FIBRESHIP
INTEGRAL COMPOSITE SHIP

2nd FIBRESHIP WORKSHOP

Breakout session 1: MATERIALS

La Ciotat

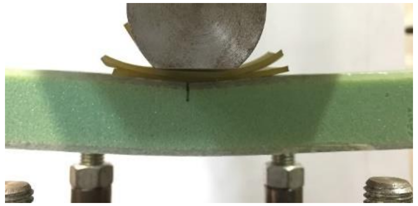
June 24th 2019

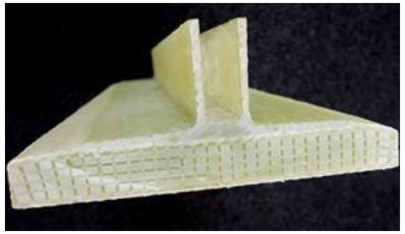
INTRODUCTION

COMPOSITES IN MARINE ENGINEERING:

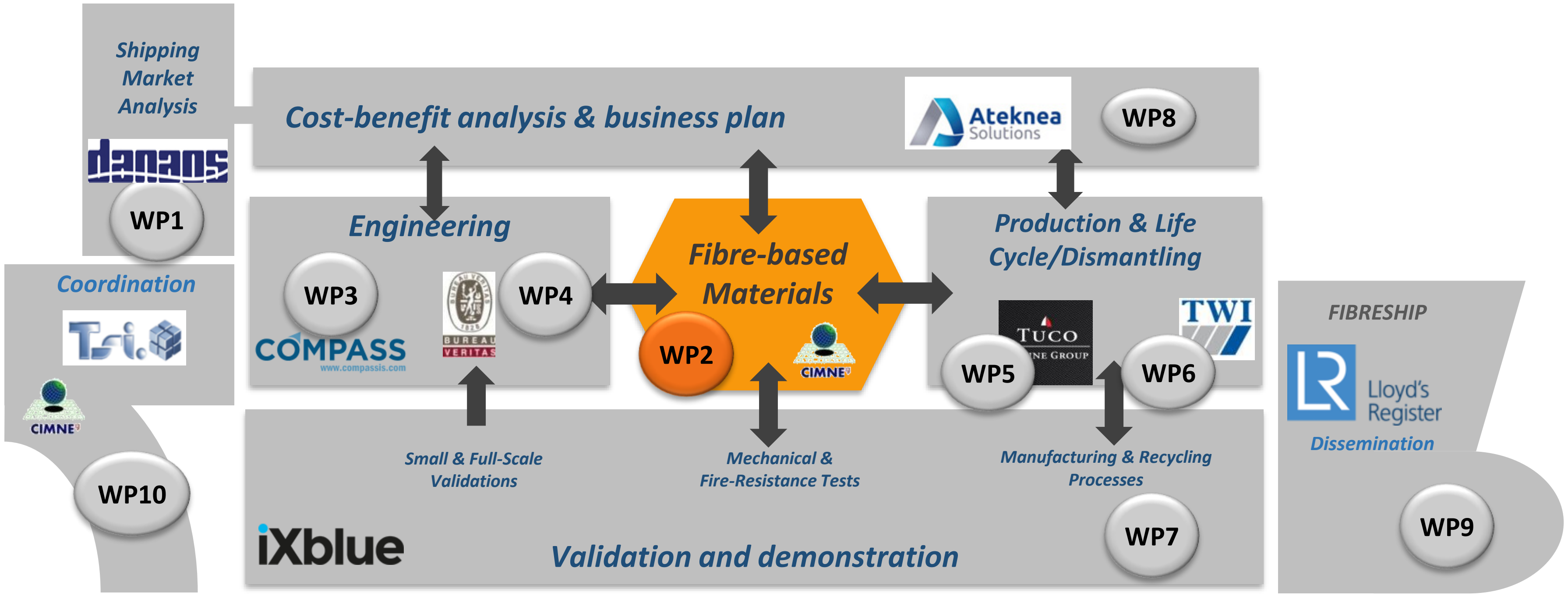
The use of composite materials in the marine industry is quite large for small crafts, or in high performance crafts such as the competition ones.

Fibreship aims using these materials in large commercial vessels.





Materials are at the core of Fibreship project, as they interact with the rest of workpackages. Specially with the engineering and production ones.



FIBRESHIP PROJECT APPROACH TO MATERIALS SELECTION, CHARACTERIZATION AND ANALYSIS

The main outcomes of FIBRESHIP project regarding materials are:

1. Define a material selection criteria
2. Define a characterization procedure for the selected materials (experimental)
3. Define material models to be used in the analysis of fibreships
4. Assess connection technology and propose a new connection configuration with disassembling capabilities

The result of this work will be outlined in a

Catalogue of applicable materials and joining techniques recommended by class

MATERIAL SELECTION

MATERIAL SELECTION HAS BEEN CONDUCTED IN TWO PHASES:

1. Selection of the most promising resin
2. Selection of the best fibre-resin system. Analysis of Sandwich laminates

NOTES:

- The selection of what is named as the *best material* does not imply that other materials are disregarded.
- Other materials can be used in different ship sections when specific properties are required.

SELECTION OF THE MOST PROMISING RESIN

Seven different resin materials have been tested, all of them with UD glass fibre reinforcement.

RESIN CLASS	RESIN/REINFORCEMENT
VINYLESTER	LEO SYSTEM/ LEO UD 940gsm Glass
URETHANE ACRYLATE	CRESTAPOL 1210/ UD 996gsm Glass[2]
EPOXY	PRIME 27/ UD 996gsm Glass[2]
	SR1125/ UD 996gsm Glass[2]
BIO-EPOXY	SUPER SAP CLR/ UD 996gsm Glass[2]
PHENOLIC	CELLOBOND J2027X/ UD 996gsm Glass[2]
THERMOPLASTIC	ELIUM/ UD 996gsm Glass[2]

Their mechanical and fire performance have been experimentally characterized:

- 3PB test, ILSS test, Fibre content, Density
- Cone calorimeter, Thermogravimetric analysis

It was also evaluated their manufacturability.

MATERIAL SELECTION

THE SELECTION CRITERIA HAS BEEN DEFINED BY ALL PROJECT PARTNERS (ENGINEERING, SHIPYARDS, CLASS)

	Mechanical Properties (Dry Condition)			Manufacturing				Impact				Total Score /110	
Weight	**20**			**50**				**40**					
	ILSS[1]	Flexural Strength[2]	Flexural Stiffness[3]	Elevated Temp infusion/ cure[4]	Post Cure[5]	Infusion capability[6]	Worldwide knowledge (possibility to be used worldwide)	Cost[8]	Claimed FR[9]	Worker health impact[10]	Recyclability[11]		
Weight	**/10**	**/5**	**/5**	**/10**	**/10**	**/20**	**/10**	**/15**	**/21**	**/2**	**/2**		
Synolite 8488 G-2	?	?	?	10	10	20	10	15	0	1	1	67	To be completed
DION 9102-683				10	10	20	10	13	0	1	?	64	
Leo system	7	1.5	1.5	5	0	14	10	12	21	1	0	73	System to be checked with Saertex
Crestapol 1210	7	3	3	10	10	20	0	7	0	1	0	61	
Primo 27	10	3	5	5	0	12	5	10	0	1	0	51	
SR1125	7	3	3	5	0	12	5	8	21	1	0	65	
SUPER SAP CLR	7	3	3	0	0	6	5	7	0	1	0	32	OUT due to high infusion T°
CELLOBOND	4	3	3	0	0	6	0	15	21	0	0	52	OUT due to high infusion T° and gel time too short
ELIUM	7	5	3	10	10	12	0	0	0	2	1	50	

Traction strenght ?

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

SELECTION OF THE FIBRE-RESIN SYSTEM

Three different fibres have been analysed with the SICOMIN SR1125 epoxy resin down-selected:

REINFORCEMENT	COST [€/m²]	FIBRE VOLUME FRACTION [%]	DENSITY [g/cm3]	ILSS [MPa]	FLEXURAL STRENGTH [MPa]	FLEXURAL MODULUS [GPa]
GLASS fibres SAERTEX U-E-996g/m	2.00	53	1.842	50.53	853.8	30.35
CARBON fibres Saertex U-C-314g/m2	10.50	51	1.371	51.25	798.8	74.43
BASALT fibres Basaltex BAS UNI 350	5.95	32	1.655	40.63	577.9	22.71

The down-selected vinylester has not been tested with different fibres because the LEO system is a closed system (fibre+matrix) with improved fire properties, which will be lost if the fibre is modified.

Despite the improved properties that present carbon vs. glass fibres, specially regarding the flexural modulus, the fibres selected for Fibreship application are GLASS FIBRES. These are 5 times cheaper.

MATERIAL CHARACTERIZATION

MATERIAL CHARACTERIZATION – MECHANICAL PROPERTIES

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A thorough mechanical characterization has been made of the down-selected materials in order to know their exact properties and to have all required parameters for their numerical simulation.

