Analysis of the Design & Construction Methodologies for Carbon Composite Motor Yacht Superstructures

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Master Thesis
Erasmus Mundus Course in "Integrated Advanced Ship Design"
University of Genoa | Azimut Benetti Shipyards

Motor Yacht (MY) Design

Fast
Fuel Efficient

Spacious
Open Design

Affordable
Cost Competitive

Structural Design

Lightweight Structure

Minimal Structural Interference

Economical Material Use

Why Carbon?

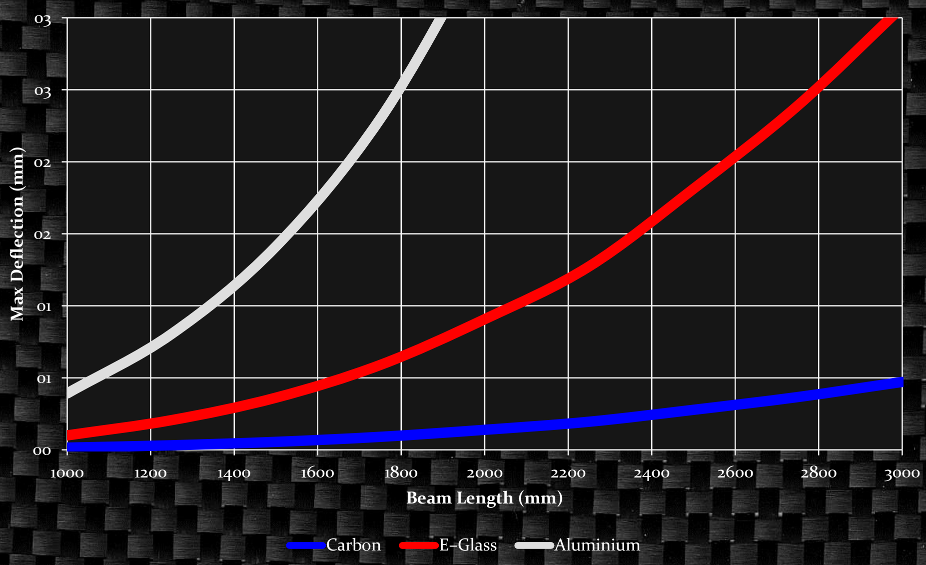
Carbon is Future.

SGL Group – The Carbon Company.

Raw Material Properties

Material Grade / Fibre	Steel ASTM A131 – A	Aluminum 5083 – H321	Glass Fibre E – Glass	Carbon Fibre Torayca T300
Density (kg/m^3)	7,850	2,660	2,580	1,760
Tensile Modulus (GPa)	140	70	72	230
Tensile Strength (MPa)	400	317	1,950	3,530
Shear Modulus (GPa)	80	26	30	12
Shear Strength (MPa)	280	190	1,125	2,036
Strain to Fail (%)	24.0	16.0	5.0	1.5

Panel Bending Deflections



E – Glass and Carbon as Sandwich Panels (20mm Core)
Aluminum solid beam 30mm Thickness

