INTRODUCTION

COMPOSITES IN MARINE ENGINEERING:
The use of composite materials in the marine industry is quite large for small crafts, or in high performance crafts such as the competition ones.

Fibreship aims using these materials in large commercial vessels.

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FIBRESHIP SPECIFIC MATERIAL CHALLENGES:

Fibership project will use the expertise of the partners involved and the knowledge obtained from other industrial fields to solve the different technical challenges posed by large length ships. These are:

1. Material selection and characterization. Fatigue performance
2. Fire Performance
3. Structural connections between parts
4. Numerical material modelling

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The result of these studies will be outlined in a

*Catalogue of applicable materials and joining techniques recommended by class*
FIBRE BASED MATERIALS ANALYSIS AND SELECTION

1st FIBRESHIP WORKSHOP – June 14th 2018 – London UK
Identification of new fibre based material systems for large scale vessels is a key objective of Fibreship.

Comprehensive list of candidate constituents.
### Phase 1 – Material Candidates – Mechanical Properties

<table>
<thead>
<tr>
<th>Resin Class</th>
<th>Resin/Reinforcement</th>
<th>Vf (% Fibre Volume Fraction)</th>
<th>Density</th>
<th>Apparent Interlaminar Shear Strength</th>
<th>Flexural Strength</th>
<th>Flexural Modulus</th>
<th>Resin Cost ($ per kg)</th>
<th>Resin/Hardener Mixture Cost ($ per kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vinyl Ester</td>
<td>LEO System/LEO UD 940gsm Glass</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Epoxy</td>
<td>PRIME 27/UD 996gsm Glass</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SR1125/UD 996gsm Glass</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bio-Epoxy</td>
<td>SUPER SAP CLR/UD 996gsm Glass</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phenolic</td>
<td>CELLOBOND J2027X/UD 996gsm Glass</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>THERMOPLASTIC</td>
<td>ELIUM/UD 996gsm Glass</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### FIBRE BASED MATERIALS ANALYSIS AND SELECTION

#### PHASE 1 – MATERIAL CANDIDATES – Mechanical Properties

<table>
<thead>
<tr>
<th>RESIN CLASS</th>
<th>RESIN/REINFORCEMENT</th>
<th>V&lt;sub&gt;f&lt;/sub&gt; (FIBRE VOLUME FRACTION)</th>
<th>DENSITY</th>
<th>APPARENT INTERLAMINAR SHEAR STRENGTH</th>
<th>FLEXURAL STRENGTH</th>
<th>FLEXURAL MODULUS</th>
<th>Resin Cost&lt;sup&gt;1&lt;/sup&gt; (€ per kg)</th>
<th>Resin/Hardener Mixture Cost&lt;sup&gt;2&lt;/sup&gt; (€ per kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VINYL ESTER</td>
<td>LEO SYSTEM/LEO UD 940gsm Glass</td>
<td>56% (4.3%)</td>
<td>2.233 g/cm&lt;sup&gt;3&lt;/sup&gt; (1.8%)</td>
<td>44.42 MPa (8.6%)</td>
<td>592.0 MPa (22%)</td>
<td>22.03 GPa (21%)</td>
<td>€11.14</td>
<td>€14.00</td>
</tr>
<tr>
<td>EPOXY</td>
<td>Epoxy/Premix 27/UD 996gsm Glass</td>
<td>58% (0.9%)</td>
<td>2.061 g/cm&lt;sup&gt;3&lt;/sup&gt; (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>BIO-EPoxy</td>
<td>SUPER SAP CLR/UD 996gsm Glass</td>
<td>60% (0.6%)</td>
<td>2.158 g/cm&lt;sup&gt;3&lt;/sup&gt; (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</td>
<td>58% (0.4%)</td>
<td>1.984 g/cm&lt;sup&gt;3&lt;/sup&gt; (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</td>
<td>56% (1.0%)</td>
<td>1.999 g/cm&lt;sup&gt;3&lt;/sup&gt; (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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# FIBRE BASED MATERIALS ANALYSIS AND SELECTION