SR1125

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

Down-select > Move forward with a single reinforcement

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

MATERIALS	• SR1125 with Glass
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

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)

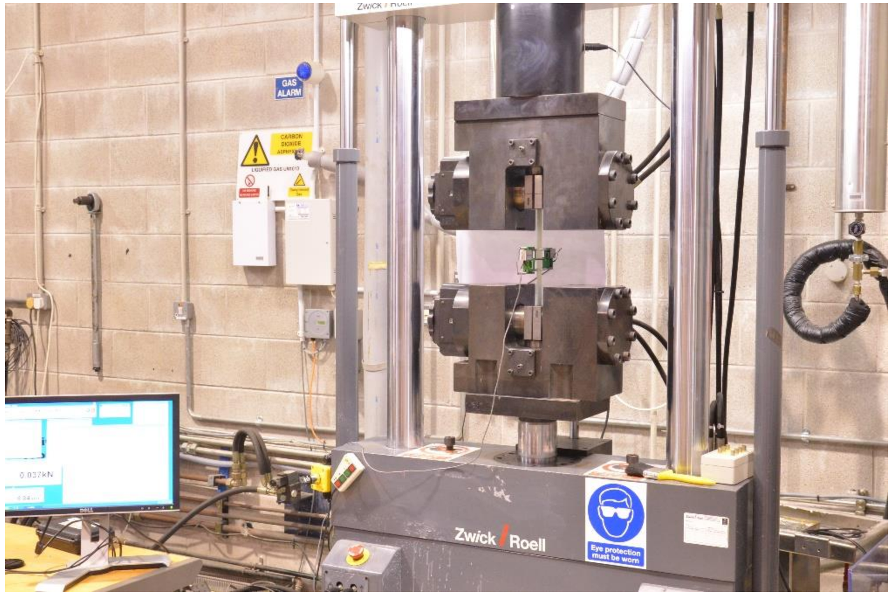
OUTPUTS	• Flexural Strength • Flexural Modulus

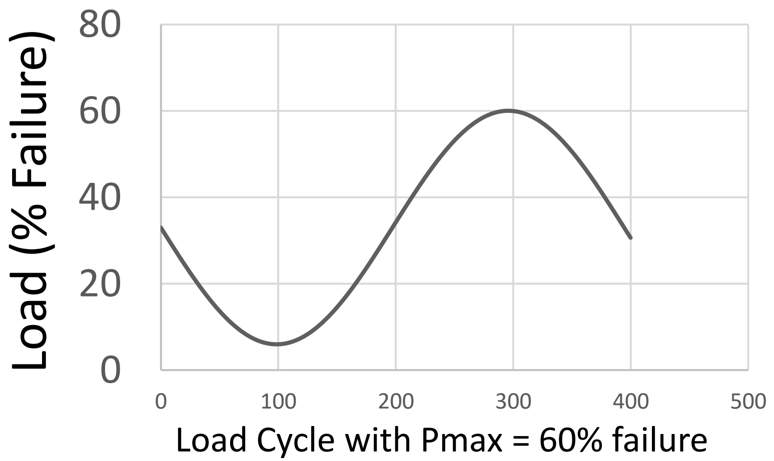
Fatigue testing (ASTM D3479) of LEO SYSTEM

Fatigue Tests

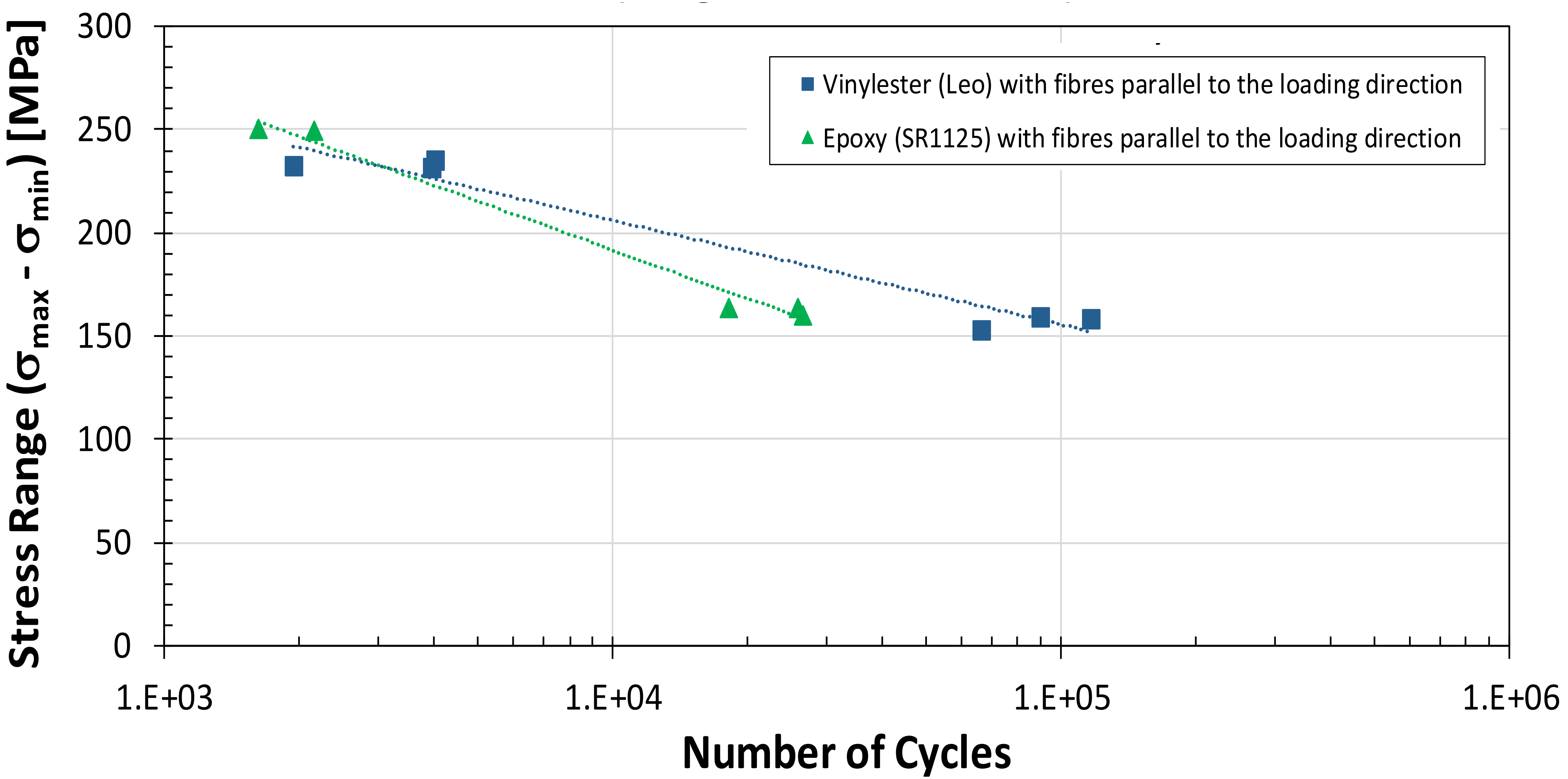
	P_{max}: 60 % failure	P_{max}: 40 % failure
LEO / Glass	3 samples	3 samples
Sicomin / Reinforcement*	3 samples	3 samples

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



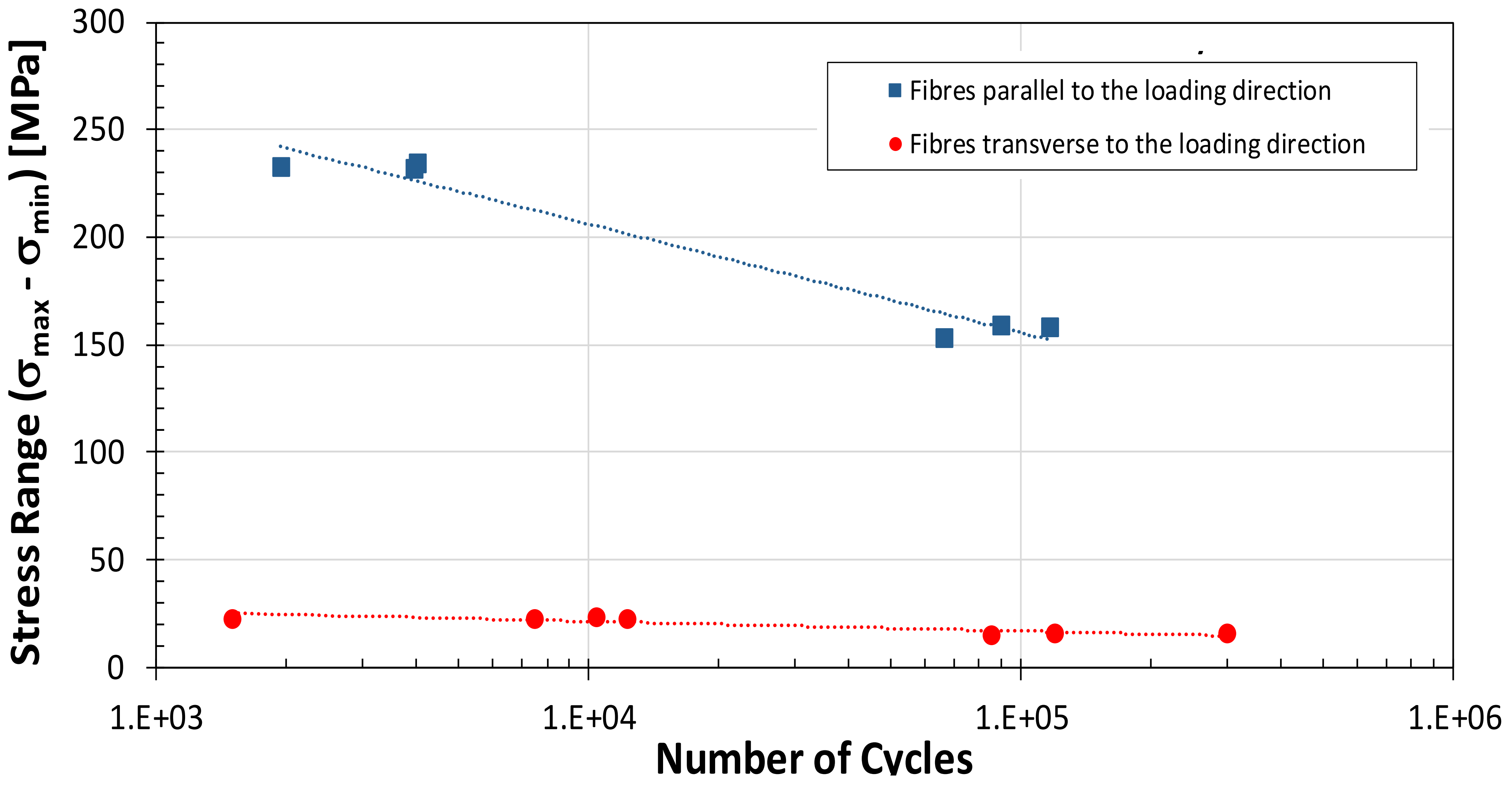


S-N Curve Leo (Vinyl Ester) and SR 1125 (Epoxy) – Fibres parallel to the loading direction



