Materials for large length fibre-based ships.
Characterization, selection, and numerical analysis

Participants: CIMNE, COMPASSIS, ULIM, VTT, TWI, LR, BV, RINA, TUCO, I rBLUE, TSI

Madrid, October 1st 2019
We need to know:

- The performance of the material (characterization)
- Numerical tools to help engineers in the structural design
CHARACTERIZATION AND SIMULATION OF FIBRE-BASED MATERIALS

• Model to analyze the mechanical performance of composites
• Calibration process and numerical results
• Fatigue Analysis

SELECTION OF COMPOSITE MATERIALS FOR MARINE APPLICATIONS

• Testing campaign – 1st phase
• Selection criteria
• Testing campaign – 2nd phase
• Fire performance

BRIEF DESCRIPTION

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SELECTION OF COMPOSITE MATERIALS FOR MARINE APPLICATIONS

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Identification of new fibre based material systems for large-scale vessels is a key objective of Fibreship.

Comprehensive list of candidate constituents.

Extensive small scale experimental campaign to down-select the best resin candidates.

Selection of reinforcement material and detailed characterization of the best composite candidates for Fibreship application.

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<table>
<thead>
<tr>
<th>Thermoplastic</th>
<th>Phenolic</th>
<th>Bio-Epoxy</th>
<th>Epoxy</th>
</tr>
</thead>
<tbody>
<tr>
<td>UD 996gsm Glass</td>
<td>UD 996gsm Glass</td>
<td>UD 996gsm Glass</td>
<td>UD 996gsm Glass</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Resin Matrix</th>
<th>Resin/Reinforcement</th>
<th>Density</th>
<th>Interlaminar Shear Strength</th>
<th>Flexural Strength</th>
<th>Flexural Modulus</th>
<th>Resin Cost € per kg</th>
<th>Hardener Mixture Cost € per kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vinylester Leo System/LEO UD 940gsm Glass</td>
<td>CRESTAPOL 1210/UD 996gsm Glass</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Epoxy Prime 27/UD 996gsm Glass</td>
<td>SR1125/UD 996gsm Glass</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Phenolic Cellobond J2027X/UD 996gsm Glass</td>
<td>Elium/UD 996gsm Glass</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Bio-Epoxy Super Sap CLR/UD 996gsm Glass</td>
<td>Thermoelum/UD 996gsm Glass</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

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## TESTING CAMPAIGN – 1ST PHASE

