HEXCEL®

Prepreg and Infusion: Processes for Modern Wind Turbine Blades

Chris Shennan

5th September 2013

Agenda

- **Introduction**
- **Wind blades: requirements and drivers**
- **Prepreg and infusion technologies: comparisons**
  - Laminate morphology
  - Mechanical performance
- **Prepreg and infusion matrices: M79**
- **Co-infusion**
- **Conclusions**

Introduction

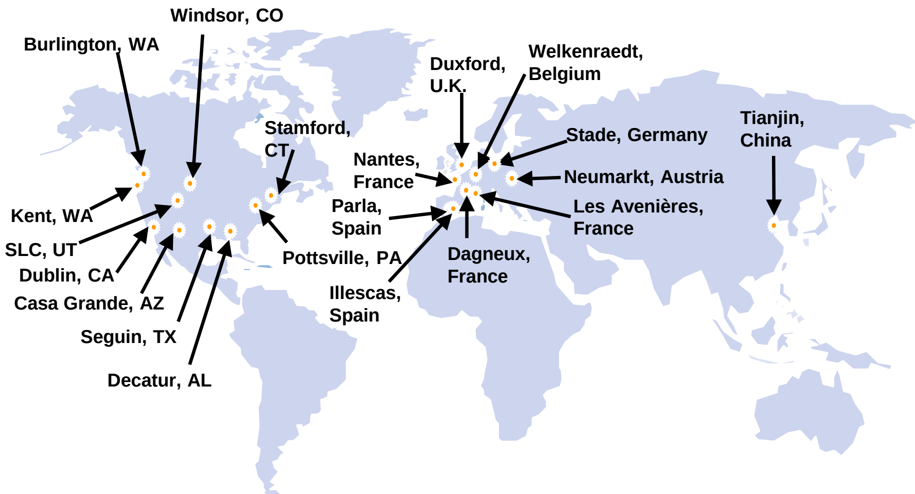
Company Profile

- **Technology leader in advanced composites**
- **Serving commercial aerospace, space & defense and industrial**
- **Net Sales 2012: $1.58 Billion**
- **5,000 employees worldwide**
- **19 manufacturing sites (including JV in Malaysia)**
- **Headquarters in Stamford, CT, USA**
- **Listed on New York and Paris Stock Exchanges**



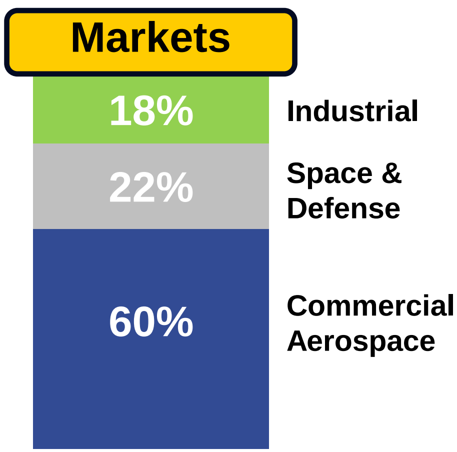


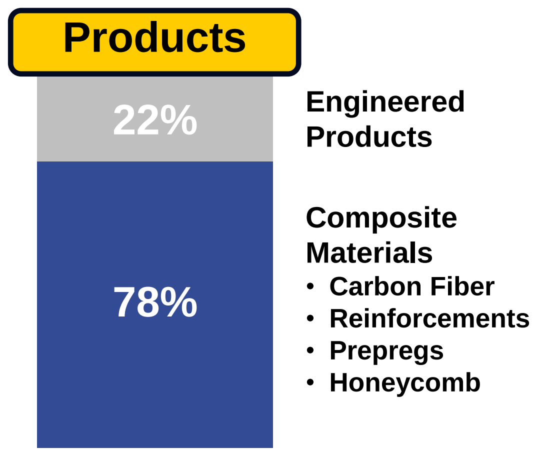
Overview

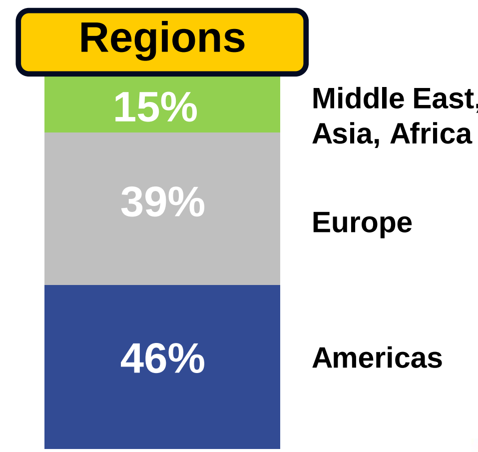


- ***Leading advanced composites company with 65 years of experience***
- ***Excellent customer relationships***
- ***Technology leader with a broad range of products and qualifications***
- ***Leading positions in all of our markets***
- ***Demonstrated operational excellence***

Hexcel 2012 Total Sales of $1.58 Billion







Hexcel in Global Wind Energy

- Market Leader for prepreg materials in Wind Energy
- Annual capacity of >20 000t
- Supplier for over 20 years
- Global Supply, Sales, Technical Support and R&T
- Product development in close cooperation with key accounts

Plant for wind energy at Windsor Colorado, opened in 2009 (Other dedicated plants in Austria and in Tianjin, China)