MATERIAL CHARACTERIZATION – MECHANICAL PROPERTIES

S-N Curve Leo 0° vs Leo 90°



MATERIAL CHARACTERIZATION – FIRE PERFORMANCE PROPERTIES

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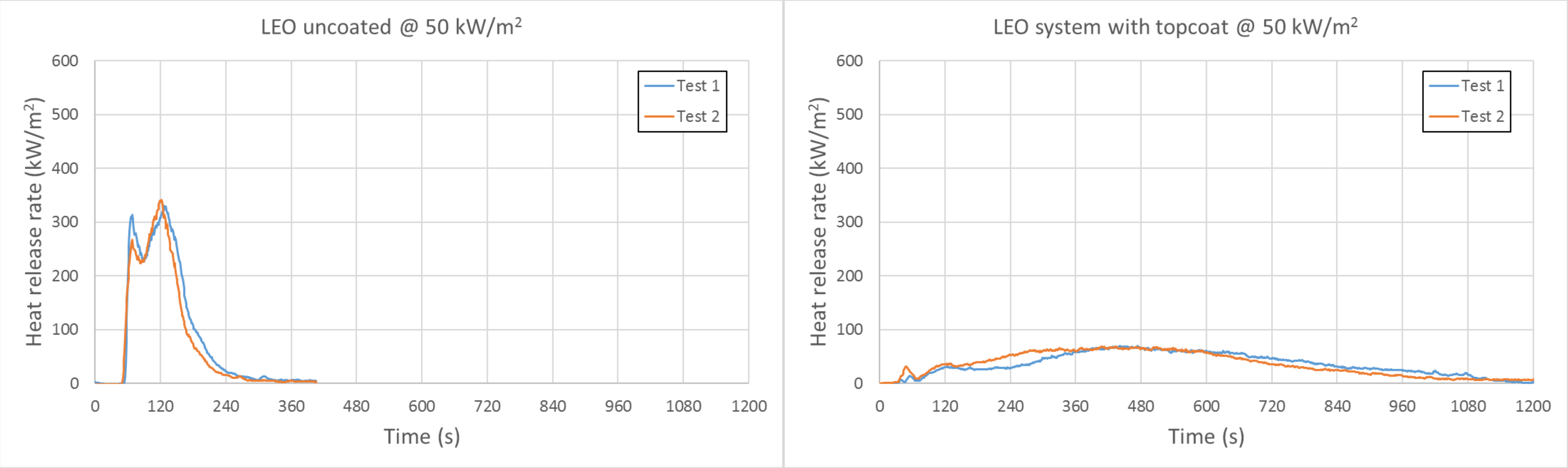
A complete fire performance analysis has been made of the down-selected materials.

The experimental campaign has also been made in two phases, and the tests conducted have been the following ones:

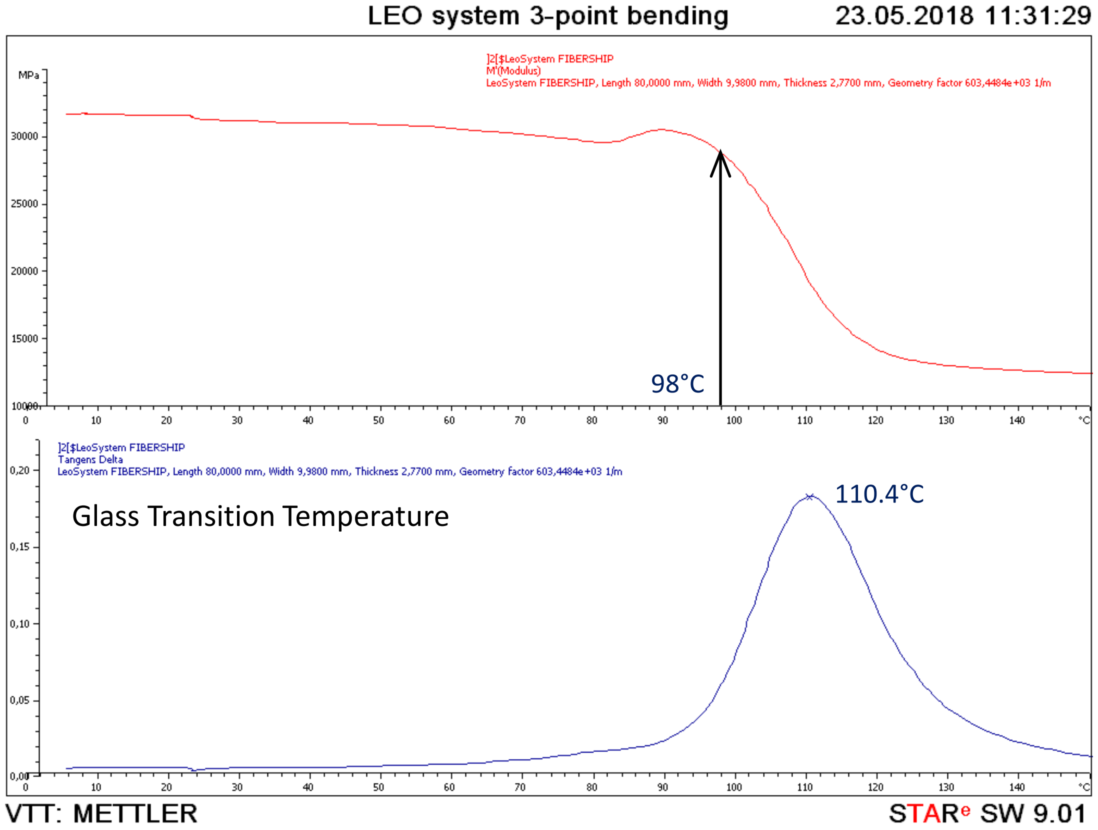
TEST METHOD	PHASE	OUTCOME
Cone calorimeter	1 & 2	time to ignition, heat release and smoke production data per unit area, mass loss
TGA	1	mass loss as a function of temperature
MCC	2	heat release as a function of temperature
DMTA	2	temperature dependency of key mechanical properties (storage modulus, loss modulus), glass transition temperature
DSC	2	specific heat capacity
TPS	2	thermal conductivity

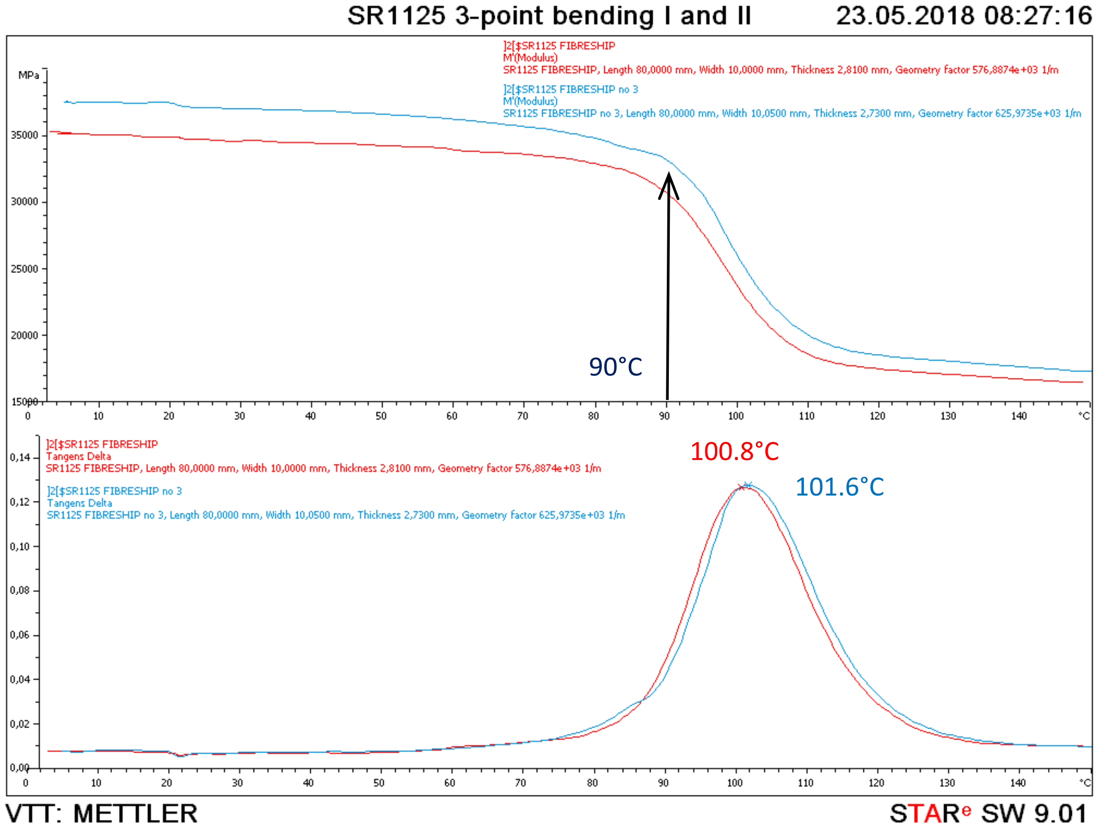
Tests where made in materials with and without coatings

Example of the effect of the coating in the Heat Release Rate obtained from the CC test



DMTA (Dynamic Mechanical Thermal Analysis) results for the LEO and the Sicomin resins (without coating)





Storage modulus (in MPa) and loss factor (tangens delta) values as the function of temperature with 1 Hz frequency measured in three point bending.