Reduced Reinforcement Material

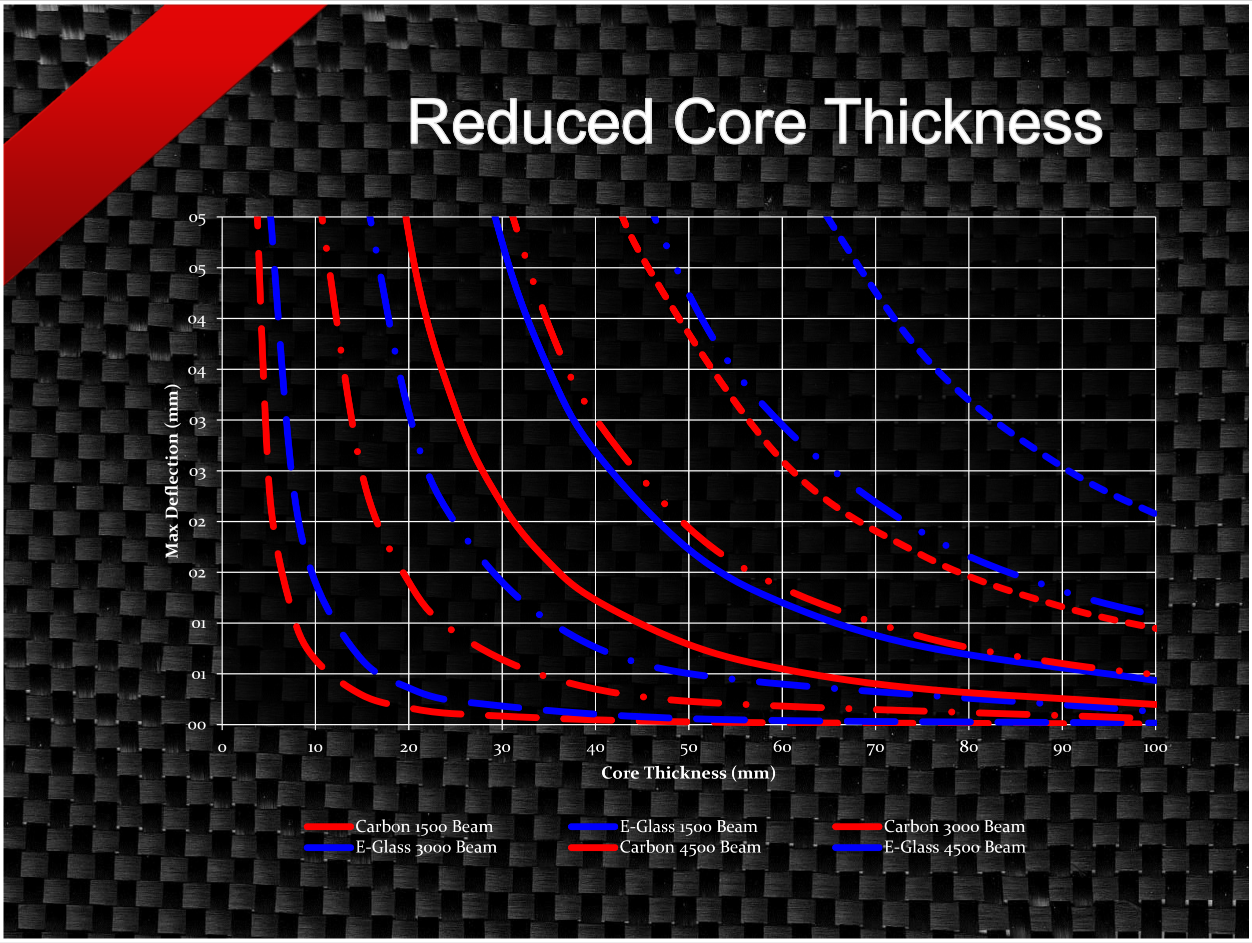
- Carbon Epoxy 3 – Core – 3 layup
- E – Glass Epoxy 6 – Core – 6 layup
- 35mm Core Thickness