### PHASE 1 – MATRIX CANDIDATES – Mechanical Properties – All tested with GLASS FIBRES

<table>
<thead>
<tr>
<th>RESIN CLASS</th>
<th>RESIN/REINFORCEMENT</th>
<th>% (FIBRE VOLUME FRACTION)</th>
<th>DENSITY</th>
<th>APPARENT INTERLAMINAR SHEAR STRENGTH</th>
<th>FLEXURAL STRENGTH</th>
<th>FLEXURAL MODULUS</th>
<th>Resin Cost(^3) (€ per kg)</th>
<th>Resin/Hardener Mixture Cost(^3) (€ per kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VINYLESTER</td>
<td>LEO SYSTEM/LEO UD 940gsm Glass</td>
<td>56% (4.3%)</td>
<td>2.233 g/cm(^3) (1.8%)</td>
<td>44.42 MPa (8.8%)</td>
<td>592.0 MPa (22%)</td>
<td>22.03 GPa (21%)</td>
<td>€11.14</td>
<td>€14.00</td>
</tr>
<tr>
<td>URETHANE ACRYLATE</td>
<td>CRESTAPOL 1210/UD 996gsm Glass</td>
<td>57% (0.3%)</td>
<td>2.017 g/cm(^3) (1.7%)</td>
<td>42.09 MPa (3.0%)</td>
<td>790.61 MPa (11.3%)</td>
<td>34.52 GPa (2.0%)</td>
<td>€8.50</td>
<td>€8.46</td>
</tr>
<tr>
<td>EPOXY</td>
<td>PRIME 27/UD 996gsm Glass(^2)</td>
<td>58% (0.9%)</td>
<td>2.061 g/cm(^3) (0.5%)</td>
<td>58.04 MPa (2.4%)</td>
<td>917.1 MPa (2.4%)</td>
<td>35.37 GPa (2.8%)</td>
<td>€9.10</td>
<td>€10.34</td>
</tr>
<tr>
<td></td>
<td>SR1125/UD 996gsm Glass(^2)</td>
<td>58% (3.0%)</td>
<td>2.198 g/cm(^3) (2.3%)</td>
<td>50.53 MPa (1.7%)</td>
<td>853.8 MPa (8.5%)</td>
<td>30.35 GPa (8.1%)</td>
<td>€17.60</td>
<td>€18.47</td>
</tr>
<tr>
<td>BIO-EPOXY</td>
<td>SUPER SAP CLR/UD 996gsm Glass(^2)</td>
<td>60% (0.6%)</td>
<td>2.158 g/cm(^3) (0.9%)</td>
<td>57.78 MPa (3.6%)</td>
<td>865.2 MPa (8.9%)</td>
<td>32.80 GPa (3.8%)</td>
<td>€10</td>
<td>€13.10</td>
</tr>
<tr>
<td>PHENOLIC</td>
<td>CELLOBOND J2027X/UD 996gsm Glass(^2)</td>
<td>58% (0.4%)</td>
<td>1.984 g/cm(^3) (0.9%)</td>
<td>33.51 MPa (4.8%)</td>
<td>858.8 MPa (6.7%)</td>
<td>34.92 GPa (4.1%)</td>
<td>€4.13</td>
<td>€4.48</td>
</tr>
<tr>
<td>THERMOPLASTIC</td>
<td>ELIUM/UD 996gsm Glass(^2)</td>
<td>56% (1.0%)</td>
<td>1.999 g/cm(^3) (0.4%)</td>
<td>56.87 MPa (3.6%)</td>
<td>942.8 MPa (3.8%)</td>
<td>33.86 GPa (1.6%)</td>
<td>€27.25</td>
<td>€26.83</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>RESIN CLASS</th>
<th>RESIN/REINFORCEMENT</th>
<th>RESIN: HARDENER BY WEIGHT</th>
<th>VISCOSITY (from datasheet)</th>
<th>TOOL</th>
<th>INFUSION TIME (t)</th>
<th>INFUSION TEMPERATURE</th>
<th>CURING SCHEDULE</th>
<th>POST-CURING SCHEDULE</th>
</tr>
</thead>
<tbody>
<tr>
<td>VINYLESTER</td>
<td>LEO SYSTEM/LEO UD 940gsm Glass</td>
<td>100 : 2</td>
<td>340 cP at 20°C</td>
<td>HEATED ALUMINIUM</td>
<td>20 mins</td>
<td>17.3°C (RT)</td>
<td>Overnight at 30°C</td>
<td>6 hours at 80°C</td>
</tr>
<tr>
<td>URETHANE ACRYLATE</td>
<td>CRESTAPOL 1210/UD 996gsm Glass</td>
<td>100 : 2 : 1 : 1</td>
<td>175 cP at 25°C</td>
<td>GLASS</td>
<td>11 mins</td>
<td>21.1°C (RT)</td>
<td>60 mins at RT</td>
<td>No post-cure required</td>
</tr>
<tr>
<td>EPOXY</td>
<td>PRIME 27/UD 996gsm Glass</td>
<td>100 : 28</td>
<td>285 cP at 20°C 150 cP at 30°C</td>
<td>GLASS + HEATED MAT</td>
<td>15 mins</td>
<td>18.8°C (RT)</td>
<td>1 hour at 45°C Overnight at RT</td>
<td>7 hours at 65°C</td>
</tr>
<tr>
<td></td>
<td>SR1125/UD 996gsm Glass²</td>
<td>100 : 14</td>
<td>680 cP at 20°C 305 cP at 30°C 160 cP at 40°C</td>
<td>GLASS + HEATED MAT</td>
<td>40 mins</td>
<td>19.9°C (RT)</td>
<td>16 hours at 40°C</td>
<td>8 hours at 80°C</td>
</tr>
<tr>
<td></td>
<td>BIO-EPOXY</td>
<td>SUPER SAP CLR/UD 996gsm Glass²</td>
<td>100 : 33</td>
<td>300 cP at 25°C</td>
<td>HEATED ALUMINIUM</td>
<td>92 mins</td>
<td>35°C</td>
<td>Overnight at RT</td>
</tr>
<tr>
<td></td>
<td>PHENOLIC</td>
<td>CELLOBOND J2027X/UD 996gsm Glass²</td>
<td>100 : 4</td>
<td>270 cP at 25°C</td>
<td>HEATED ALUMINIUM</td>
<td>36 mins</td>
<td>60°C</td>
<td>15 mins at 60°C</td>
</tr>
<tr>
<td></td>
<td>THERMOPlASTIC</td>
<td>ELIUM/UD 996gsm Glass²</td>
<td>100 : 2.5</td>
<td>100 cP at 25°C</td>
<td>GLASS</td>
<td>23 mins</td>
<td>21.9°C (RT)</td>
<td>Overnight at RT</td>
</tr>
</tbody>
</table>
# SELECTION CRITERIA

