Thermo-mechanical analysis of laminated composites exposed to fire

Application to the analysis of ship structures

D. Di Capua¹, J. García²,³, R. Pacheco², O. Casals³, T. Korhonen⁴,
T. Hakkarainen⁴, A. Paajanen⁴

¹RMEE, Polytechnic University of Catalonia, Spain
²CEN, Polytechnic University of Catalonia, Spain
³Compass Ingeniería y Sistemas SA, Spain
⁴VTT Technical Research Centre of Finland Ltd, Finland

May 12th, 2019
1. OBJECTIVES
   1. GENERAL
      1. FIRE & COLLAPSE ASSESSMENT TOOL
   2. SPECIFIC
      1. UNIQUE GUI
      1. FIRE DYNAMICS TOOL
      2. THERMO-MECHANICAL TOOL
      3. HEAT TRANSFER + PYROLYSIS TOOL
      4. CHARACTERISATION OF COMPOSITE MATERIALS EXPOSED TO FIRE

2. VERIFICATION

3. CONCLUSIONS

Register for free at https://www.scipedia.com to download the version without the watermark
OBJECTIVES

Solution:
Fire simulation & collapse assessment tool

Objectives:
- Development of a unique GUI with the following features:
  - Structural Non-Linear Constitutive Laminate Composite assessment tool
  - Heat Transfer + Pyrolysis assessment tool
  - Fire Dynamics tools
  - Characterisation of the materials properties

Components:
- Tools:
  - FDS
  - GiD
  - Tdyn Ramses

Register for free at https://www.scipedia.com to download the version without the watermark
COUPLING ANALYSIS FOR COLLAPSE ASSESSMENT

- Fire specification, ship compartments configuration, wall thermal properties
- Temperature time evolution curves
- Through-thickness temperature distribution in beams and shells
- Beams and shells structural analysis (RamSeries)
- Beams and shells thermal analysis (RamSeries)
- Collapse risk assessment
- Fire dynamics analysis (FDS)
- Thermomechanical analysis
  - Displacements, strains and stresses over structural components using a thermomechanical constitutive model including pyrolysis

Temperature distribution due to fire is obtained at the surface of decks, bulkheads and other structural elements due to their exposure to fire.

Register for free at https://www.scipedia.com to download the version without the watermark
GUI FOR THE DEFINITION OF COLLAPSE ASSESSMENT MODELS

A complete GUI for the definition of FDS models was integrated into the RamSeries FEM simulation suite.

• A unique geometrical model can be used for the definition of both, FDS fire dynamics and RamSeries structural models.
• A common materials database is shared by the two solvers.
• It allows an easy definition of the communication interface and the data to be transferred between the two solvers.

Register for free at https://www.scipedia.com to download the version without the watermark.
MATERIALS DATABASE: Definition of composite materials

Definition of individual components

Definition of composite layers

Definition of laminate materials

Register for free at https://www.scipedia.com to download the version without the watermark
THERMOMECHANICAL: Composite Constitutive Model

Classic Solution (Rule of Mixtures)
- FEBLE link between micro-macro scale.
- Properties referred to the EQUIVALENT composite.
- LOWER computational cost.
- ORTHOTROPIC materials.
- LOWER transversal estimation and DIFFICULT prediction in Non-Linear range.

Precise Solution (Serial-Parallel ROM)
- STRONGER link between micro-macro scale.
- Properties referred to EACH component.
- HIGHER computational cost.
- ISOTROPIC material.
- GOOD transversal estimation and ACCURATE prediction in Non-Linear range.

Register for free at https://www.scipedia.com to download the version without the watermark
THERMOMECHANICAL: Composite Constitutive Model

Serial-Parallel Rule of Mixtures (Rastellini et al., 2008)[1]

Orthotropy achieved by CLOSURE EQUATIONS.
Separate internal variables.