Impregnation of Fibre and Fabrics with Resin

Prepreg production is now highly industrialised for optimum cost and quality

Wind Turbine Blades

Requirements and Drivers

Overall Blade Structure

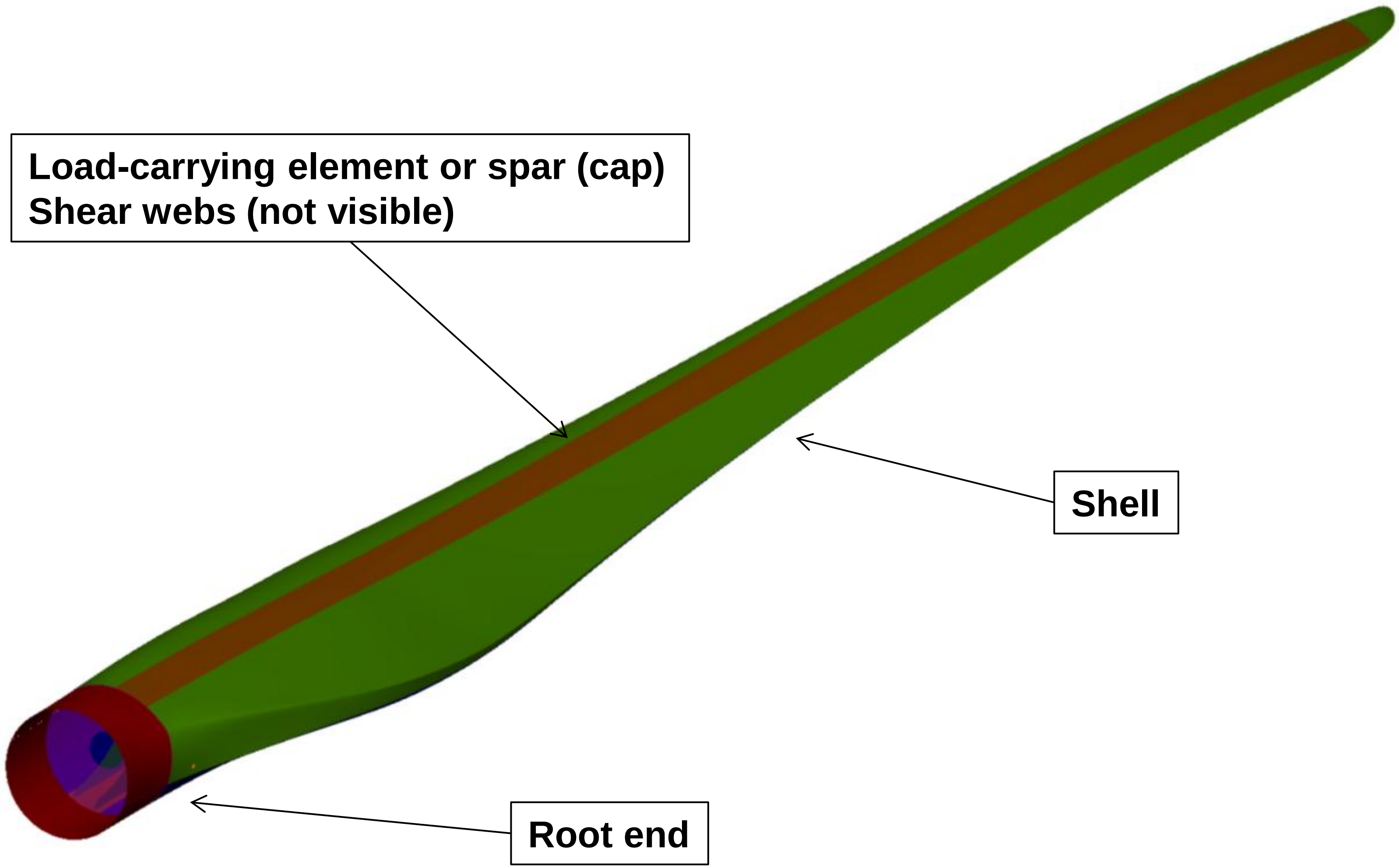


Image: © STRUCTeam Ltd

Shells

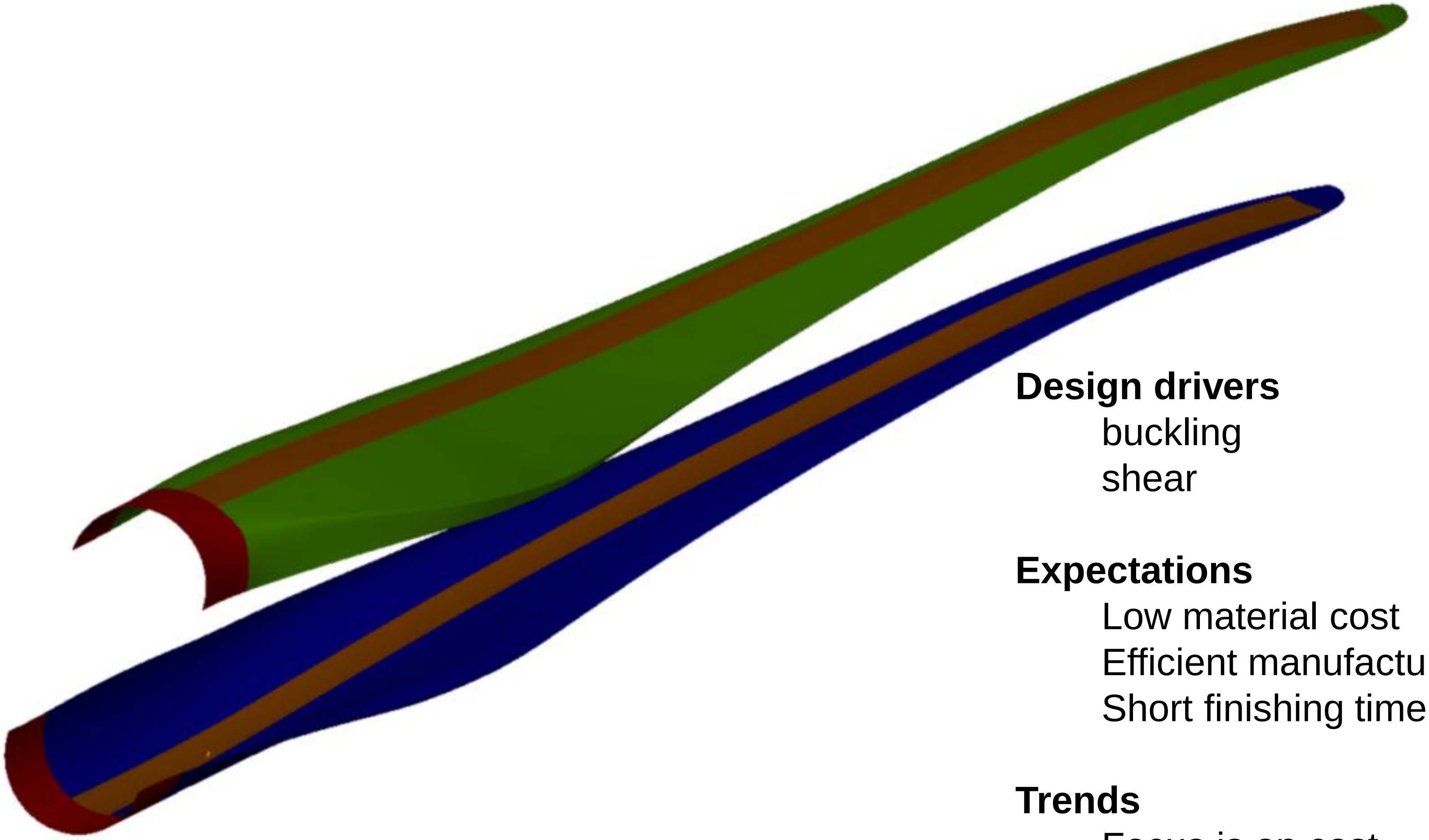


Image: © STRUCTeam Ltd

Design drivers
- buckling
- shear

Expectations
- Low material cost
- Efficient manufacturing process
- Short finishing time

Trends
- Focus is on cost
- Importance of core materials
- Improved finishing
- Longer term innovations

Load-carrying Elements (1)