## PHASE 1 – MATERIAL CANDIDATES – DEFINITION OF A CRITERIA FOR MATERIAL DOWN-SELECTION

<table>
<thead>
<tr>
<th>Material</th>
<th>Mechanical Properties</th>
<th>Manufacturing</th>
<th>Impact</th>
<th>Total Score / Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Weight [g/cm³]</td>
<td>Flexural Strength 1</td>
<td>Flexural Stiffness 1</td>
<td>Elevat Tem Infusion Cure 1</td>
</tr>
<tr>
<td></td>
<td>/15</td>
<td>/100</td>
<td>/10</td>
<td>/10</td>
</tr>
<tr>
<td>Leo system</td>
<td>10</td>
<td>6</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>Crestapol 1210</td>
<td>10</td>
<td>6</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>Prime 37</td>
<td>10</td>
<td>6</td>
<td>6</td>
<td>10</td>
</tr>
<tr>
<td>SR1125</td>
<td>10</td>
<td>6</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>SUPER SAP CLEAR COUM</td>
<td>10</td>
<td>6</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

**Notes:**

1. ILSS (Interlaminar shear strength): Interlaminar shear strength established from short beam shear test.  **Highest 15 | all others 10 | Lowest 5**
2. Flexural Strength: Flexural strength established from 3-point bend test.  **Highest 10 | all others 6 | Lowest 3**
3. Flexural Modulus: Flexural Modulus established from 3-point bend test.  **Highest 10 | all others 6 | Lowest 3**
4. Elevated Temperature Infusion and/or Cure Requirement: As specified by resin supplier. Certain resin systems require elevated temperature curing to achieve full mechanical properties / to achieve a specified glass transition temperature.  **10 (Elevated temperature Not Required) | 0 (Required)**
5. Elevated Temperature Post Cure Requirement: As specified by resin supplier. Certain resin systems require elevated temperature postcure to achieve full mechanical properties / to achieve specified glass transition temperature.  **10 (Post Cure Not Required) | 0 (Required)**
6. Infusion Time: Time required to fully infuse a flat panel as recorded during laboratory infusion trials.  **(6 mins) | (15 mins) | (15-30 mins) | (30 mins) | (60 mins) | (90 mins) | (120 mins) | (180 mins)**
7. No. of Components required: Number of components in resin system (resin, catalyst, initiator etc.).  **5 (2 part resin system) | 0 (2 part resin system)**
8. Cost: Cost of samples as purchased by UDM.  **Lowest 10 | all others 5 | Highest 0**
9. Claimed Fire Retardancy: Fire retardancy as claimed by resin supplier.  **Yes | No**
10. Styrene: Resins based on styrene reactive diluent technology (e.g. polyester/vinylster/urethane acrylate) present issues with styrene emissions/migration, and manufacturing personnel exposure.  **5 (No styrene content) | 0 (Contains styrene)**
11. Recyclability: Thermoplastic resins can be reformed on heating and as such have a high potential for recycling. Thermosetting resins cannot be reformed on heating and are inherently difficult to recycle.  **5 (Thermoplastic resin) | 0 (Thermosetting resin)**