Serial direction, $\Delta\sigma^{sp}_{p} = \sigma^{sp}_{p} = \epsilon^{sp}_{p}$, $k^{sp}_{p} \Delta\epsilon^{sp}_{p}$
Parallel direction, $\Delta\sigma^{pp}_{p} = \sigma^{pp}_{p} = \epsilon^{pp}_{p}$, $k^{pp}_{p} \Delta\epsilon^{pp}_{p}$

Matrix formulation:

$$[\Delta\sigma^{m}_{p}] = A^{m}_{p} [\Delta\epsilon^{m}_{p}] + k^{m}_{p} (\sigma^{m}_{p} - C^{m}_{p}) \Delta\sigma^{m}_{p} - k^{m}_{p} \Delta\epsilon^{m}_{p}$$

References:


HEAT TRANSFER AND PYROLYSIS – 1D

The thermal model analyses the energy transfer processes of heat conduction, pyrolysis of the polymer matrix, and diffusion of decomposition gases. The resultant model is expressed as a one-dimensional non-linear equation that incorporates these processes:

\[
\rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) - \frac{\partial}{\partial x} \left( \dot{w}_g h_g \right) + \dot{m}_{\text{gas}} (Q_p + h_f)
\]

\[
\rho = F \rho_0 + (1 - F) \rho_f
\]

Henderson et al., 1985[3]

HEAT TRANSFER AND PYROLYSIS – 1D

Initial Conditions
\[ \rho(0) = \rho_0 \]
\[ T(0) = T_0 \]

Boundary Conditions
Hot face:
\[ q(0, t) = -k \frac{\partial T}{\partial x} = \sigma \varepsilon_m \left( T_{ad}^4 - T_k^4 \right) + h_{conv} \left( T_{ad} - T \right) \]
Cold face:
\[ q(1, t) = -k \frac{\partial T}{\partial x} = \sigma \varepsilon_m \left( T_k^4 - T_{ad}^4 \right) + h_{conv} \left( T - T_\infty \right) \]

Evolution Law
\[ \frac{dF}{dt} = -A \left[ \frac{\rho - \rho_f}{\rho_0 - \rho_f} \right] \frac{E}{T_k} \gamma_k = - \Delta F^N e^{E/RT} \]


Register for free at https://www.scipedia.com to download the version without the watermark
HEAT TRANSFER AND PYROLYSIS – 2D

Extension of 1D HTP+Pyrolysis to 2D for Non-Linear Constitutive Beams

- Addition of convective term (gas escapement)
  \[ \rho_g C_{pg} \mathbf{v}_g \]

- Estimation of the gas velocity by the pressure inside the cross section
  \[ \mathbf{v}_g = -\frac{k_s}{\mu_g} \nabla p_g \]

- Coupling between HTP+Pyrolysis and Darcy physics (temperature and pressure) to estimate the fluxes.
  - Improvement of the hot/cold end B.C.
  - More natural solution.

- 1D theory is used for PLATES and BULKHEADS (shells).
- 2D theory is used for BEAMS as shell reinforcement elements.
- Provides a high accuracy solution with low computational cost.

\[ \rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (k_f \nabla T) - \rho_g C_{pg} \mathbf{v}_g \cdot \nabla T + \dot{m}_{s\rightarrow g} (Q_p + h_c - h_g) \]

\[ \frac{\partial (\phi_g \rho_g)}{\partial t} = -\nabla \cdot (\rho_g \mathbf{v}_g) + \dot{m}_{s\rightarrow g} \]

\[ \frac{\partial \rho}{\partial t} = -\nabla \cdot (\mathbf{w}_s) - \dot{m}_{s\rightarrow g} \]
Within the scope of FiberShip there is a budget dedicated to the characterization of composite materials.

Cone calorimeter test ISO 5660-1
**THERMAL AND PYROLYSIS CHARACTERISATION OF COMPOSITE MATERIALS**

First stage tests performed by VTT Technical Research Centre of Finland Ltd, Finland. Properties measured are time of ignition, heat release rate per unit area, total heat release per unit area, total smoke production.