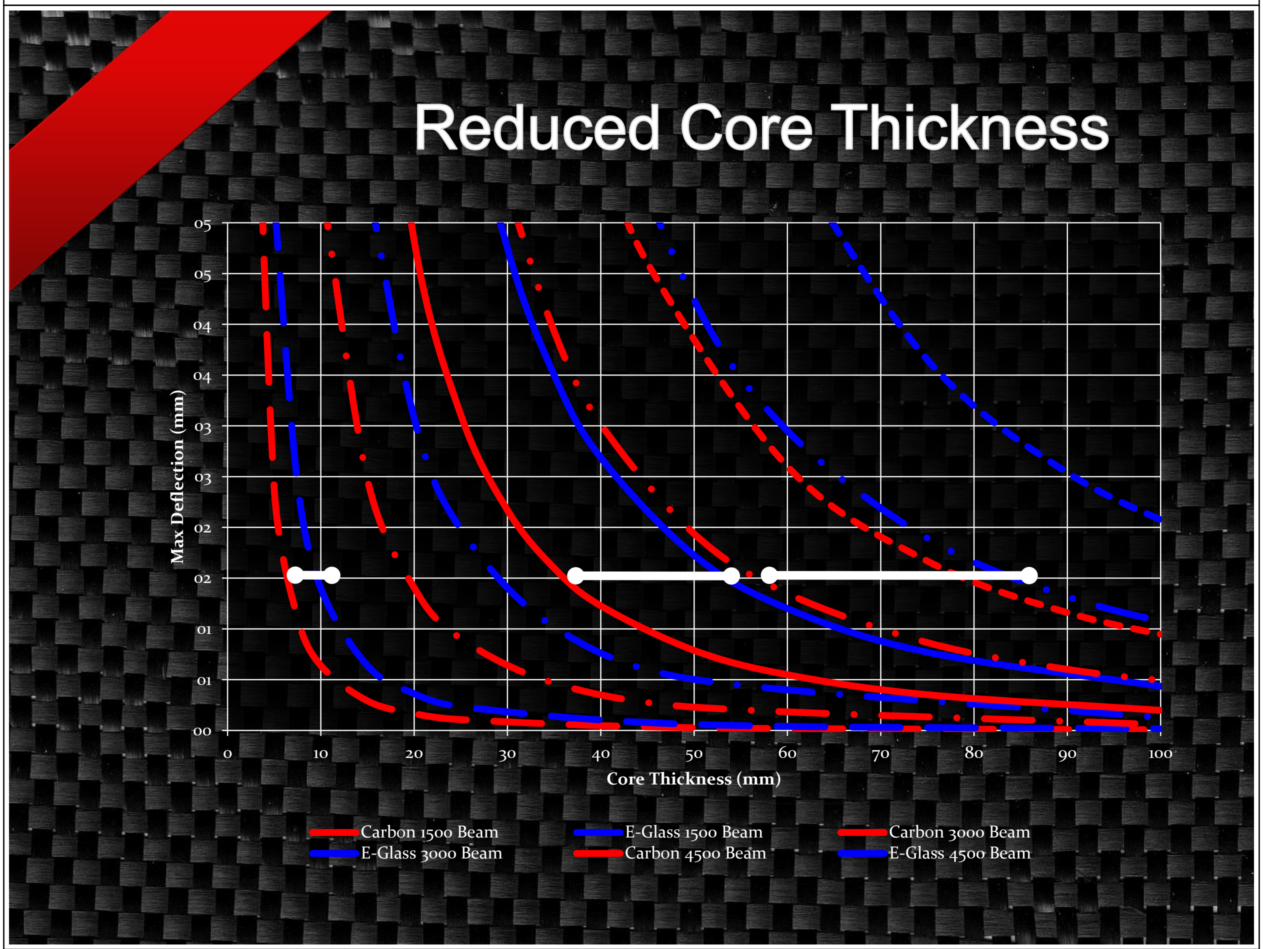
Beam Scenario	Variable	Carbon	E – Glass
500 x 1250 Beam	Max Deflection	0.063	0.068
	Bending Stress	204	103
500 x 2500 Beam	Max Deflection	0.554	0.601
	Bending Stress	448	225
500 x 5000 Beam	Max Deflection	4.634	5.020
	Bending Stress	934	470

Reduced Reinforcement Material

- Plate panel sized to sample Azimut Yacht design dimensions
- 2003 and 2013 reinforcement pricing of layups

Beam Scenario	Variable	Carbon	E – Glass	% Difference
1585 x 1840 Panel 8mm Core	Total Layers in Layup	6 + Core	12 + Core	+100
	Max Deflection (mm)	1.215	1.273	+5
	Bending Stress (MPa) Safety Factor	426 SF = 1.7	214 SF = 2.5	-50
	Layup Weight (g/m^2)	1,165	3,301	+183
	2003 Reinforcement Cost (€)	128	28	-78
	2013 Reinforcement Cost (€)	216	288	+33


Reduced Core Thickness
Max Deflection (mm)
05
05
04
04
03
03
02
02
01
01
00
0 10 20 30 40 50 60 70 80 90 100
Core Thickness (mm)
Carbon 1500 Beam
E-Glass 1500 Beam
Carbon 3000 Beam
E-Glass 3000 Beam
Carbon 4500 Beam
E-Glass 4500 Beam