1st draft ranking: (1) Elium | (2) Crestapol 1210 | (3) SR1125
<table>
<thead>
<tr>
<th>Material</th>
<th>Weight</th>
<th>ILSS</th>
<th>Flexural Strength</th>
<th>Flexural Stiffness</th>
<th>Elevated Temp infusion/Post Cure</th>
<th>Infusion capability</th>
<th>Worldwide knowledge (possibility to be used worldwide)</th>
<th>Cost</th>
<th>Claimed FR</th>
<th>Worker health impact</th>
<th>Recyclability</th>
<th>Total Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synolite 8488 G-2</td>
<td></td>
<td>10</td>
<td>1.5</td>
<td>1.5</td>
<td>5</td>
<td>10</td>
<td>10</td>
<td>15</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>67</td>
</tr>
<tr>
<td>DION 9102-683</td>
<td></td>
<td>10</td>
<td>1.5</td>
<td>1.5</td>
<td>5</td>
<td>10</td>
<td>10</td>
<td>13</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>64</td>
</tr>
<tr>
<td>Leo system</td>
<td>7</td>
<td>1.5</td>
<td>1.5</td>
<td>5</td>
<td>0</td>
<td>14</td>
<td>10</td>
<td>12</td>
<td>21</td>
<td>1</td>
<td>0</td>
<td>73</td>
</tr>
<tr>
<td>Crestapol 1210</td>
<td>7</td>
<td>3</td>
<td>3</td>
<td>10</td>
<td>0</td>
<td>10</td>
<td>20</td>
<td>0</td>
<td>7</td>
<td>0</td>
<td>1</td>
<td>61</td>
</tr>
<tr>
<td>Prime 27</td>
<td>10</td>
<td>1</td>
<td>5</td>
<td>5</td>
<td>0</td>
<td>12</td>
<td>5</td>
<td>10</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>51</td>
</tr>
<tr>
<td>SR1125</td>
<td>7</td>
<td>3</td>
<td>3</td>
<td>5</td>
<td>0</td>
<td>12</td>
<td>5</td>
<td>8</td>
<td>21</td>
<td>1</td>
<td>0</td>
<td>65</td>
</tr>
<tr>
<td>SUPER SAP CLR</td>
<td>7</td>
<td>3</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>6</td>
<td>5</td>
<td>7</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>32</td>
</tr>
<tr>
<td>CELLOBOND</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>6</td>
<td>0</td>
<td>15</td>
<td>21</td>
<td>0</td>
<td>0</td>
<td>52</td>
</tr>
<tr>
<td>ELIUM</td>
<td>7</td>
<td>5</td>
<td>3</td>
<td>10</td>
<td>10</td>
<td>12</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>50</td>
</tr>
</tbody>
</table>

**Total Score /110**

**Ranking if FR is an option**
- 1st Leo System, 2nd SR 1125
- 1st Leo System, 2nd Synolite 8488 G-2 / DION 9102-683, 3rd SR 1125

**Ranking if FR is not an option**
- 1st Leo System, 2nd Synolite 8488 G-2 / DION 9102-683

Previous ponderation values
- 35(15/10/10)
- 35(10/10/10/5)
- 30(10/10/5/5)

**ILSS**

**Flexural Strength**

**Flexural Stiffness**

**Elevated Temp infusion/Post Cure**

**Infusion capability**

**Worldwide knowledge (possibility to be used worldwide)**

**Cost**

**Claimed FR**

**Worker health impact**

**Recyclability**

**To be completed**

System to be checked with Saertex

OUT due to high infusion T°

OUT due to high infusion T° and gel time too short
**Testing Campaign – 2nd Phase**

**Phase 2 – Material Detailed Material Characterization**

**SR125**

Evaluate SR125 with various reinforcements: Carbon, Basalt, Glass

- **Materials:**
  - SR125 / Glass (Completed)
  - SR125 / Basalt
  - SR125 / Carbon

- **Outputs:**
  - Interlaminar shear strength
  - Flexural strength
  - Flexural stiffness
  - Density
  - Fibre volume fraction

Down-select > Move forward with a single reinforcement

**X3 material systems**

**Establish Tensile and Flexural properties of SR125 with one down-selected reinforcement**

- **Materials:**
  - SR125 with Glass OR Carbon OR Basalt

- **Outputs:**
  - Tensile strength
  - Tensile modulus
  - Flexural strength
  - Flexural modulus
  - Fibre volume fraction

