( t \) denotes the time, \( \rho \) is the density, \( C_p \) is the specific heat, \( k \) is the heat conduction coefficient tensor, the subscript \( r \) designates the resin, \( \Delta h \) is the total enthalpy of the polymerization of the resin, \( \alpha \) is the resin cure.
Permeability of the reinforcements

- Permeability is **fiber volume content** dependent (degree of compaction)
- It also depends on the **draping** of the reinforcements (fiber “shearing”)
- Fiber volume content and draping results can be computed with PAM-FORM and imported in PAM-RTM

Viscosity of the resin

- It is **temperature** and **degree of conversion** dependent

Kinetics of the resin

- Defined through pre-defined **Kamal-Sourour** models or **User defined models**
### Coupling of physical phenomena

<table>
<thead>
<tr>
<th>Category</th>
<th>Phenomenon</th>
<th>Mathematical model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rheologic</td>
<td>Resin flow in a porous medium</td>
<td>Darcy’s law</td>
</tr>
<tr>
<td></td>
<td>Variations of viscosity</td>
<td>Constitutive law</td>
</tr>
<tr>
<td>Thermal</td>
<td><strong>Mold:</strong> conduction, loss in surface</td>
<td>Heat equation, transfer coefficient (convection-radiance)</td>
</tr>
<tr>
<td></td>
<td><strong>Part:</strong> conduction, convection, generation of heat, superficial heat loss</td>
<td>Equation of convection-diffusion with source term, model with one temperature</td>
</tr>
<tr>
<td>Chemical</td>
<td>Transport of chemical species, diffusion, polymerization</td>
<td>Equation of convection-diffusion with source term, kinetic model (Kamal-Sourour)</td>
</tr>
</tbody>
</table>
Fluid-Mechanics coupling solver

- Includes Navier-Stokes law
- Introduced to treat in a more accurate way processes as Compression-RTM and Infusion
Infusion Application

Large dimensions parts

Filling time

Curing time

30 meters wind spar cap infusion

Filling degree

Fan blade of an aircraft engine RTM

Fuselage panel infusion
Light RTM Application

Bus body side

“In this project, the RTM simulation helped us to secure and to optimize the process. Today, we are using ESI’s PAM-RTM not only to assess process parameters, including injection time and pressure in mold, but also to fine-tune mold design.”

Jérôme RAYNAL
Sales and Export Director
Pôle de Plasturgie de l’Est

Optimum resin flow pattern computed with PAM-RTM

- 13*6.5 feet
- fiberglass Chopped Strand Mat (CSM)
- integrated flow media
- Polyester resin
Infusion Application

Inner liner for hull reinforcement

Very complex part including high shapes (1.2m)
Injection analysis allows determination of injection strategy (injection points/channels and vents location as well as open/closing sequence) to minimize:
- Dry spots
- Filling and curing times
- Fiber washing
- Pressure in the mold

Flow front during injection

Initial injection points

Secondary injection points/channels

Vents location
TECABS project
Renault – Mines de Douai

RTM Application
Automotive floor panel

Floor pan injection
Infusion Application

Wind blade

Zoom-in on flow media influence on resin flow front
Simulation helped to divide infusion time by almost 5 while producing better quality parts with less scraps (better reproducibility)
RTM Application

Automatic reduction of porosities

Porosity prediction and reduction:
- Principle: Critical impregnation velocity:

\[ \max \| \vec{v}_{\text{front}} \| \leq \| \vec{v}_{\text{crit}} \| \]

Impregnation velocity

- Low
  - Fluid flow
  - Void formation phenomena
    - Macro
      - Fluid flow
    - Micro

- High

Void formation phenomena

- a
  - Fluid flow
- b

Copyright © ESI Group, 2015. All rights reserved.
RTM Application
Automatic reduction of porosities

- Porosity prediction and reduction:
  - PAM-RTM input data:

![Graph showing voids content vs. flow velocity](image)

Optimum velocity
Based on experiment

- Macro-void
- Micro-void

Experimental data
PAM-RTM input curve

\[ Ca = \frac{\mu v}{\gamma \cos \theta} \]
RTM Application
Automatic reduction of porosities

Porosity prediction and reduction:
- PAM-RTM output: injection flow rate curve

(a) Constant injection pressure
(b) Constant injection flow rate
(c) Optimized injection flow rate

Capillary number at flow front
PAM-DISTORTION Simulation

What for?

To simulate

- Process induced distortions such as spring-in and warping

To Define and Optimize parameters such as:

- Stacking definition
- Curing cycle
- Mold material and design
- Mold geometrical compensation

Through the prediction of

- Internal stresses during curing
- Residual stresses after de-molding
- Deformation during curing
- Deformation after de-molding

Takes into account

- Material history during curing process (temperature and degree of cure)
- Thermal and Mechanical interaction with the mold
PAM-DISTORTION Simulation

Physical phenomena

PAM-DISTORTION computes

- Thermal strains

  \[ \varepsilon_{ij}^T = \alpha_{ij} \Delta T \]

- Chemical strains

  \[ \varepsilon_{ij}^C = \beta_{ij} \Delta \alpha \]

-\( \alpha_{ij} \): Coefficient of thermal expansion tensor
-\( \Delta T \): Temperature variation
-\( \beta_{ij} \): Coefficient of chemical shrinkage tensor
-\( \Delta \alpha \): Degree of cure variation

It takes into account resin phase transformation during curing

- Initially the resin is **liquid**: no stress, no strain
- When the resin reaches gelation (\( \alpha = \alpha_{gel} \)) the resin becomes **rubbery**. From this point the resin can sustain stresses.
- When the resin reaches the glass transition temperature (Temperature of the resin = glass transition temperature) the resin becomes **glassy**.
- **Glass transition temperature** evolution is defined using Di Benedetto function.
PAM-DISTORTION Simulation

Physical phenomena

Phases of the resin for 1 element during curing

- Green curve is the temperature evolution
- Red curve is the degree of cure evolution
- Blue curve is the glass transition temperature evolution

Resin is liquid  |  Resin is rubbery  |  Resin is glassy
PAM-DISTORTION simulation

Fuselage Panel

Temperature evolution during curing

Degree of cure evolution during curing

Deformed shape / springback

Initial and deformed geometries
KTM Race Car Application
Front Splitter

Fiber: Tenax–J STS 40 F13 24 K 1800 tex; Binding type: plain
Resin + Hardener: EpikoteResin04695/1 and EpikureCuringAgent 05357
Core: Büfadur67 –15, PUR Foam
Preforming of upper plies
With PAM-FORM
Preforming Simulation
To predict and optimize Thickness distribution

Thinning contour

**Thinning (engineer value)**
- Min = -1.065471
- Max = 0.038729

winkles
Preforming Simulation
To predict and optimize Shearing

Shear angle

Shear angle

Min = 1.525879e-005
Max = 60.237064
Preforming Simulation
To predict and optimize Fiber orientations

Export your fiber orientation for injection simulation or structural analysis
Injection Simulation
To predict and optimize
Dry spots & Porosities

3D Injection with PAM-RTM

- Takes into account fiber orientations (impact on permeability) from preforming simulation
Injection Simulation
To predict and optimize Filling time

Filling time

Bottom view

Top view
Selected Industrial References
THANK YOU

composites@esi-group.com