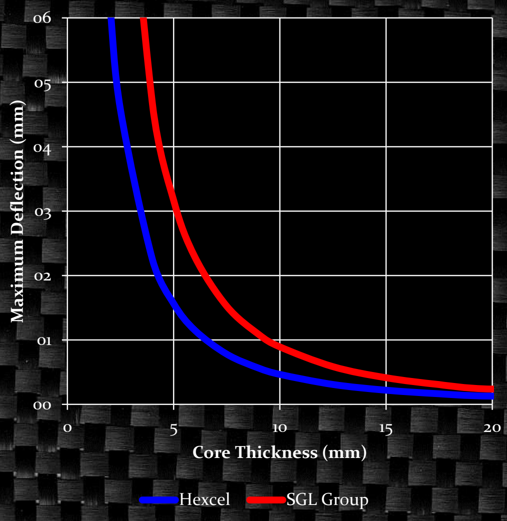

Reduced Core Thickness
Max Deflection (mm)
05
05
04
04
03
03
02
02
01
01
00
0 10 20 30 40 50 60 70 80 90 100
Core Thickness (mm)
Carbon 1500 Beam
E-Glass 1500 Beam
Carbon 3000 Beam
E-Glass 3000 Beam
Carbon 4500 Beam
E-Glass 4500 Beam

Manufacture Process

- Consideration of full 'picture' required
  - Reinforcement (0/90º, +/-45º, Weave Type, Woven / Stitched)
  - Resin (Chemical Type, Polymerisation Process Chosen)
  - Curing (Temperature Regime, Min Pressure, Time)
- Claimed Mechanical Properties (Testing Method)

Material Property		Hexcel (0/90º)	SGL Group (4x +/- 45º)	Δ (%)
Areal Weight	g/m^2	600	673	12.2
Tensile Modulus	GPa	65	54	-16.9
Tensile Strength	MPa	900	810	-10.0
Tensile FVF	-	0.60	0.50	-16.7
Cured Ply Thickness	mm	0.575	0.460	-20.0

Manufacture Process

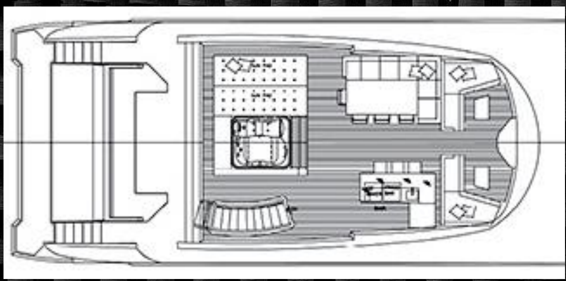


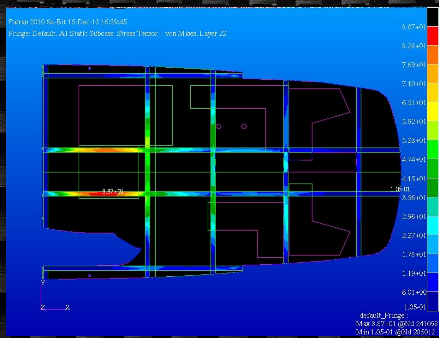
Hexcel Corporation
- Single Bi-Directional Fabric (0/90º)
- 673 g/m^2
- 0.8 bar, 60ºC for 16 hours

SGL Group
- 4 Layer Double Bias (+- 45º)
- 600 g/m^2
- 0.7 bar, 60ºC for 16 hours

Modulus Δ ≈ 17%
Deflection Δ > 80%
(Minimal Absolute Δ)