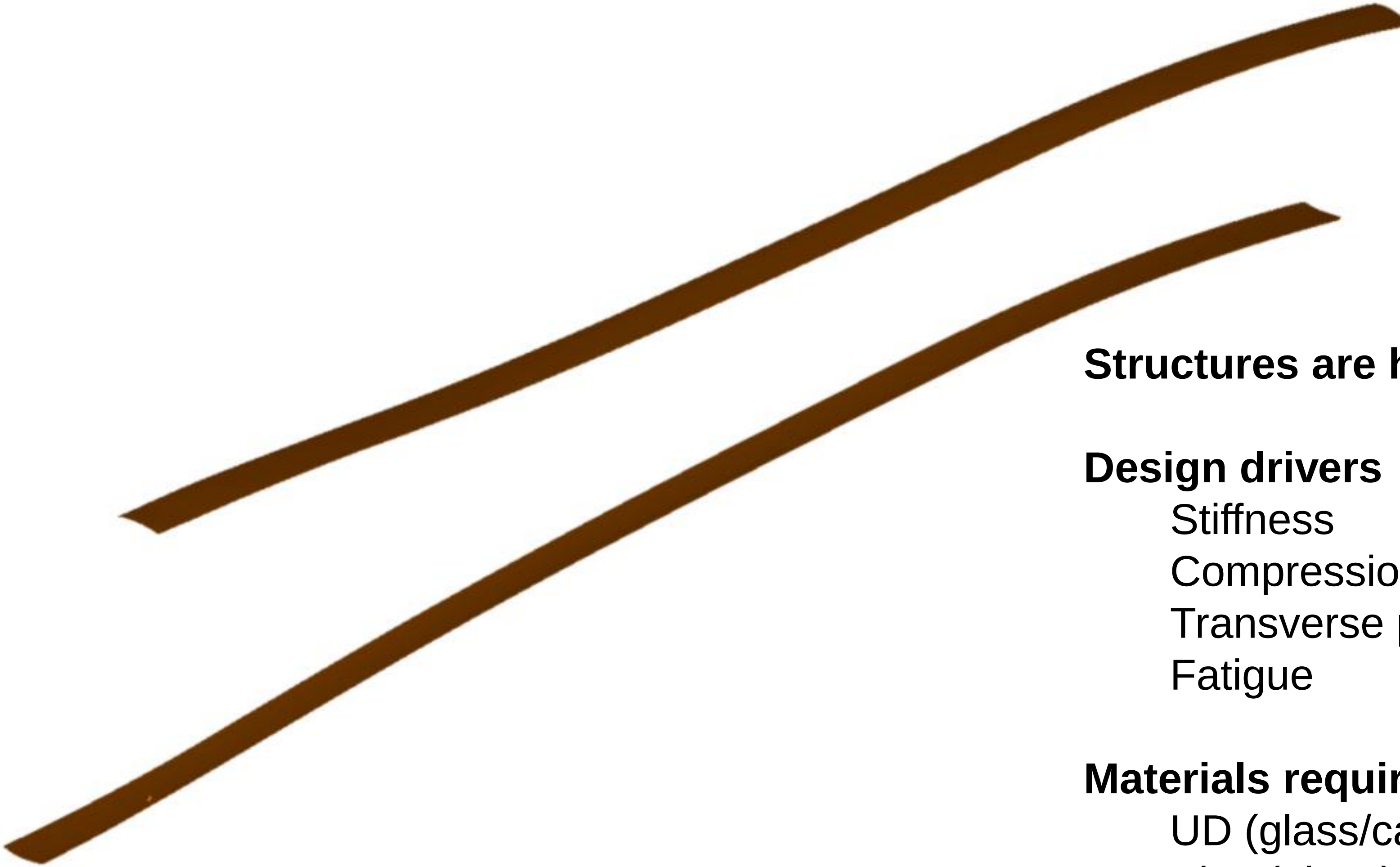


Image: © STRUCTeam Ltd

Structures are highly loaded

Design drivers

- Stiffness
- Compression strength
- Transverse properties
- Fatigue

Materials required

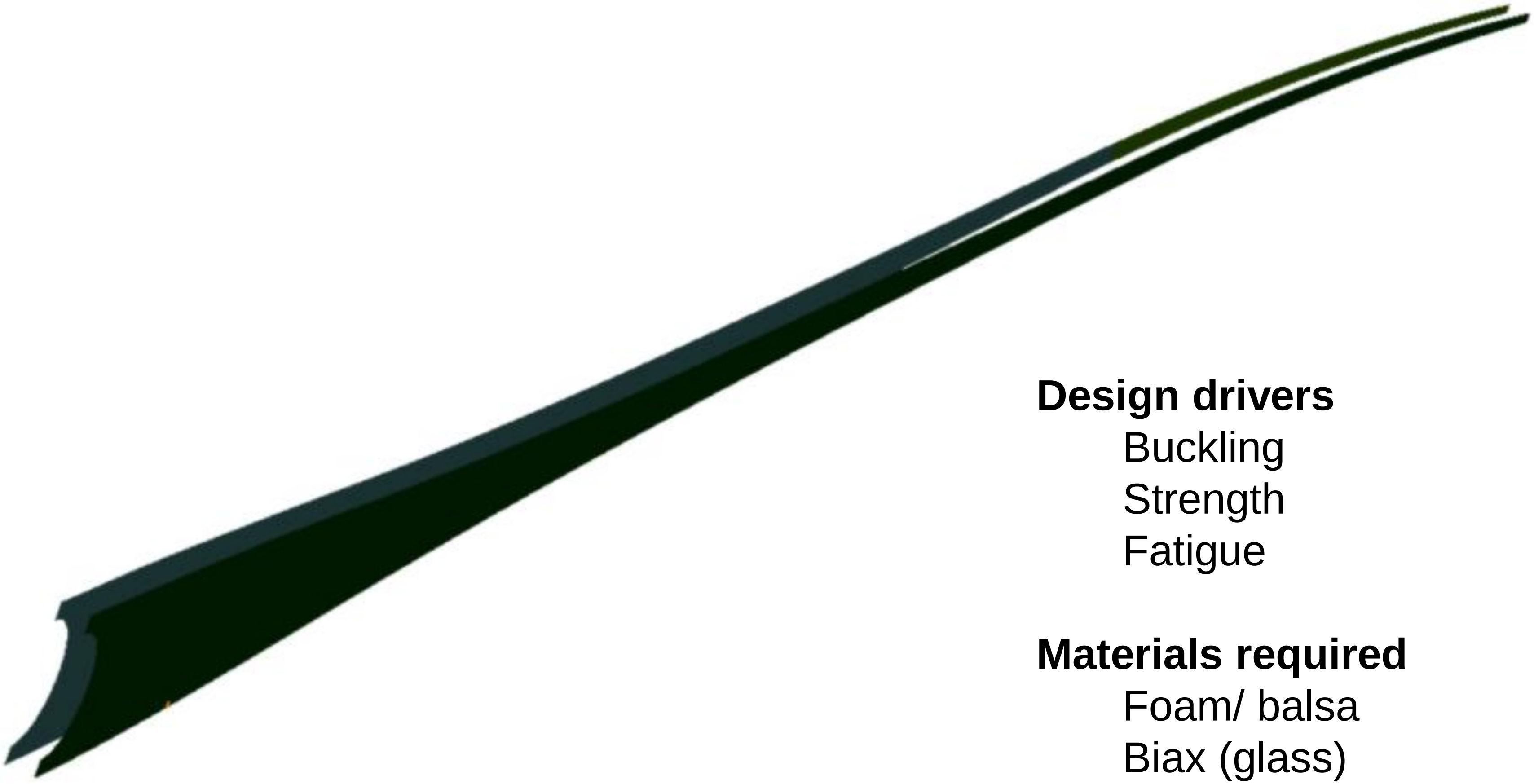
- UD (glass/carbon)
- Biax (glass)
- Resin

Load-carrying Elements (2)

- **Debate about the preferred fibre continues (carbon, E-glass, higher modulus glass…)**
- **Materials can be pre-impregnated, dry and infused, or pre-cured elements such as laminates**
  - Greater opportunity for new materials
- **Main expectations and issues**
  - Performance is the major driver
  - Fibre alignment and fibre wet out are critical