## PHASE 1 – MATERIAL CANDIDATES – Manufacturing details

<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</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 : 1</td>
<td>340 cP at 20°C</td>
<td>HEATED ALUMINIUM</td>
<td>20 mins</td>
<td>17.3°C (RT³)</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</td>
<td>175 cP at 25°C</td>
<td>GLASS + HEATED MAT</td>
<td>11 mins</td>
<td>21.1°C (RT³)</td>
<td>60 mins at RT³</td>
<td>No post-cure required</td>
</tr>
<tr>
<td>EPOXY</td>
<td>PRIME 27/ UD 996gsm Glass²</td>
<td>100 : 28</td>
<td>285 cP at 20°C</td>
<td>GLASS + HEATED MAT</td>
<td>15 mins</td>
<td>18.8°C (RT³)</td>
<td>1 hour at 45°C</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</td>
<td>GLASS + HEATED MAT</td>
<td>40 mins</td>
<td>19.9°C (RT³)</td>
<td>16 hours at 40°C</td>
<td>8 hours at 80°C</td>
</tr>
<tr>
<td></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 RT³</td>
<td>2 hours at 120°C</td>
</tr>
<tr>
<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>
<td>3 hours at 80°C</td>
</tr>
<tr>
<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 (RT³)</td>
<td>Overnight at RT³</td>
<td>No post-cure required</td>
</tr>
</tbody>
</table>

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### FIBRE BASED MATERIALS ANALYSIS AND SELECTION

#### PHASE 1 – MATERIAL CANDIDATES – DOWN-SELECTION

<table>
<thead>
<tr>
<th>Weight</th>
<th>Mechanical Properties (Dry Condition)</th>
<th>Manufacturing</th>
<th>Impact</th>
<th>Total Score /110</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ILSS¹</td>
<td>Flexural Strength²</td>
<td>Flexural Stiffness³</td>
<td>Elevated Temp infusion/ Post Cure⁴</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>10</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>Leo system</td>
<td>7</td>
<td>1.5</td>
<td>1.5</td>
<td>5</td>
</tr>
<tr>
<td>Crestapol 1210</td>
<td>7</td>
<td>3</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>Prime 27</td>
<td>10</td>
<td>3</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>SR1125</td>
<td>7</td>
<td>3</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>SUPER SAP CLR</td>
<td>7</td>
<td>3</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>CELLOBOND</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>ELIUM</td>
<td>7</td>
<td>5</td>
<td>3</td>
<td>10</td>
</tr>
</tbody>
</table>

Traction strength?

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**Ranking if FR is an option**
- 1st Leo System, 2nd SR 1125

**Ranking if FR is not an option**
- 1st Leo System, 2nd Synolite 8488 G-2 / DION 9102-683, 3rd SR 1125
Evaluate SR1125 with various reinforcements: Carbon, Basalt, Glass

MATERIALS:
- SR1125 / Glass (Completed)
- SR1125 / Basalt
- SR1125 / Carbon

OUTPUTS:
- Interlaminar shear strength
- Flexural Strength
- Flexural Stiffness
- Density
- Fibre volume fraction

Establish Tensile and Flexural properties of SR1125 with one down-selected reinforcement

MATERIALS:
- SR1125 with Glass OR Carbon OR Basalt

OUTPUTS:
- Tensile Strength
- Tensile Modulus
- Flexural Strength
- Flexural Modulus
- Fibre volume fraction

Sandwich Panel Manufacture and Evaluation (SR1125 with one down-selected reinforcement)

OUTPUTS:
- Flexural Strength
- Flexural Modulus

Fatigue testing (ASTM D3479) of SR1125

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
Fatigue Tests

<table>
<thead>
<tr>
<th></th>
<th>$P_{\text{max}}$: 60 % failure</th>
<th>$P_{\text{max}}$: 40 % failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEO / Glass</td>
<td>3 samples</td>
<td>3 samples</td>
</tr>
<tr>
<td>Sicomin / Reinforcement*</td>
<td>3 samples</td>
<td>3 samples</td>
</tr>
</tbody>
</table>

Test Details

- **Loading:** Fatigue (Constant Amplitude, Tension-Tension)
- **Nominal Dimensions:** L (400 mm) W (25 mm) T (3 mm)
- **Sample Lay-up:** Uni-directional
- **Loading Frequency:** 4 Hz
- **R-Ratio:** 0.5
- **Stop Test:** On Failure or after 300k cycles
- **Outputs:** Stiffness every 100k cycles (extensometers) | Retained Strength @ 300k cycles