**Sandwich Panel Manufacture and Evaluation (SR125 with one down-selected reinforcement)**

- **Outputs:**
  - Flexural strength
  - Flexural modulus

**Fatigue testing (ASTM D3479) of SR125**

**LEO SYSTEM**

Move forward with LEO compatible glass reinforcement only

**Establish Tensile and Flexural properties of LEO SYSTEM with LEO Glass**

- **Materials:**
  - LEO SYSTEM with LEO Glass

- **Outputs:**
  - Tensile strength
  - Tensile modulus
  - Flexural strength
  - Flexural modulus
  - Density
  - Fibre volume fraction

**Sandwich Panel Manufacture and Evaluation (LEO SYSTEM)**

- **Outputs:**
  - Flexural strength
  - Flexural modulus

**Fatigue testing (ASTM D3479) of LEO SYSTEM**
## Comparison of fibre properties

<table>
<thead>
<tr>
<th>RESIN CLASS</th>
<th>RESIN</th>
<th>REINFORCEMENT</th>
<th>Reinforcement Cost</th>
<th>FIBRE VOLUME FRACTION</th>
<th>DENSITY*</th>
<th>APPARENT INTERLAMINAR SHEAR STRENGTH</th>
<th>FLEXURAL STRENGTH</th>
<th>FLEXURAL MODULUS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoxy</td>
<td>SR 1125</td>
<td>Glass fibres SAERTEX U-E-996g/m²</td>
<td>2.00 €/m²</td>
<td>53% (1.3%)</td>
<td>1.842 g/cm (1.9%)</td>
<td>50.53 MPa (1.7%)</td>
<td>853.8 MPa (8.5%)</td>
<td>30.35 GPa</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Carbon fibres Saertex U-C-314g/m²</td>
<td>10.50 €/m²</td>
<td>51% (1.6%)</td>
<td>1.371 g/cm (2.5%)</td>
<td>51.25 MPa (8.4%)</td>
<td>798.8 MPa (± 8.5%)</td>
<td>74.43 GPa (± 10.2%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Basalt fibres Basaltex BAS UNI 350</td>
<td>5.95 €/m²</td>
<td>32% (3.9%)</td>
<td>1.655 g/cm (1.2%)</td>
<td>40.63 MPa (3.7%)</td>
<td>577.9 MPa (4.2%)</td>
<td>22.72 GPa (4.1%)</td>
</tr>
</tbody>
</table>

## DRY VS WET Results

<table>
<thead>
<tr>
<th>RESIN CLASS</th>
<th>RESIN/REINFORCEMENT</th>
<th>APPARENT INTERLAMINAR SHEAR STRENGTH</th>
<th>FLEXURAL STRENGTH</th>
<th>FLEXURAL MODULUS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DRY</td>
<td>WET*</td>
<td>CHANGE</td>
<td>DRY</td>
</tr>
<tr>
<td>STAGE 2</td>
<td>LEO INFUSION RESIN/LEO UD 940gsm Glass</td>
<td>38.11 MPa (4.9%)</td>
<td>37.48 MPa (3.4%)</td>
<td>-1.7%</td>
</tr>
<tr>
<td>STAGE 2</td>
<td>SR1125/UD 996gsm Glass</td>
<td>50.53 MPa (1.7%)</td>
<td>51.86 MPa (1.7%)</td>
<td>+2.6%</td>
</tr>
</tbody>
</table>

*WET SAMPLES ARE SOAKED IN DEIONISED WATER FOR 28 DAYS AT 35°C
Fire performance is of utmost importance for Fibreship application and has been a key point for phase 1 and phase 2 material selection. Tests were made in materials w/o coatings.

- Cone calorimeter: time to ignition, heat release and smoke production data per unit area, mass loss
- TGA: mass loss as a function of temperature
- MCC: heat release as a function of temperature
- DMTA: temperature dependency of key mechanical properties (storage modulus, loss modulus), glass transition temperature
- DSC: specific heat capacity
- TPS: thermal conductivity
FIRE PERFORMANCE

Resins considered and results obtained from the CC test during the first phase analysis