  - Composite sections are thick, especially near the root
  - Exotherm control is a major process constraint
  - Control of mechanical performance, quality and reproducibility are all critical

Load-carrying elements are critical structures within the turbine blade

Shear Webs



Design drivers
- Buckling
- Strength
- Fatigue

Materials required
- Foam/ balsa
- Biax (glass)
- Resin

Image: © STRUCTeam Ltd

Root End (1)

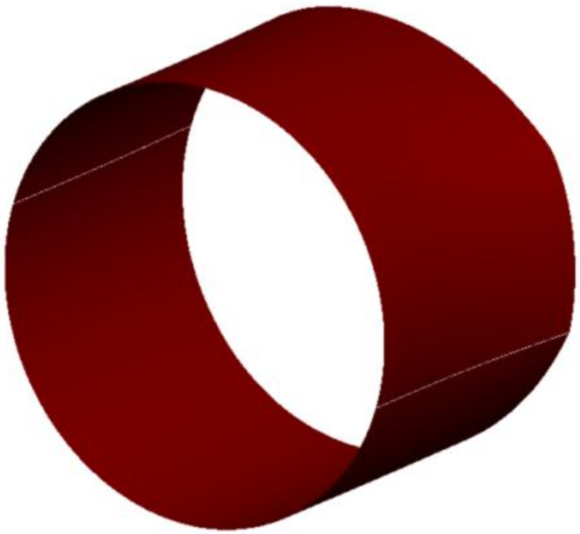


Image: © STRUCTeam Ltd

Structure is highly loaded

Design drivers

- Stiffness
- Strength
- Fatigue

Materials required

- UD (glass/carbon)
- Biax/ triax (glass)
- Resin

Root End (2)