MATERIAL MODELS

Material models must be capable of accounting for the anisotropy of composites, as well as for the different failure modes that can take place in these materials (fibre failure, matrix transverse cracking, delamination, fatigue, etc.)

The model proposed by the project to account for all these effects is the serial/parallel mixing theory. Fibreship has also develop a calibration procedure based on the experimental data obtained from the material characterization.

SERIAL/PARALLEL MIXING THEORY:

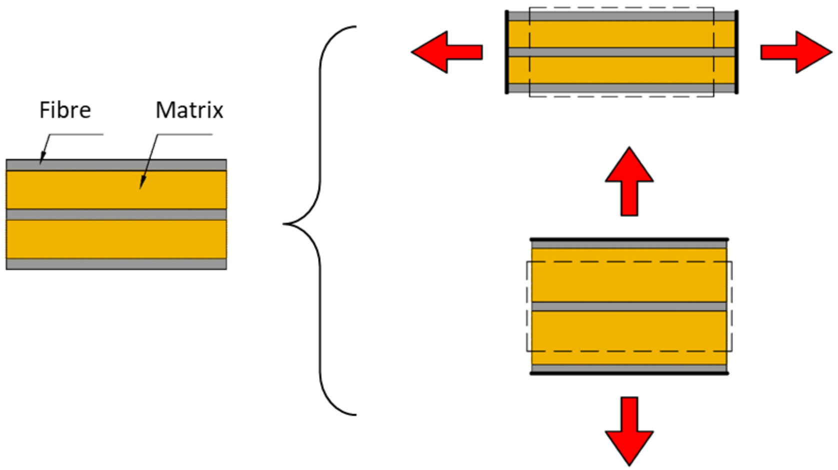
This formulation is a constitutive equations manager that provides the response of the composite by coupling the constitutive equations of its components.

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

MATERIAL MODELS – MECHANICAL ANALYSIS

SERIAL/PARALLEL MIXING THEORY – FORMULATION BASICS

Compatibility relations between components



Parallel behavior

$\varepsilon_1 = \varepsilon_2 = \ldots = \varepsilon_n$

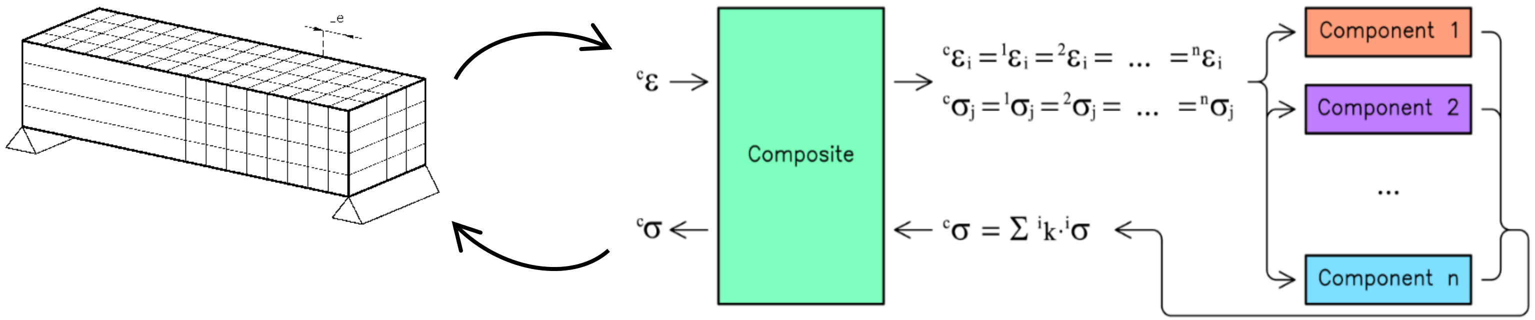
$$\begin{cases} {}^{c}\varepsilon_P = {}^{m}\varepsilon_P = {}^{f}\varepsilon_P \\ {}^{c}\sigma_P = {}^{m}k\,{}^{m}\sigma_P + {}^{f}k\,{}^{f}\sigma_P \end{cases}$$

Serial behavior

$\sigma_1 = \sigma_2 = \ldots = \sigma_n$

$$\begin{cases} {}^{c}\varepsilon_S = {}^{m}k\,{}^{m}\varepsilon_S + {}^{f}k\,{}^{f}\varepsilon_S \\ {}^{c}\sigma_S = {}^{m}\sigma_S = {}^{f}\sigma_S \end{cases}$$

Structural analysis using the serial/parallel mixing theory



CALIBRATION PROCESS – PARAMETERS REQUIRED

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

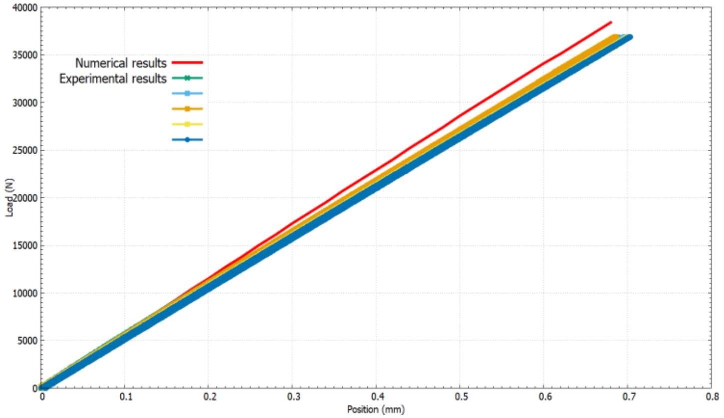
From constituents: Young modulus, Poisson coefficient, Shear modulus, Volumetric participation, Non-linear parameters (strengths, fracture energy)

Elastic properties			
Material	Young Modulus (Gpa)	Poisson coefficient	Shear Modulus (Gpa)
Leo Fiber E-Glass	70	0.22	1.66
Leo Vinyl Ester	3	0.3	0.455

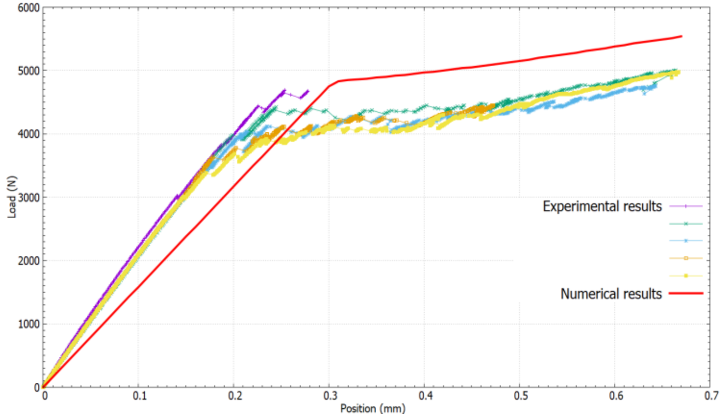
Non-Linear properties					
Material	Yield criteria	Constitutive law	Compressive threshold strength (MPa)	Shear strength (MPa)	Fracture energy (J/m2)
Leo Fiber Glass	Norm principal stress	Exponential damage	1400	1400	185000
Leo Vinyl Ester	Norm principal stress	Exponential damage	120	70.6	5370