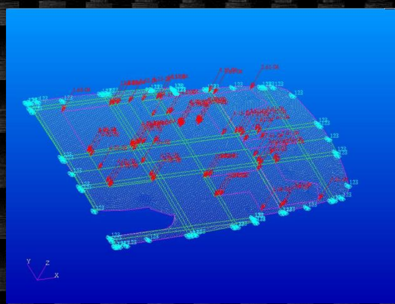
Application to Structural Design

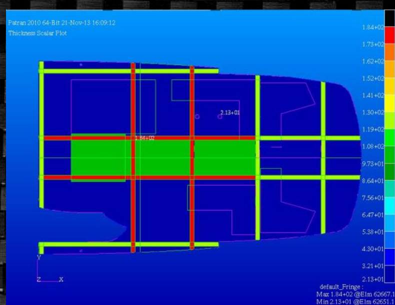




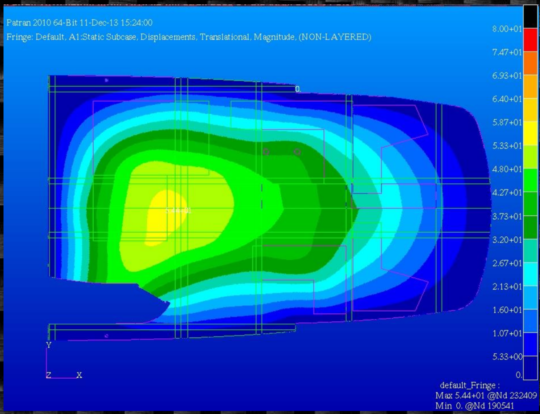
All Carbon Design

- RINA Class Compliant Design, Azimut Stiffness & Depth Compliant
- Prepreg Epoxy Fabrics Used
  - Bi-Axial 200 g/m^2
  - UD 476 g/m^2
- Plate Layups
  - 3 – Core – 3 Layups (+2 UD in High σ Areas)
  - 20mm and 100mm Core
- Stiffener Layups
  - 120 or 180mm Total Depth
  - 20mm Plate + 100/160 Core + 10 UDs
  - 100mm Plate + 80 Core + 10 UDs

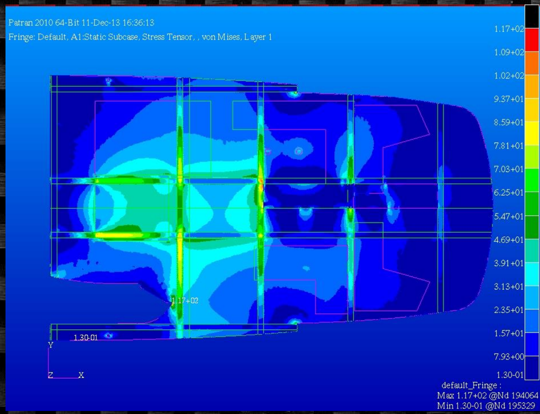




All Carbon Design



Displacement [Magnitude] (mm)
Max Displacement = 54.4



Stress [VM] (MPa)
Max Stress= 117
(RINA = 304 MPa)

Equivalent Stiffness

All E-Glass

- E-Glass reinforcement
  - Plate and Stiffener
- Prepreg Epoxy
  - Bi-Axial 600g/m^2
  - UD 600g/m^2
- Method to obtain stiffness
  - Increased Core Thickness
  - Additional Reinforcement Layers
  - Reduction in Stiffener Spacing

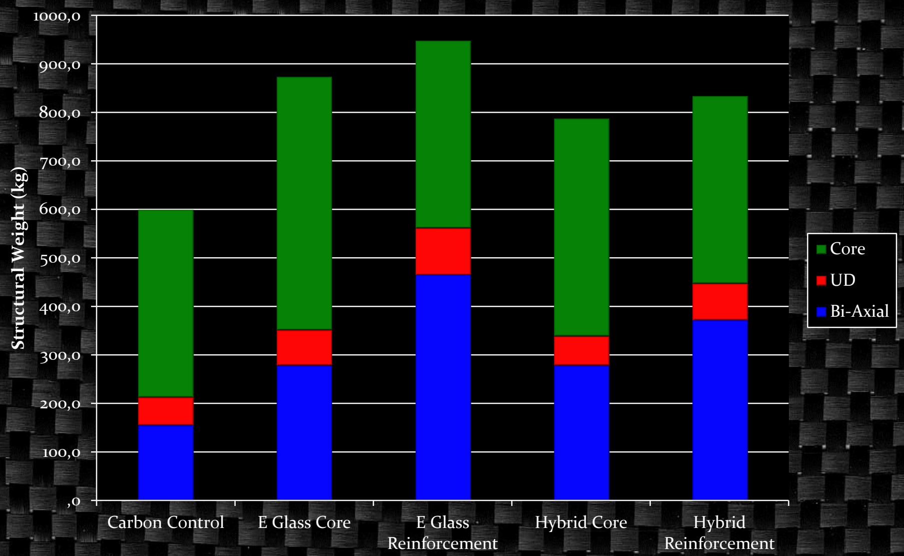
Hybrid Structure

- Material Combination
  - E-Glass for Plate Reinforcement
  - Carbon stiffener flange
- Prepreg Epoxy
  - E-Glass Bi-Axial 600g/m^2
  - E-Glass UD 600g/m^2
  - Carbon UD 476g/m^2
- Method to obtain stiffness
  - Increased Core Thickness
  - Additional Reinforcement Layers