- **Root ends tend to be manufactured separately**
- **There is a trade-off between cost and weight (low cost ≡ heavy; higher cost ≡ light)**
- **Preference is for a light solution at low total cost**
- **Main issues**
  - Fibre alignment
  - Fixation to mould, where used
  - Composite sections are thick
  - Exotherm control is a process constraint
  - Transition to the load-carrying element
  - Integration of the bushings/ root fixings

Root ends are critical structures within the turbine blade

Summary of Blade Requirements

Blade element	Function	Performance requirements	Main driver
Root	a) Connect blade to hub b) Transfer loads from blade to hub	a) Highly loaded b) Provide space for bushings	*Cost versus performance*
Spar Cap	Structural integrity of blade	a) Provide stiffness b) Carry loads c) New materials	*Performance*
Shear web	Transfer shear forces between shells	Low to moderate	*Cost*
Shell	Aerodynamic efficiency	a) Surface quality b) Aerodynamic surface	*Cost*

Different parts of the blade have different drivers which lead to requirements for different materials and processes

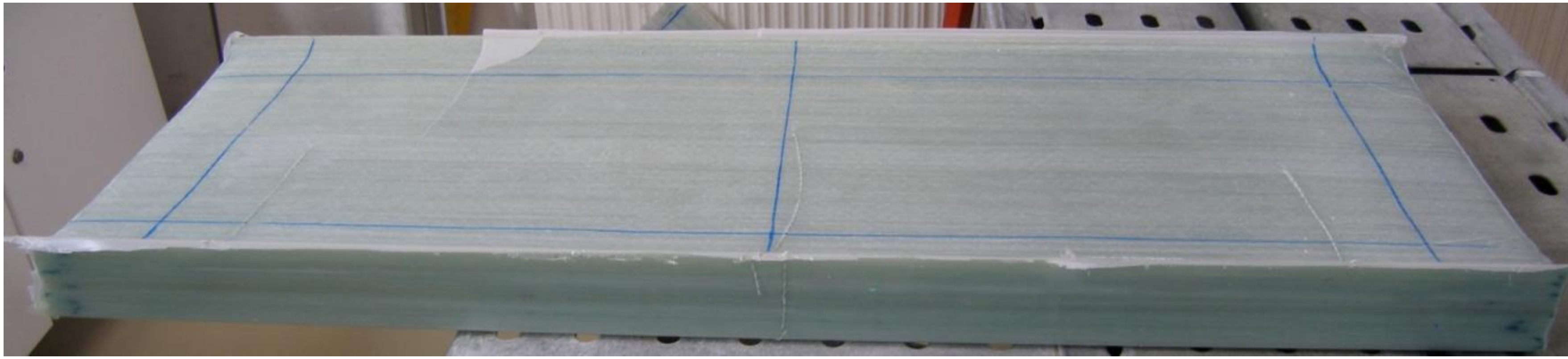
HEXCEL®

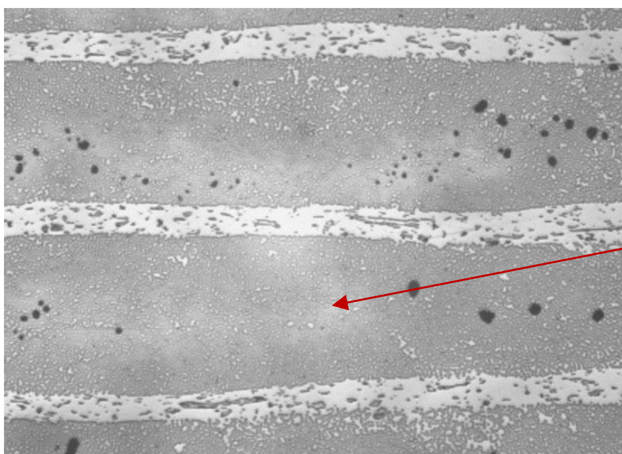
Prepreg and Infusion Technologies

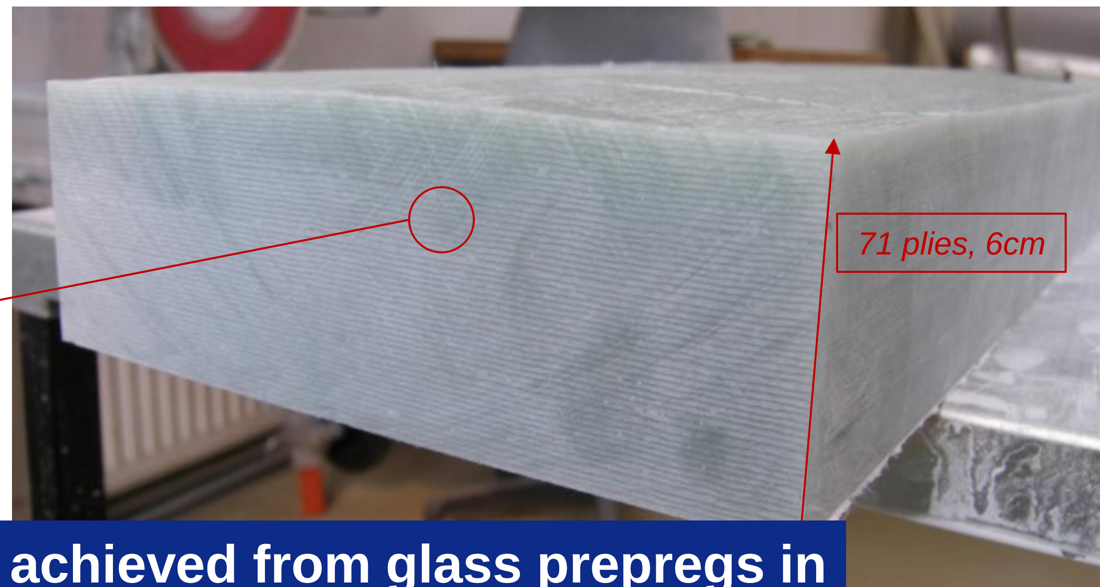
- Laminate Morphology, Porosity

- Mechanical Properties, a Comparison

Thick Glass Laminates using Prepregs

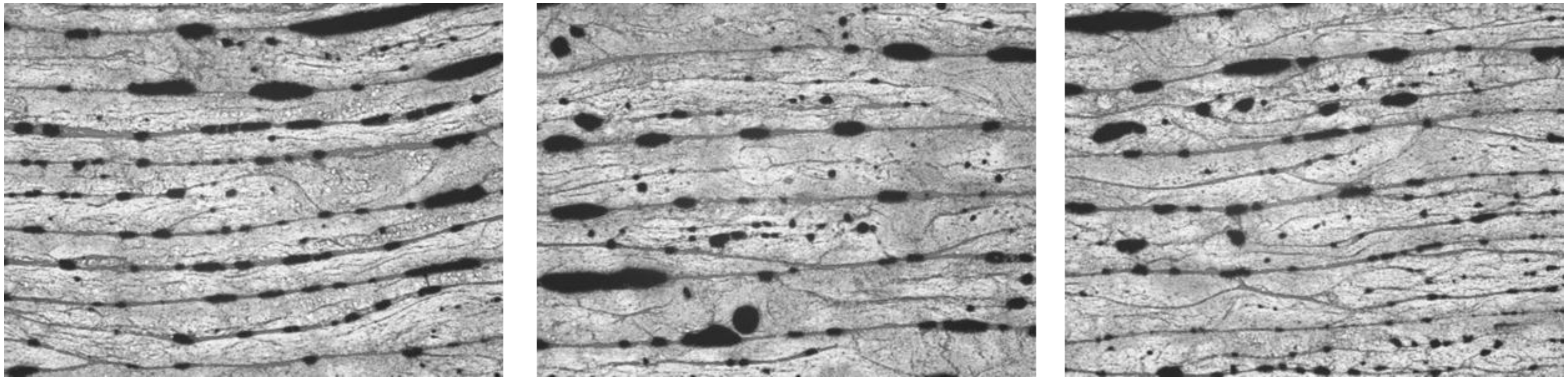






Very low porosities can be achieved from glass prepregs in thick laminates with optimised prepreg architecture

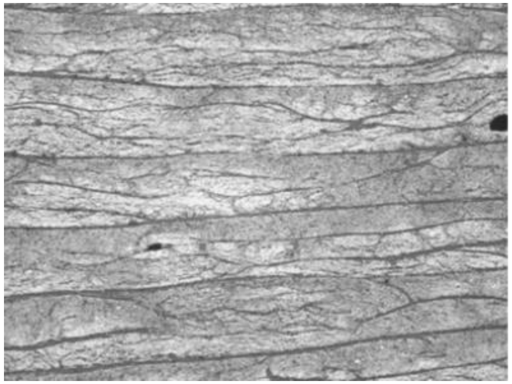
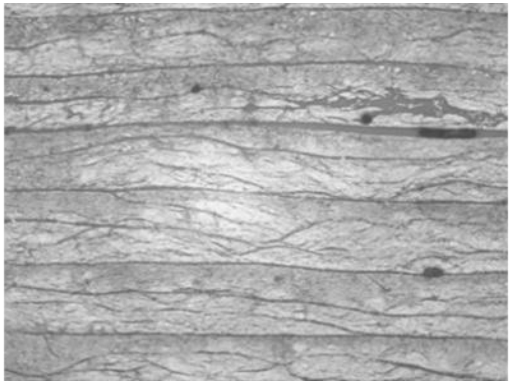
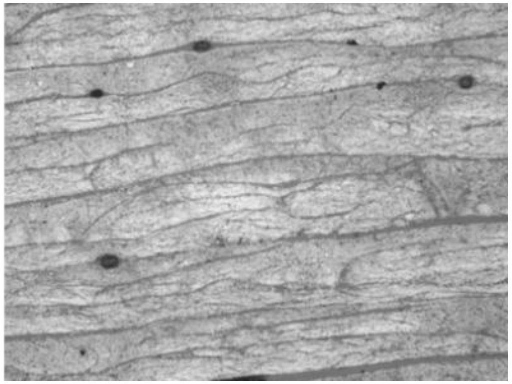
Thick Carbon Laminates – Conventional Technology



64 ply laminates using 600 g/m^2 carbon (HS) prepreg and conventional technology
Porosity ~7%