MATERIAL MODELS – MECHANICAL ANALYSIS

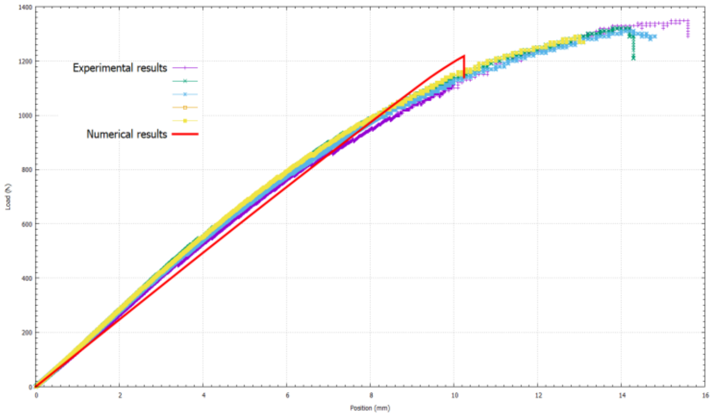
COMPARISION OF NUMERICAL vs EXPERIMENTAL RESULTS FOR GF/VINYLESTER LEO SYSTEM



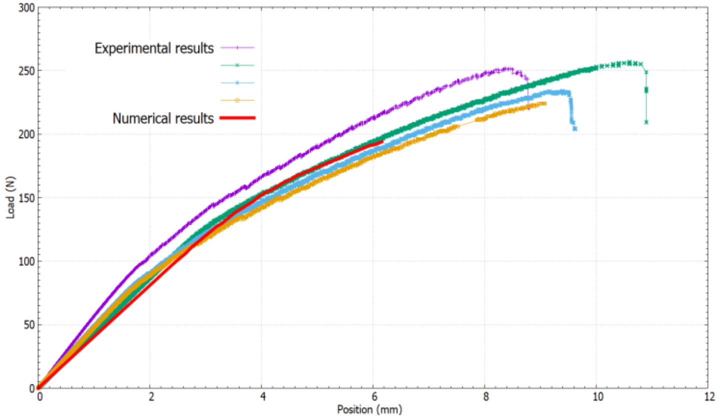
Longitudinal tensile test



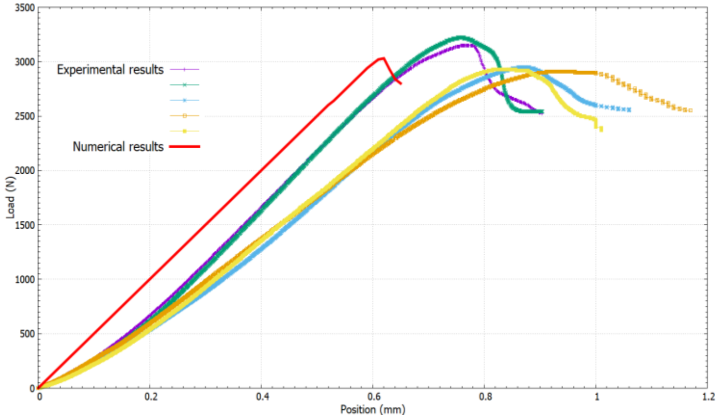
Transversal tensile test



Longitudinal flexure test



Transversal flexure test

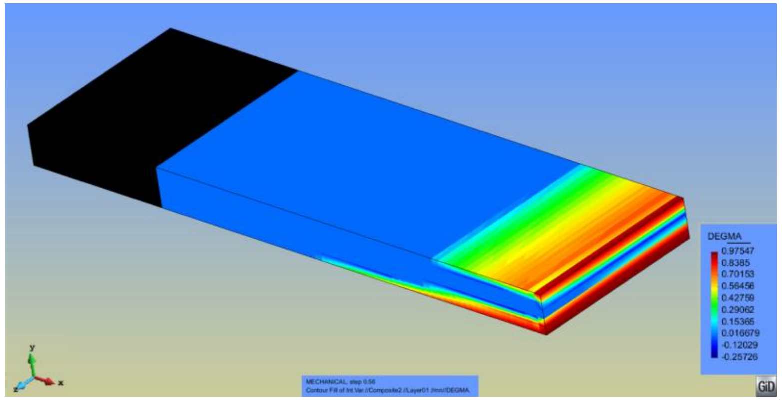


Shear test

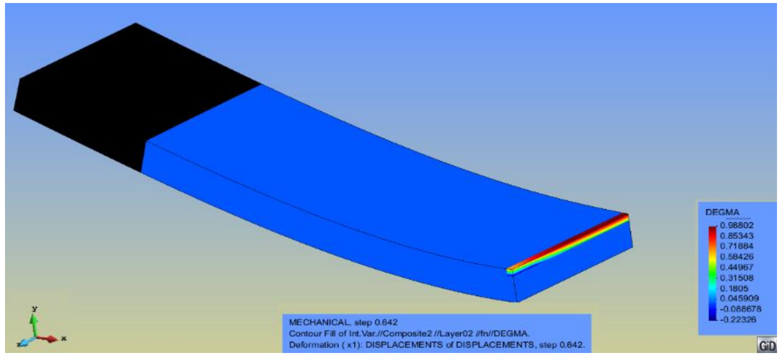
RESULTS FEM MODEL. Failure modes.

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

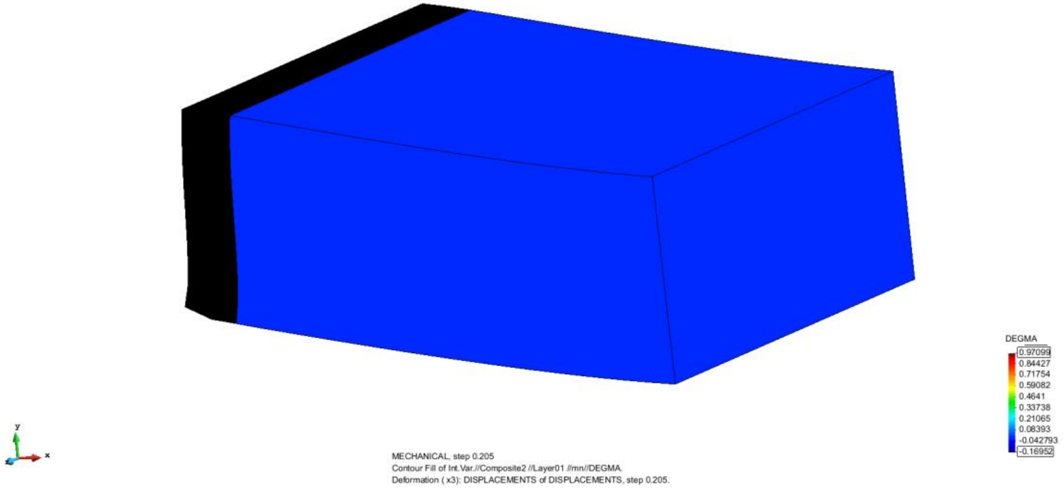
3P Bending in fibre direction



3P Bending perpendicular to fibre direction



Shear test



MATERIAL MODELS – FATIGUE ANALYSIS

The fatigue analysis is introduced by modifying the constitutive law of the material, by means of a reduction function, in order to account for the effect of cyclic loads:

$$f(\sigma) - f_N(N, \sigma_m, R) \cdot K(\sigma_{th}) \leq 0$$

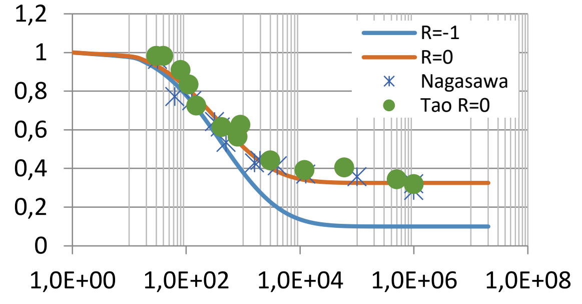
Reduction function

Quasi-static strength

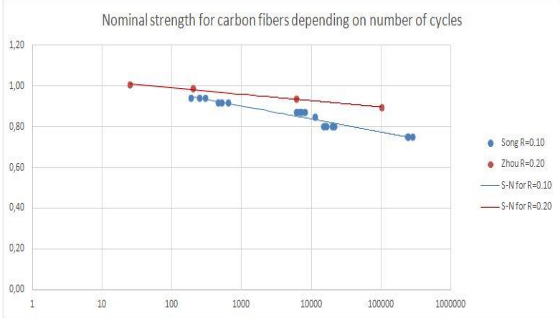
The fatigue model is applied to the constitutive equations of both, fibre and matrix materials, which are combined afterwards with the serial-parallel mixing theory.

The fatigue models for fibre and matrix are obtained from the composite fatigue curves for 0º and 90º, respectively.