Summary of Designs

Scenario	Bi-Axial Layers	UD Layers	Plate Core Thickness (mm)	Stiffener Core Thickness (mm)	Δ%
Carbon Control	6	2 + 10	20, 100	120, 180	–
E-Glass Extra Core	6	2 + 10	27, 135	162, 243	+35%
E-Glass Reinforcement	10	3 + 13	20, 100	120, 180	+42%
Hybrid Extra Core	6	2 + 10	23, 116	139, 209	+16%
Hybrid Reinforcement	8	3 + 12	20, 100	120, 180	+25%

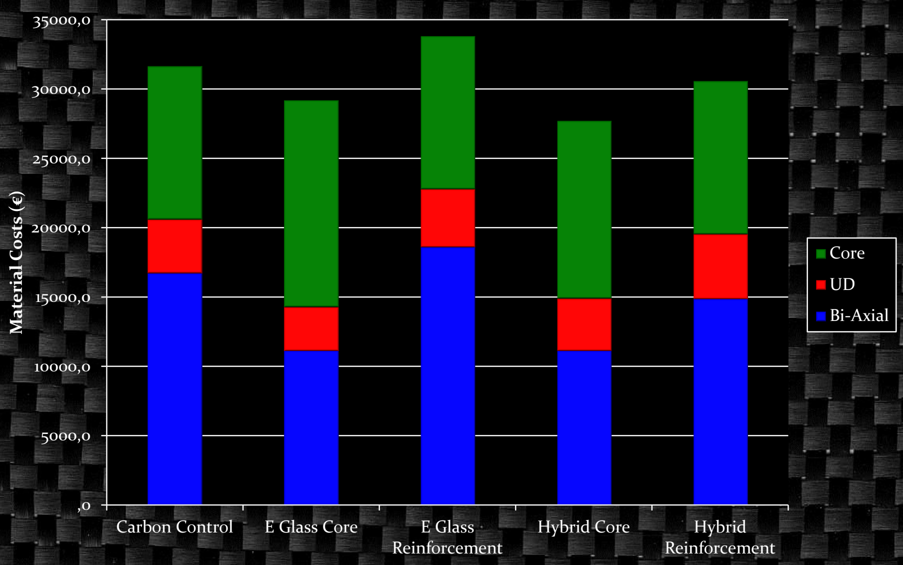
Structural Weight Breakdown



Structural Weight Advantage

Reinforcement Material	Model Setup Details	Max Deflection (mm)	Structural Weight (kg)
All Carbon	180mm Max Depth, RINA, Azimut Reqs.	54.4	600
All E–Glass	180mm Max Depth (Control)	79.8	738
	–50% Stiffener Spacing	61.9	811
	+35% Core Thickness	53.0	874
	+42% Reinforcement Layers	52.2	948
E–Glass Plate, Carbon Stiffeners	180mm Max Depth (Control)	67.1	726
	+16% Core Thickness	54.3	800
	+25% Reinforcement Layers	53.7	849

Material Cost Breakdown



Material Cost Comparison

Reinforcement Material	Model Setup Details	Max Deflection (mm)	Material Costs (€)
All Carbon	180mm Max Depth, RINA, Azimut Reqs.	54.4	31,634
All E–Glass	180mm Max Depth (Control)	79.8	25,329
	–50% Stiffener Spacing	61.9	27,996
	+35% Core Thickness	53.0	29,188
	+42% Reinforcement Layers	52.2	33,810
E–Glass Plate, Carbon Stiffeners	180mm Max Depth (Control)	67.1	25,943
	+16% Core Thickness	54.3	27,706
	+25% Reinforcement Layers	53.7	30,561

Depth, Weight, Cost

Material Setup	Max. Number of Layers	Stiff. Depth (mm)	Weight Increase (kg)	Cost Reduction (€)
Carbon Control	16	180	(600)	(31,364)
E – Glass Core	16	243	+274	2,446
E – Glass Reinforcement	23	180	+349	[-2,176]
Hybrid Core	16	209	+188	3,927
Hybrid Reinforcement	20	180	+234	1,073