Conventional prepregs are not optimised for thick carbon laminates

Thick Carbon Laminates – Optimised Architecture

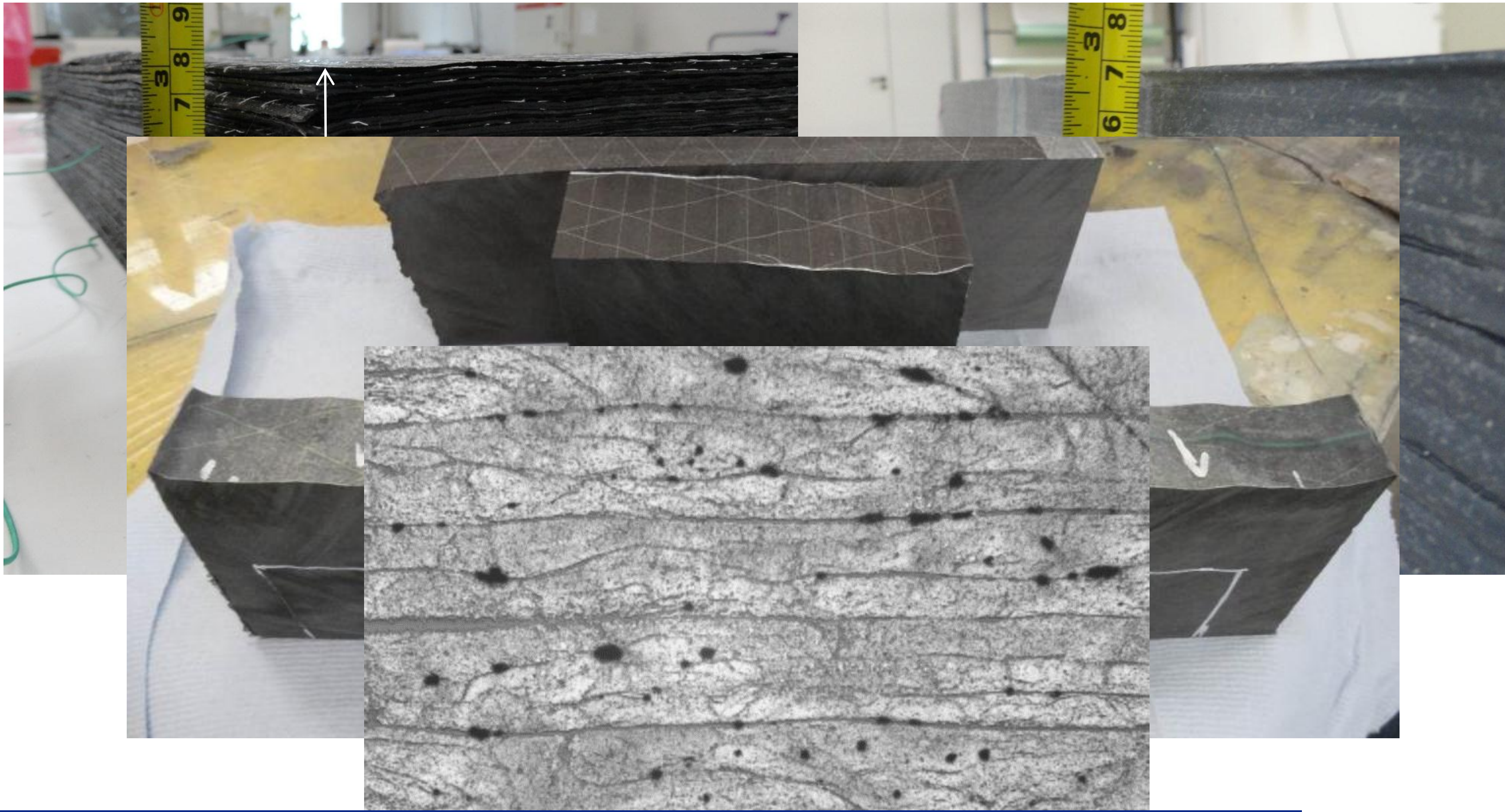




Prepreg architecture designed for thick laminates using Hexcel technology
Porosity <<1%

Layer uniformity can be further improved by optimising the stack sequence

Optimised architecture in carbon UD prepregs consistently gives low porosity

Thick Carbon Laminates – Optimised Architecture

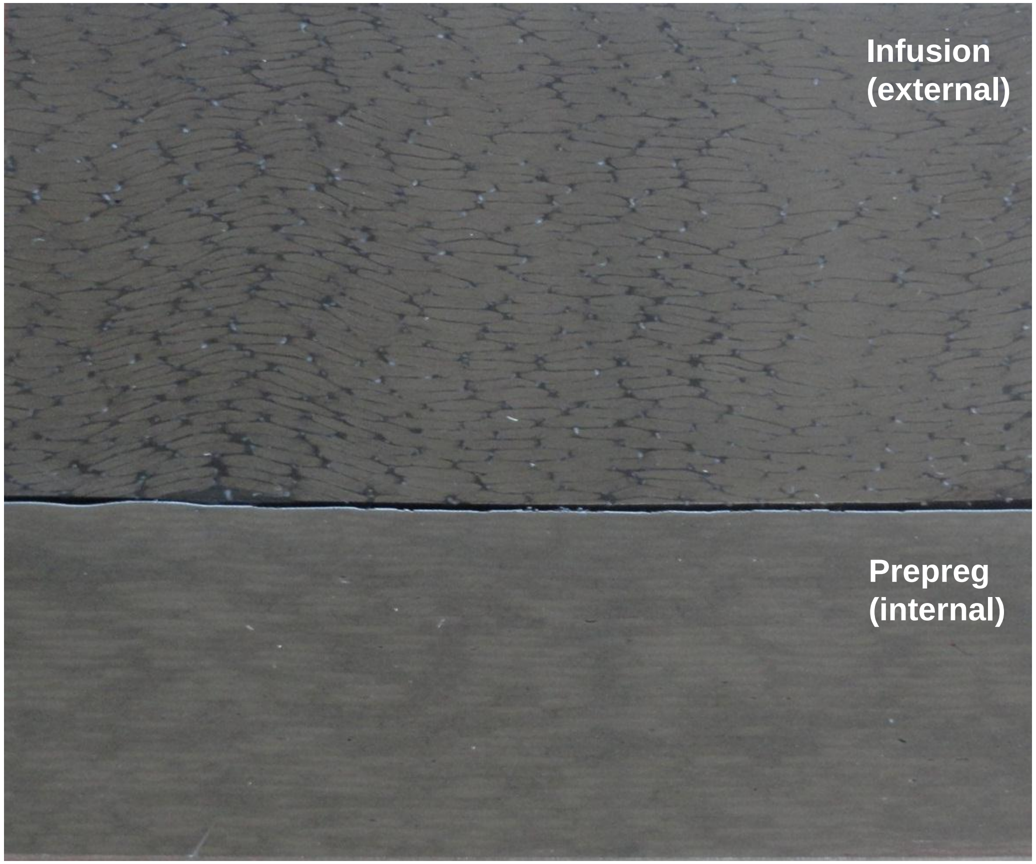


Even in the thickest laminates, optimised architecture consistently gives low porosity