<table>
<thead>
<tr>
<th>RESIN CLASS</th>
<th>RESIN DETAILS</th>
<th>$t_{ig}$ (s)</th>
<th>HRR$_{max}$ (kW/m$^2$)</th>
<th>THR (MJ/m$^2$)</th>
<th>TSP (m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vinylester</td>
<td>LEO system with topcoat</td>
<td>75</td>
<td>69</td>
<td>42.3</td>
<td>8.8</td>
</tr>
<tr>
<td></td>
<td>LEO without topcoat</td>
<td>50</td>
<td>336</td>
<td>33.5</td>
<td>15.1</td>
</tr>
<tr>
<td>Urethane acrylate</td>
<td>Crestapol 1210</td>
<td>44</td>
<td>314</td>
<td>35.4</td>
<td>9.3</td>
</tr>
<tr>
<td>Epoxy</td>
<td>Prime 27</td>
<td>60</td>
<td>496</td>
<td>39.4</td>
<td>10.7</td>
</tr>
<tr>
<td></td>
<td>SR1125 with topcoat</td>
<td>53</td>
<td>261</td>
<td>40.7</td>
<td>9.3</td>
</tr>
<tr>
<td></td>
<td>SR1125 without topcoat</td>
<td>53</td>
<td>546</td>
<td>42.5</td>
<td>13.5</td>
</tr>
<tr>
<td>Bio-epoxy</td>
<td>Super Sap CLR</td>
<td>61</td>
<td>520</td>
<td>42.0</td>
<td>12.0</td>
</tr>
<tr>
<td>Phenolic</td>
<td>Cellobond J2027X</td>
<td>*)</td>
<td>71</td>
<td>9.9</td>
<td>0.4</td>
</tr>
<tr>
<td>Thermoplastic</td>
<td>Elium</td>
<td>23</td>
<td>255</td>
<td>40.7</td>
<td>1.8</td>
</tr>
</tbody>
</table>

*) Exceptional ignition behaviour: small local flame in ca. 90 s, 50 % of area ignited in ca. 120 s, whole surface ignited in ca. 180 s
FIRE PERFORMANCE

EXAMPLES OF THE RESULTS OBTAINED IN THE FIRST PHASE – LEO SYSTEM

HEAT RELEASE RATE:

LEO uncoated @ 50 kW/m²

LEO system with topcoat @ 50 kW/m²
Storage modulus (in MPa) and loss factor (tangens delta) values as the function of temperature with 1 Hz frequency measured in three point bending.
CHARACTERIZATION AND SIMULATION OF FIBRE-BASED MATERIALS
INTRODUCTION. Challenges with composites

• Different materials, with different mechanical performance, are coupled providing combined response

• Anisotropic behaviour: material properties are orientation-dependency.

• Different and complex failure modes (delamination, matrix cracking, fibre breakage,...)

• Lack of experimental data compared with other materials.
MODEL TO ANALYZE THE MECHANICAL PERFORMANCE OF COMPOSITES

Numerical models for composite material characterization will be based on the serial/parallel mixing theory, which acts as constitutive equations manager, providing the non-linear response of the composite by coupling the constitutive equations of its components.

It assumes that the contribution of each component to the composite performance is proportional to its volumetric participation in the composite.

Parallel behavior
\[ \varepsilon_1 = \varepsilon_2 = \ldots = \varepsilon_n \]
\[ \sigma_1 = \sigma_2 = \ldots = \sigma_n \]

Serial behavior
\[ \begin{align*}
\varepsilon_p &= m \varepsilon_p + f \varepsilon_p \\
\sigma_p &= m \sigma_p + f \sigma_p \\
\varepsilon_s &= m \varepsilon_s + f \varepsilon_s \\
\sigma_s &= m \sigma_s + f \sigma_s 
\end{align*} \]

COMPATIBILITY EQUATIONS

Classic RoM
\[ c \sigma = f k \cdot f \sigma + m k \cdot m \sigma \]

S/P RoM
\[ i \sigma = \frac{\partial \Psi^i}{\partial \varepsilon^i} \quad \rightarrow \quad c \sigma = f k \cdot \frac{\partial \Psi^f}{\partial \varepsilon^f} + m k \cdot \frac{\partial \Psi^m}{\partial \varepsilon^m} \]
MODEL TO ANALYZE THE MECHANICAL PERFORMANCE OF COMPOSITES

Implementation of the serial/parallel mixing in a code based on the Finite Element Method

\[ K \cdot D = F \]
\[ \varepsilon = B : D \]
\[ \sigma = C : \varepsilon \]