Carbon Case Study Yachts

Ermis[2]
- LOA = 38m
- V_{max} = 55 knots

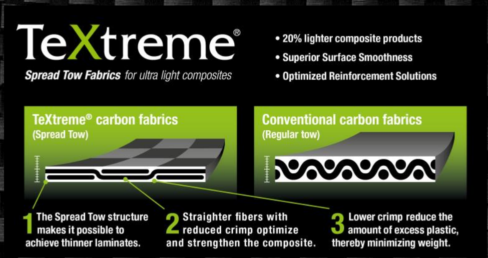
Laurel
- LOA = 73m
- Low S/S Profile Requirement

Production Methods

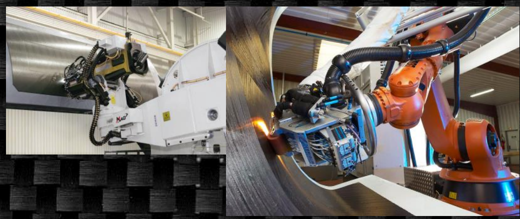
- Improving Fibre Volume Fractions
  - Open Mould Hand Layup
  - Closed Mould Resin Infusion
  - Vacuum Bagging w/ Prepregs
- Decrease in required resin
  - Void Reduction
  - Consistency of cured properties
  - Higher performance resins (Epoxy)
- Shipyard Emission Reductions
  - Environmental & Worker Safety
  - Move to Closed Moulding

Future Technologies

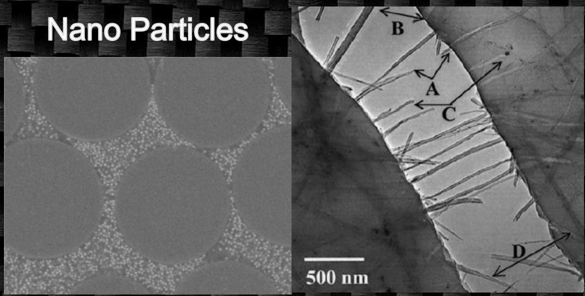
Fabric Improvements



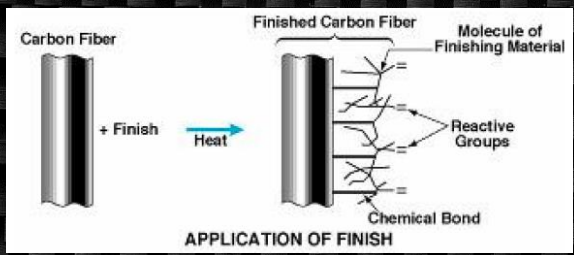
Fibre Placement Technology



Nano Particles

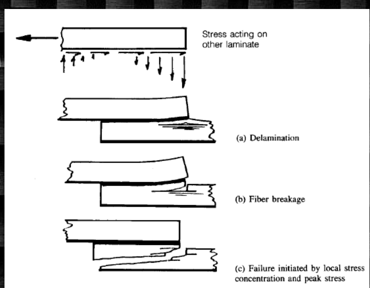


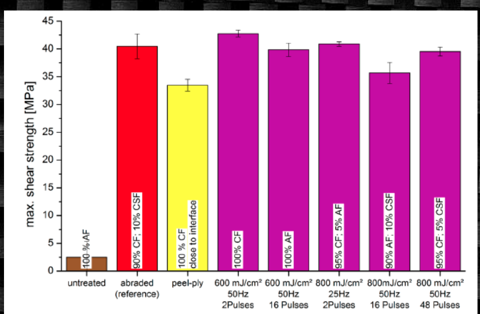
Fibre Sizing (Esp. Vinyl Ester)



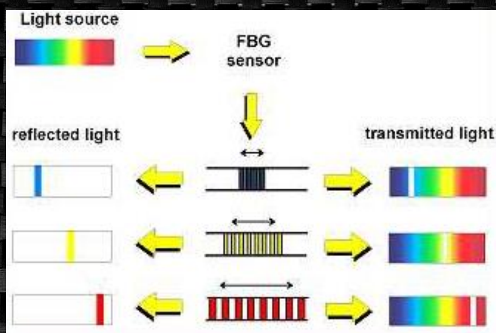
Future Technologies

Adhesive Bonding Improvements





Improved Understanding of Inter – Layer Stresses



Questions

Minimal Structure ↔ Lightweight Structure ↔ Economical Material Use

The Right Reinforcement

The Right Resin