Constitutive law for matrix

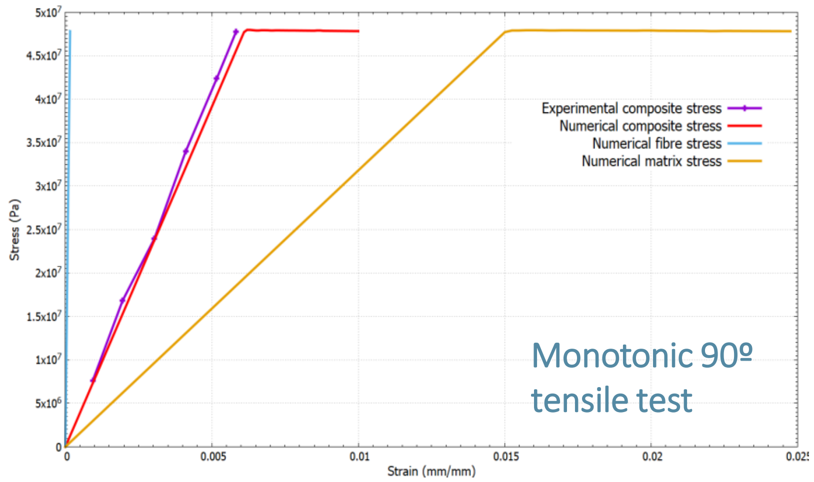


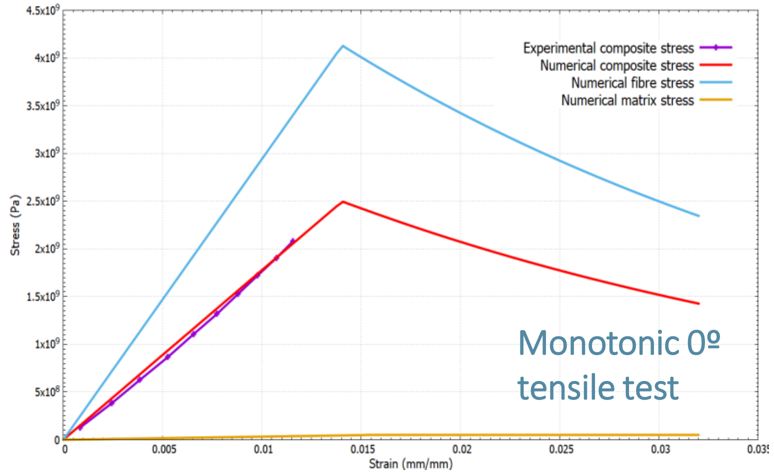
Constitutive law for fibers

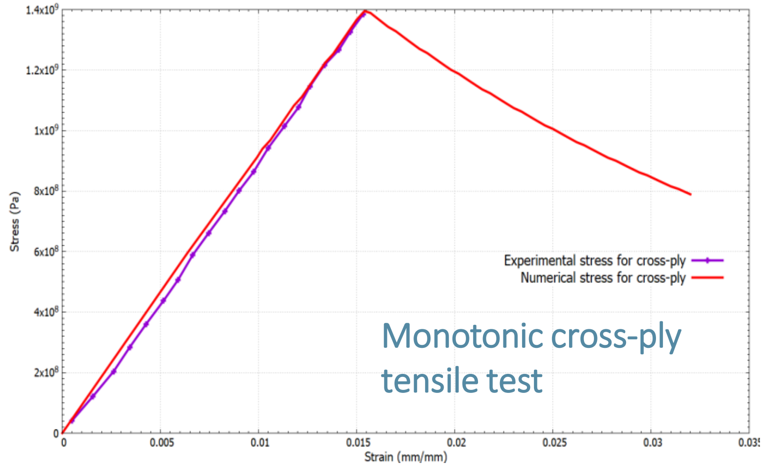


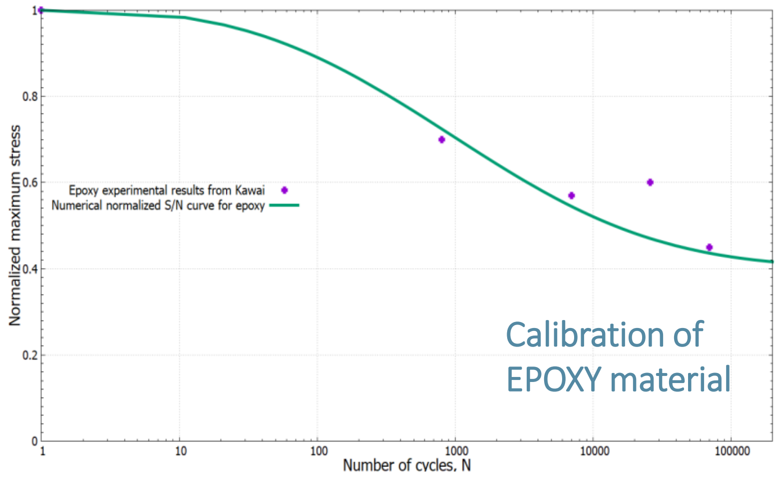
MATERIAL MODELS – FATIGUE ANALYSIS

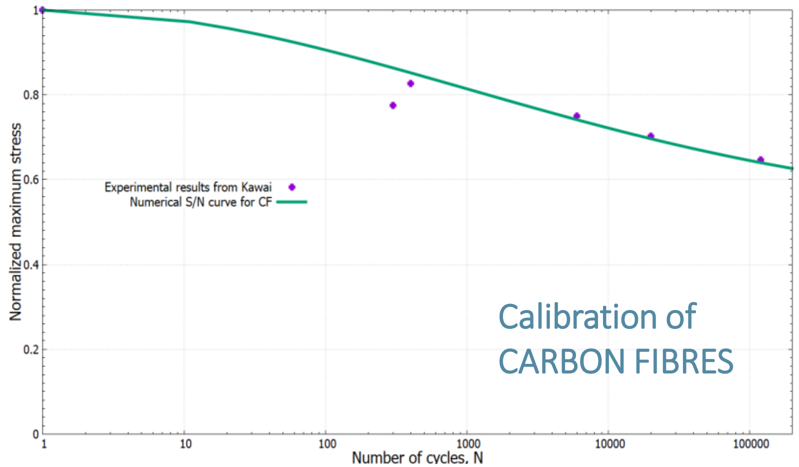
VALIDATION OF THE FORMULATION

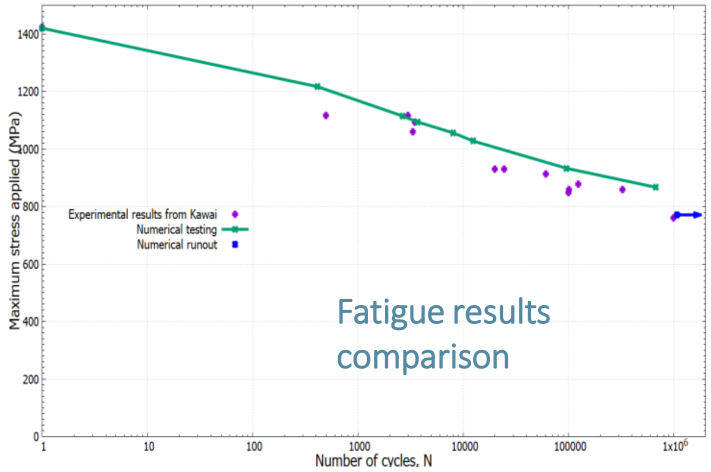








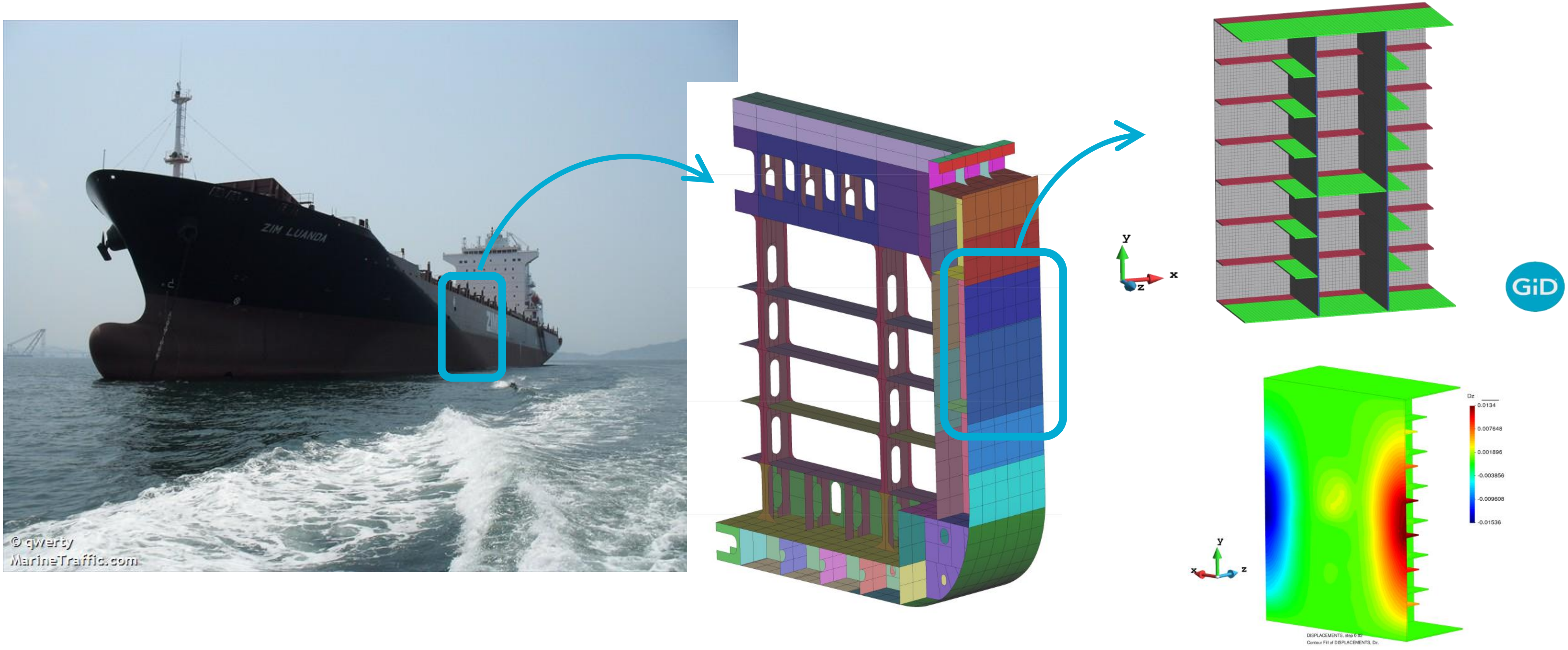




MATERIAL MODELS – FATIGUE ANALYSIS

FIBRESHIP INTEGRAL COMPOSITE SHIP

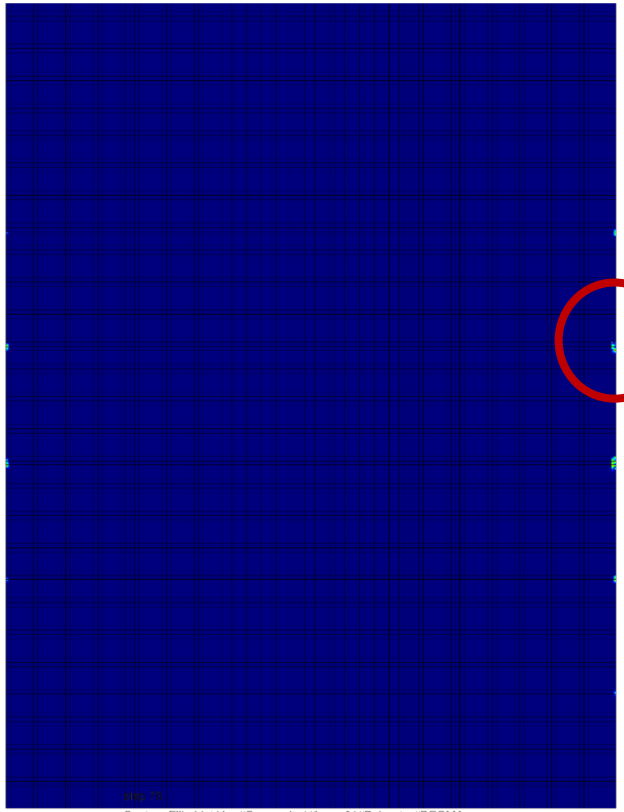
The procedure developed is applied to the Zim Luanda container ship vessel