<table>
<thead>
<tr>
<th>Material</th>
<th>LEO system without topcoat</th>
<th>LEO system with topcoat</th>
<th>Crestapol 1210</th>
<th>Prime 27</th>
<th>SR1125 without topcoat</th>
<th>SR1125 with SGi 128 topcoat</th>
<th>Super Sap CLR</th>
<th>Cellobon d J2027X</th>
<th>Elium</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>tig (s)</strong></td>
<td>50</td>
<td>75</td>
<td>44</td>
<td>60</td>
<td>53</td>
<td>52</td>
<td>61</td>
<td>0</td>
<td>23</td>
</tr>
<tr>
<td><strong>HRRmax (kW/m²)</strong></td>
<td>336</td>
<td>69</td>
<td>314</td>
<td>496</td>
<td>546</td>
<td>261</td>
<td>520</td>
<td>71</td>
<td>255</td>
</tr>
<tr>
<td><strong>THR (MJ/m²)</strong></td>
<td>33.5</td>
<td>42.3</td>
<td>35.4</td>
<td>39.4</td>
<td>42.5</td>
<td>40.7</td>
<td>42</td>
<td>9.9</td>
<td>40.7</td>
</tr>
<tr>
<td><strong>TSP (m²)</strong></td>
<td>15.1</td>
<td>8.8</td>
<td>9.3</td>
<td>10.7</td>
<td>13.5</td>
<td>9.3</td>
<td>12</td>
<td>0.4</td>
<td>1.8</td>
</tr>
</tbody>
</table>
MATERIALS SELECTED FOR THE SECOND PHASE

1. Leo system with topcoat
2. SR1125 with SGi128 topcoat

- Extra property classes taken into account in the selection:
  - mechanical properties
  - manufacturing
  - Impact/safety/environment
Experimental model from Henderson et al. (1985) [3]

- Plate model of 1m x 1m.
- X, Y, Z fixed DOF.
- Structured mesh, 10 division in each direction.
- Designated material ($H41N$) is a phenolic resin with glass and talc filler.

HENDERSON BENCHMARK MODEL

Domain using FDS tool to obtain the temperature evolution map

- Compartment model\[^4\].
- Supported on the floor.
- Structured mesh size of 0.1m .
- The complete floor is on fire.

\[^4\] Automated two-way coupled CFD fire and thermomechanical FE analyses of a self-supporting sandwich panel façade system de Boer, J. G. G. M. (Author). 26 Jun 2018
Bulkhead of the compartment domain to be analysed using the thermomechanical tool

- Plate model 3.6m x 2.7m\(^4\).
- 4 points of control to retrieve from FDS.
- X, Y, Z fixed DOF.
- Structured mesh: 20 x 20 divisions.
- Included gravity as body force.
- Linear Constitutive Model.

\[4\] Automated two-way coupled CFD fire and thermomechanical FE analyses of a self-supporting sandwich panel façade system de Boer, J. G. G. M. (Author). 26 Jun 2018
FIRE DYNAMICS RESULTS

• The adiabatic surface temperature is monitored at selected control points located at the surface of the composite panel. This information is transferred to RamSeries to be used as boundary condition for the thermo-mechanical problem.

Heat release rate per unit volume (HRRPUV)
HRRPUV > 133 kW/m³

Temperature map at the middle cross-section of the room
THERMOMECHANIC RESULTS

Fire Dynamic Assessment

Thermo-Mechanical

Thermal-Mechanical

Thermal 1D

Temperature Diffusion

Degradation
CONCLUSIONS

Solution:

Fire simulation & collapse assessment tool:

✓ Development of an ambitious and innovative tool to assess fire simulation & collapse for composites.

Objectives:

Development of a unique GUI with the following features:

✓ Structural Non-Linear Constitutive Laminate Composite assessment tool.
✓ Heat Transfer + Pyrolysis assessment tool.
✓ Fire Dynamics tools.
✓ Characterisation of the materials properties.

Current Development:

- Structural Non-Linear Laminate beam theory.
- 2D Heat Transfer + Pyrolysis assessment tool
- 1D Heat Transfer + Pyrolysis adaptation with Darcy problem.
- Second stage for the characterisation of the materials properties.