Or non-linear constitutive equation

\[ \varepsilon_c = \begin{cases} \varepsilon_f \\
\varepsilon_m \end{cases} \]
\[ \sigma_f = C_f : \varepsilon_f \]
\[ \sigma_m = C_m : \varepsilon_m \]

Or non-linear constitutive equation

\[ \sigma_c = k_f \cdot \sigma_f + k_m \cdot \sigma_m \]
MODEL TO ANALYZE THE MECHANICAL PERFORMANCE OF COMPOSITES

FORMULATION PERFORMANCE:

Stress-Strain in load direction

Stress-strain perpendicular to load

Stress-Strain in load direction

Stress-strain perpendicular to load
MODEL TO ANALYZE THE MECHANICAL PERFORMANCE OF COMPOSITES

• With this formulation the composite performance is obtained from the mechanical parameters of the composite components.

• Failure is predicted by the components failure, instead of a failure criteria that considers the composite a material by itself.

CALIBRATION PROCESS – PARAMETERS REQUIRED

From composite:

Each different ply orientation, Volumetric participation of each ply with different orientation, Fiber/Matrix system

From constituent materials:

Young modulus, Poisson coefficient, Shear modulus, Volumetric participation, Non-linear parameters (strengths, fracture energy)
### MATERIAL PROPERTIES DEFINED (FROM CALIBRATION PROCESS)

#### Elastic properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Young Modulus (Gpa)</th>
<th>Poisson coefficient</th>
<th>Shear Modulus (Gpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leo Fiber E-Glass</td>
<td>70</td>
<td>0.22</td>
<td>1.66</td>
</tr>
<tr>
<td>Leo Vinyl Ester</td>
<td>3</td>
<td>0.3</td>
<td>0.455</td>
</tr>
</tbody>
</table>

#### Non-Linear properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Yield criteria</th>
<th>Constitutive law</th>
<th>Compressive threshold strength (MPa)</th>
<th>Shear strength (MPa)</th>
<th>Fracture energy (J/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leo Fiber Glass</td>
<td>Norm principal stress</td>
<td>Exponential damage</td>
<td>1400</td>
<td>1400</td>
<td>185000</td>
</tr>
<tr>
<td>Leo Vinyl Ester</td>
<td>Norm principal stress</td>
<td>Exponential damage</td>
<td>120</td>
<td>70.6</td>
<td>5370</td>
</tr>
</tbody>
</table>
RESULTS. Numerical model

Tensile test model

Flexure test model

Shear test model
CALIBRATION PROCESS AND NUMERICAL RESULTS

COMPARISION OF NUMERICAL VS EXPERIMENTAL RESULTS FOR GF/VINYLESTER LEO SYSTEM

- Longitudinal tensile test
- Transversal tensile test
- Longitudinal flexure test
- Transversal flexure test
- Shear test
RESULTS FEM MODEL. Failure modes.

A numerical simulation not only has to represent the global performance correctly, besides has to show the equivalent failure mechanism

3P Bending in fibre direction

3P Bending perpendicular to fibre direction

Shear test
Fatigue analysis is basic in naval structures and must be also considered in composites.

Fatigue performance of composites is highly anisotropic, due to the differential fatigue performance of fibres and matrix:
FATIGUE ANALYSIS

ADAPTATION OF THE FORMULATION TO COMPOSITES

• Require to establish fatigue models for fibre and matrix.

• S/P Mixing Theory couples both materials to obtain fatigue behaviour of composite.

• **Fibre and matrix performance, both static and fatigue, are obtained by tests on UD laminates.**
  • UD loaded at longitudinal direction has a fibre-dominated performance.
  • UD loaded at transverse direction has a matrix-dominated performance.
  • Failure of the laminate is supposed when damage appears on fibre for longitudinal ply.
FATIGUE ANALYSIS

VALIDATION OF THE FORMULATION

Monotonic 90° tensile test

Monotonic 0° tensile test

Monotonic cross-ply tensile test

Calibration of EPOXY material

Calibration of CARBON FIBRES

Fatigue results comparison
The procedure developed is applied to the Zim Luanda container ship vessel.
Fatigue analysis

Cycle jumps: 1, 25,000, 150,000, 225,000 cycles.
THANK YOU

www.fibreship.eu