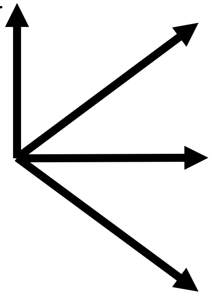


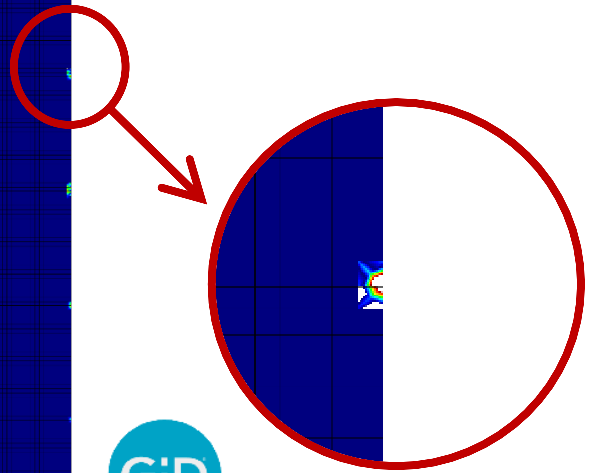
RESULTS

Damage in matrix material for layers at 0º and 90º

Damage in matrix 1

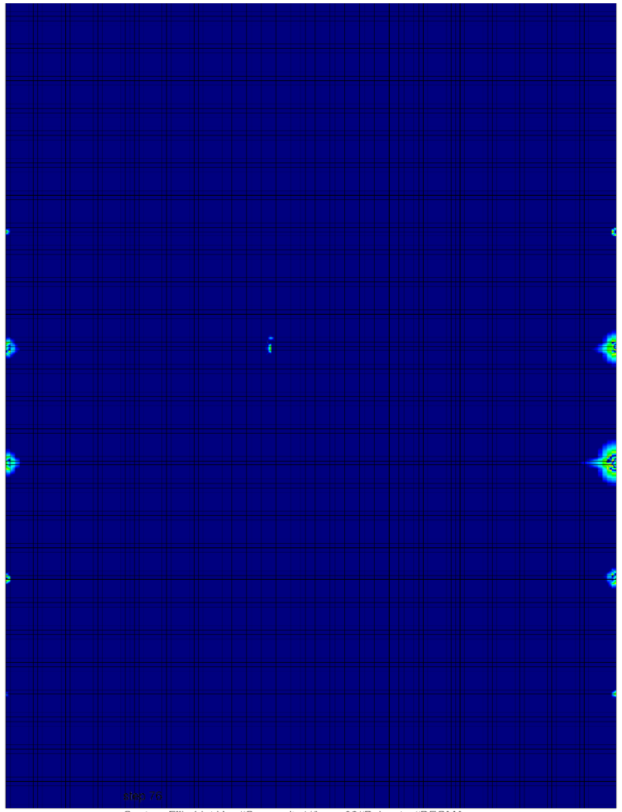


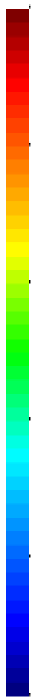




Fibre damage

Damage in matrix 2





CONNECTION TECHNOLOGY

CONNECTION TECHNOLOGY

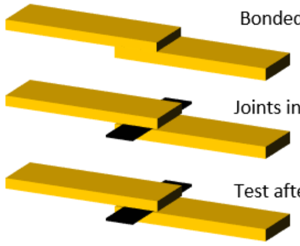
- It has been conducted a comprehensive analysis of the different joining techniques and their application to different engineering fields.
- A special look has been taken to the aerospace industry, as they have a lot of past experience.
- An innovative joining technique – Built-in disassembly mechanism "Disbond on demand" will be tested. This consist on placing a carbon fibre implant in the adhesive bondline. When a potential is applied across the implant the current flows through the carbon fibres and generates heat that facilitates the bond disassembly.

Assembly of the Boeing Dreamliner 787 (Joiner, 2012)

CONNECTION TECHNOLOGY

The experimental campaign designed is based on the analysis of coupon tests and mid-scale tests. These last ones will reproduce connections required in FIBRESHIP's demonstrator

Coupon level



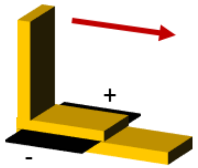
Bonded & laminated joint (baseline)

Joints incorporating resistive implant heating element

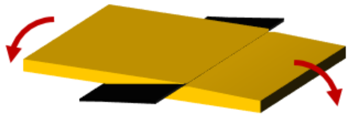
Test after heating

Mid-scale

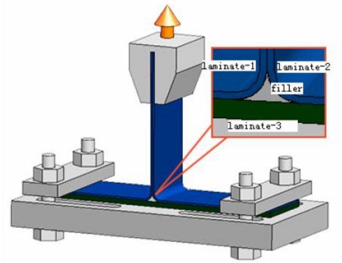
Deck/Bulkhead (angled joints)



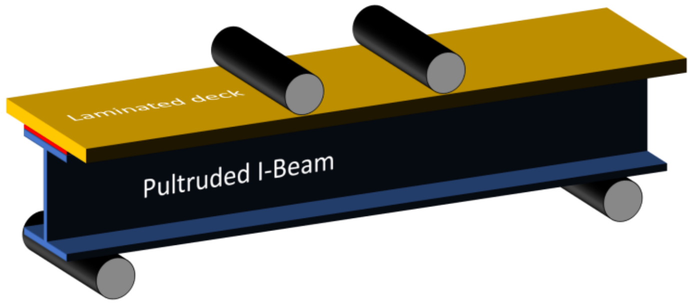
Butt/Sandwich connections



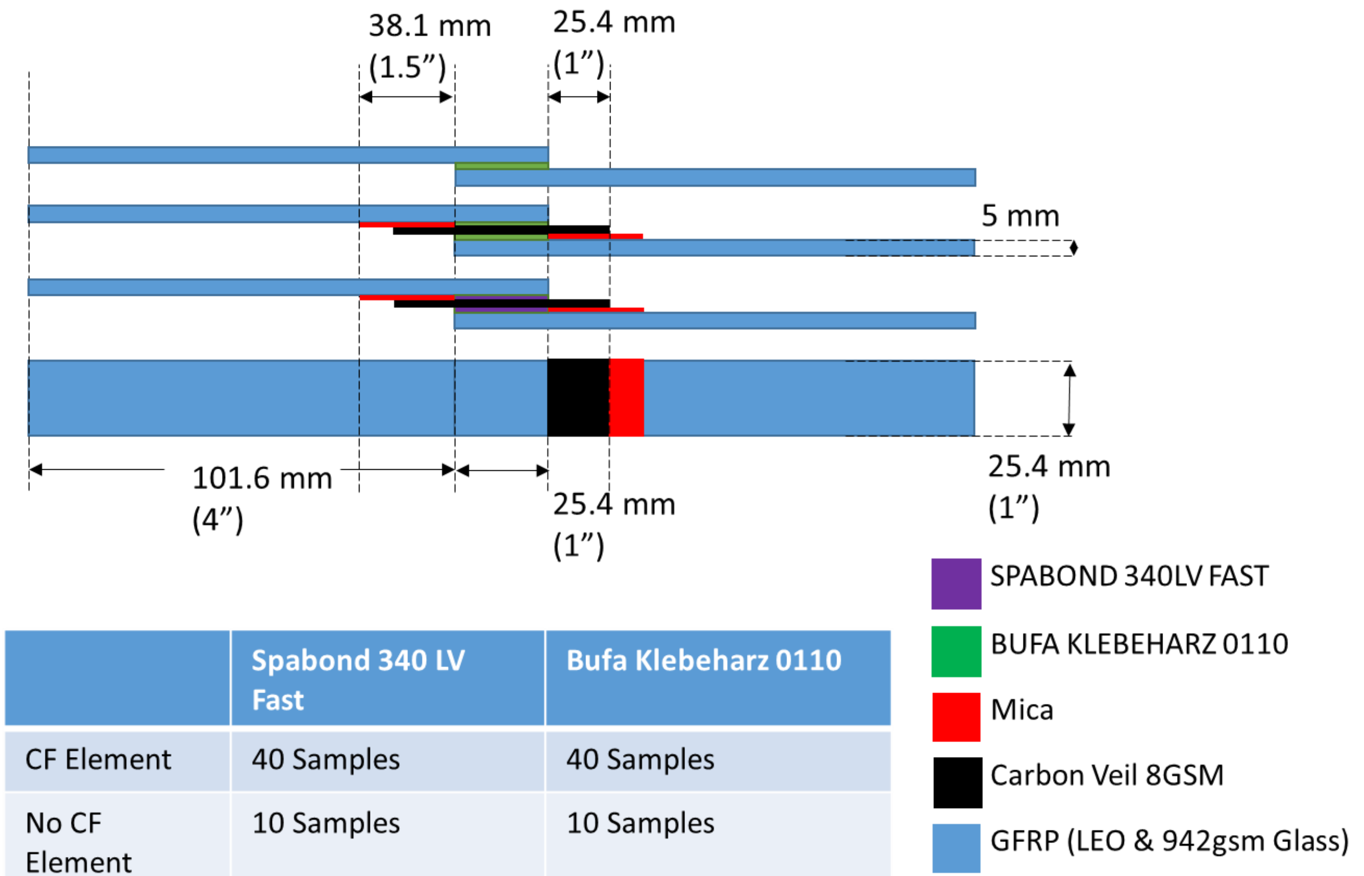
T-Connection between the bulkhead and deck/hull
Standard pull off and bending tests



Adhesively bonded I-beam/deck joint
4P Bending test



It has been already tested coupons of the "Disbond on demand" connection with promising results