![Load Cycle with Pmax = 60% failure](image)
Fatigue Tests

![Graph showing fatigue test results with maximum stress ratio (σ_max / σ_ult) vs. number of cycles. The graph includes data points for SR1125, R=0.5, LEO System, R = 0.5, and Harik Data R=0.25 (2002).]
MAIN ACTIVITIES CONDUCTED

FIRE PERFORMANCE

1st FIBRESHIP WORKSHOP – June 14th 2018 – London UK
FIRE PERFORMANCE

FIRE PERFORMANCE ANALYSIS

- Fire performance is of utmost importance for Fibreship application and has been a key point for phase 1 and phase 2 material selection.
- Fire performance study has been also conducted with a 2-phase approach.

Tests made in different resin systems:
- Thermogravimetric analysis (TGA)
- Cone-Calorimeter (CC)

Test made in down-selected resin systems:
- Micro-scale combustion calorimetry (MCC)
- Differential scanning calorimetry (DSC)
- Transient plane source (TPS)
- Dynamic mechanical thermal analysis (DMTA)
# FIRE PERFORMANCE

## RESULTS FROM 1st 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
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
SECOND PHASE ANALYSES

Currently the second phase analysis is ongoing and results will be available by mid July.

The test that are being conducted are:

**DMTA:** Used to measure the mechanical and viscoelastic properties of materials as a function of temperature, time and frequency when they are subjected to a periodic stress with fixed frequency, amplitude and temperature programme.

**MCC:** Used for measuring the heat release rate of a sample. The result is the heat of complete combustion as a function of temperature.

**TPS:** Used to obtain the thermal conductivity of the material.

**DSC:** Used to obtain the specific heat capacity and heats of reaction.
MAIN ACTIVITIES CONDUCTED

NUMERICAL MODELS

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A reliable design of Fibreships require of reliable material models, as well as reliable analysis tools.

Material analysis will be based on the serial parallel mixing theory. This formulation obtains the mechanical behaviour of the composite material from the constitutive performance of its constituents.

The composite constituents are coupled by defining two compatibility equations that relate their strain and stress tensors:
With this approach,

- The simulation provides the mechanical performance of fibre and matrix.

Leo composite stresses
Four Point Bending test (4PB)

Matrix stress

Fibre stress
With this approach,

- The simulation provides the mechanical performance of fibre and matrix.
- It is possible to obtain the non-linear behaviour of the composite.

Leo composite stresses
Interlaminar Shear Strength test (ISS)
With this approach,

• The simulation provides the mechanical performance of fibre and matrix.
• It is possible to obtain the non-linear behaviour of the composite
• And, once calibrated, the formulation is capable of reproducing the exact non-linear stress-strain response of the composite.
MAIN ACTIVITIES CONDUCTED

FIRST OUTCOME OF THE WORK CONDUCTED
AND TOPICS FOR DISCUSSION

1st FIBRESHIP WORKSHOP – June 14th 2018 – London UK
FIRST OUTCOME OF THE WORK CONDUCTED

FINAL MATERIAL SELECTION

LEO SYSTEM (Vinylester with glass fibre reinforcement)

Main reasons for this selection are:

1. Equivalent mechanical properties
2. Better fatigue performance than SR1125
3. Better fire performance than the SR1125
4. Good manufacturability
5. Good price
6. Good material knowledge by the shipyards

NOTES:
• The selection of this material does not imply that other materials are disregarded.
• The LEO system is the one better positioned for Fibreship application.
• Other materials can be used in different ship sections if specific properties are required.
TOPICS FOR DISCUSSION

1. The LEO system has been found to be the best material for Fibreship. The material selection has been made based on the most relevant parameters. Fibreship will require using different composite materials for specific applications.

2. Fire protection of a Fibreship cannot rely only on the material. There will be need of further passive and active fire protection in specific areas.

3. Connections will play an important role in Fibreship. The definition of these connections will be technically challenging, but can be solved.

4. Numerical models for composite characterization are basic. A non-linear analysis of a Fibreship is a requirement to have a reliable design.

5. There is a need for international material guidelines for Fibreships.
THANK YOU

www.fibreship.eu