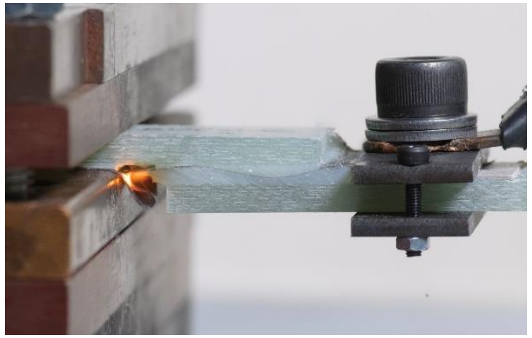


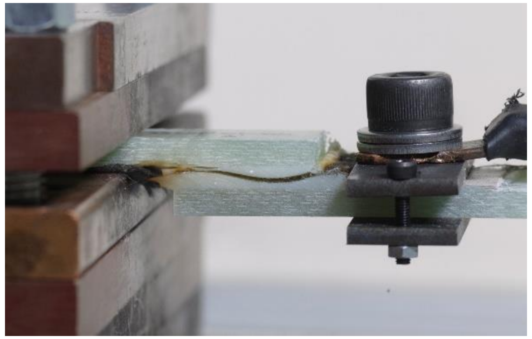
	Spabond 340 LV Fast	Bufa Klebeharz 0110
CF Element	40 Samples	40 Samples
No CF Element	10 Samples	10 Samples

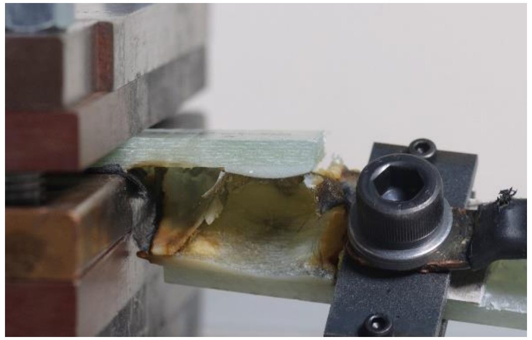
Showing lap joint with carbon element in joint

RESULTS

Adhesive used	Implant (no. of samples tested)	Time at 2 Amps (s)	Heat Energy (J)	Avg max tensile strength MPa
SPABOND 340LV FAST	No Implant (10)	N/A	0	7.04
	CF Implant (10)	N/A	0	7.84
	CF Implant (8)	10	370	4.51
	CF Implant (7)	30	1000	3.74
	CF Implant ()	50	1700	Not Tested Yet
BUFA KLEBEHARZ 0110	No Implant (10)	N/A	0	6.77
	CF Implant (10)	N/A	0	7.31
	CF Implant (10)	10	370	7.62
	CF Implant (10)	30	1000	3.98
	CF Implant ()	50	1700	Not Tested Yet







CATALOGUE OF APPLICABLE MATERIALS AND JOINING TECHNIQUES RECOMMENDED BY CLASS

CATALOGUE OF APPLICABLE MATERIALS AND JOINING TECHNIQUES

- All material information obtained in Fibreship's WP2, together with the available data from the manufacturer datasheets, is being compiled in a Catalogue of applicable materials and joining techniques recommended by class.
- This catalogue will facilitate the use of these materials by the ship industry, as it contains all the information required for design, validation and manufacturing purposes.
- The catalogue is structured to provide:
  - Mechanical performance
  - Fire test evaluation
  - Joining Solutions, as separate section to also include NDE
  - Technical data sheet
- The catalogue will not only provide information regarding structural materials, but also about other materials required in a FIBRESHIP such as fire insulation materials.

FIBRESHIP INTEGRAL COMPOSITE SHIP

SICOMIN SR1125

MANUFACTURABILITY PARAMETERS

Laminate[3] fabrication: Sicomin SR 1125 system plus Saertex UD NCF 996gsm with PPG Hybon 200L E-glass fibre manufactured using vacuum infusion

- *RT = room temperature*
- *Time taken from opening of the inlet to the closure of the outlet (dry preform size 300mm by 300mm)*
- *Laminate lay-up $[0^0]_{2S}$*

Epoxy blend SR 1125 / SD 3303		
Mix ratio by weight		100 / 14
Viscosity (mPa.s)	@ 20°C	680*
	@ 30°C	305*
	@ 40°C	160*

Tool type	Infusion time[2]	Infusion temperature	Cure time	Post-cure time
Glass / heater mat	40 mins	19.9°C[1]	16 hours at 40°C	8 hours at 80°C

1) *RT = room temperature*
2) *Time taken from opening of the inlet to the closure of the outlet (dry preform size 300mm by 300mm)*
3) *Laminate lay-up $[0^0]_{2S}$*

SICOMIN SR1125

LAMINATE MECHANICAL PARAMETERS

Stage 1: Determination of Physical properties of fabricated laminate

Fibre volume fraction (ISO 14130)	Density (ASTM D792-08)
58% (3.0%)	2.198 g/cm^3 (2.3%)

**Coefficient of variation is shown in parenthesis*

Stage 1: Determination of Mechanical properties of fabricated laminate

Resin/reinforcement	Apparent Interlaminar Shear Strength (ISO 14130)			Flexural Strength (ISO 14125)			Flexural Modulus (ISO14125)		
	Dry	Wet	Change	Dry	Wet	Change	Dry	Wet	Change
SR1125/UD996gsm Glass	50.53MPa (1.7%)	51.86MPa (1.7%)	+2.6%	853.8MPa (8.5%)	812.2MPa (1.9%)	- 4.9%	30.35GPa (8.1%)	31.02GPa (2.7%)	+2.2%

Minimum required property values for FRP laminates, Lloyds Register Book K, Procedure 14-1, Rev 1 Dec 2013: Interlaminar Shear Strength at least 15 MPa; Flexural Strength for laminate with equivalent fibre mass fraction (0.72) at least 367 MPa; Flexural Modulus for laminate with equivalent fibre mass fraction (0.72) at least 19.5 GPa

SICOMIN SR1125

FATIGUE ASSESSMENT

Test panels fabricated using liquid resin infusion under vacuum using SR1125 resin and unidirectional non-crimp glass fabric (Saertex UD NCF 996 gsm with PPG Hybon 2002 E-glass fibre)

P_{max}	GF/SR1125:[0°]$_{2S}$	Frequency (Hz)	R ratio
60% of Failure	X3 samples to failure	4	0.5
40% of Failure	X3 samples to failure	4	0.5

- *Sample size of 6 was chosen for each material system to generate an S-N curve.*
- *All tests were performed under ambient conditions in the laboratory (room temperature of approximately 20°C, atmospheric pressure and relative humidity of 55%)*

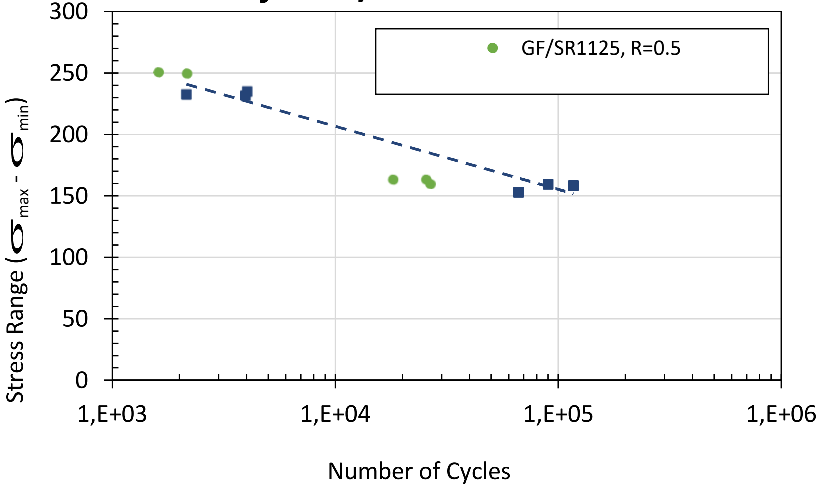
Quasi-Static Tensile Tests to Failure Evaluation

Sample ID	Failure Load (kN)	Failure Stress (MPa)
T1	63.3	873.7
T2	58.9	801.2
T3	67.9	892.4
Average:	63.4	855.8
CV	7.1%	5.6%

Result Matrix from fatigue evaluation

GF/SR1125: [0°]$_{2S}$			
Sample ID	Stress Range, σ_r (MPa)	Maximum stress as a percentage of Failure $\sigma_{max}/\sigma_{ult}$ (%)	Number of Cycles to Failure, N
T3	250.3	60	1,615
T4	249.2	60	2,165
T5	163.6	40	18,128
T6	163.6	40	25,925
T7	159.8	40	26,612

S-N curve for GR/SR1125



MAIN OUTCOMES OF THE WORK CONDUCTED

MAIN OUTCOMES

- It has been developed a procedure for material selection, that can be used to evaluate the convenience of using new materials in FIBRESHIPS.
- While developing the catalogue of applicable materials and connections techniques it has been found that the information provided by the material manufacturer do not always correspond with the properties measured in an experimental campaign.
- It is of utmost importance to have a good material characterization in order to achieve a reliable design. This WP has proposed a comprehensive testing campaign to do this characterization.
- Fire performance of composites, even the best ones, is not good enough to assess the fire protection of a FIBRESHIP. Fire insulation will be needed in certain locations.
- Numerical models can predict accurately the performance of composites and FIBRESHIPS
- A "Disbond on demand" connection has been tested. This will facilitate possible FIBRESHIP repairs or the ship dismantling when it reaches its life span.

Material technology (materials, numerical models, connections) is ready to be applied to long length fibre ships. Despite some specific solutions are required to overcome some material limitations (such as fire)

THANK YOU

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