Optical Comparison: Infusion vs. Prepreg

Morphology – infused carbon vs. carbon prepreg

- Porosity of infused part is lower
- Prepreg sample shows very uniform morphology of both fiber/matrix distribution and alignment
- Homogeneity of prepreg part is higher

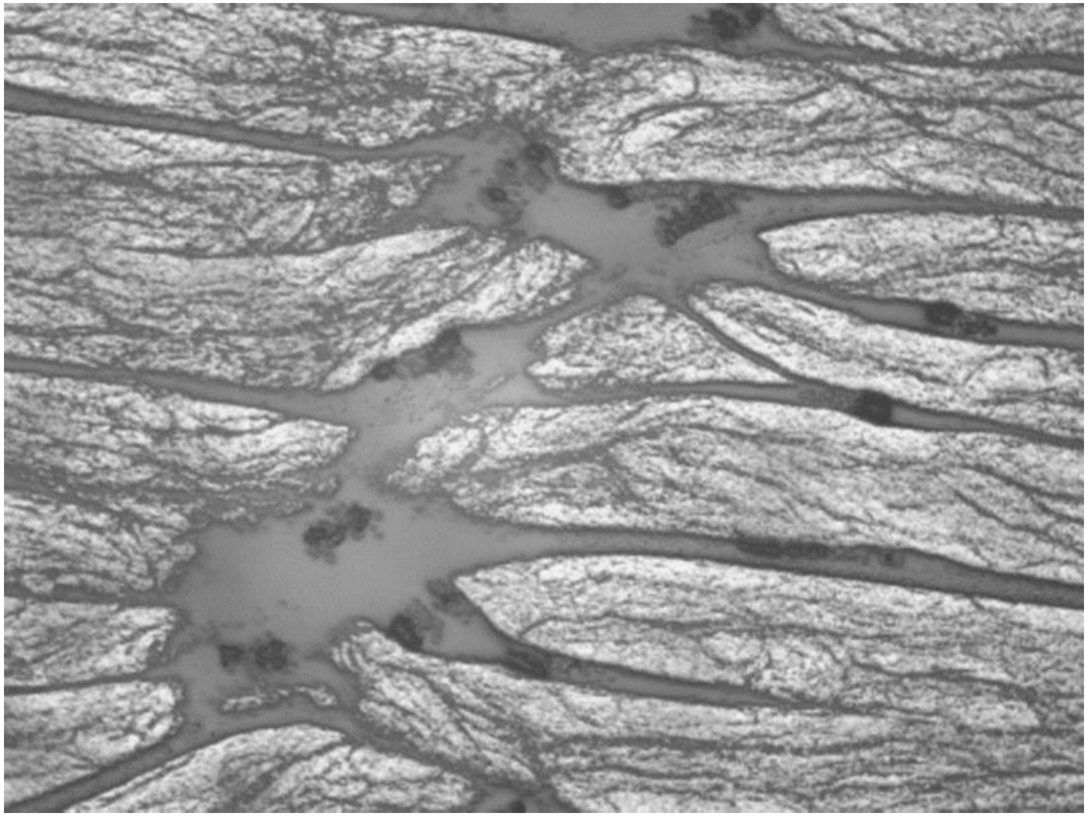


Prepreg sample shows excellent uniformity in X, Y and Z directions

Optical Comparison: Infusion vs. Prepreg

Infusion laminate: fiber/ matrix distribution

- Resin rich areas between fiber bundles are clearly evident in the infused carbon part

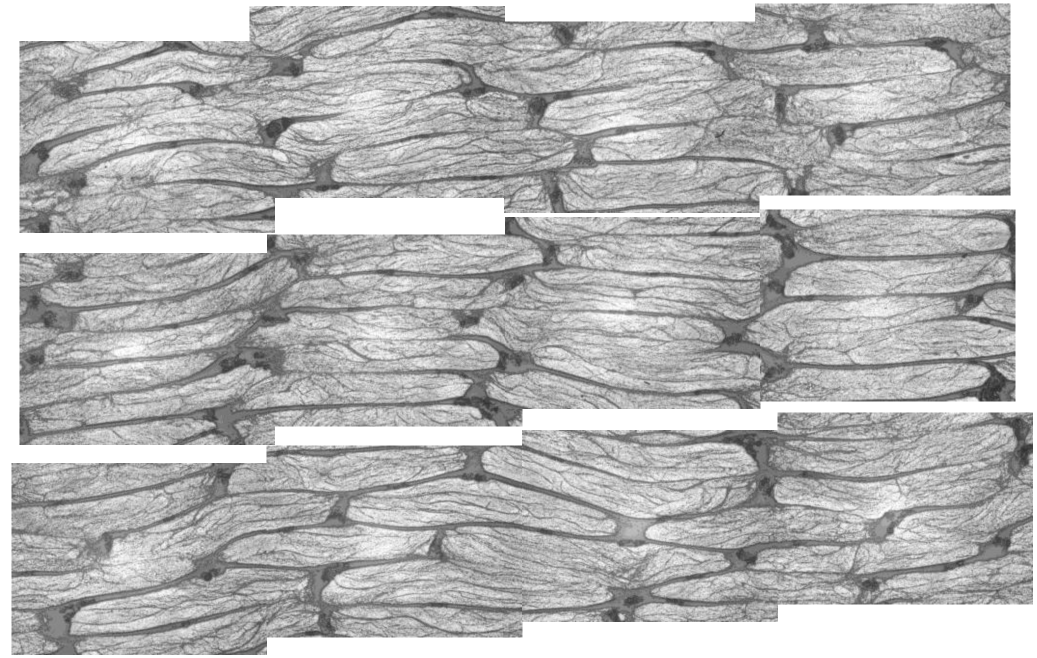


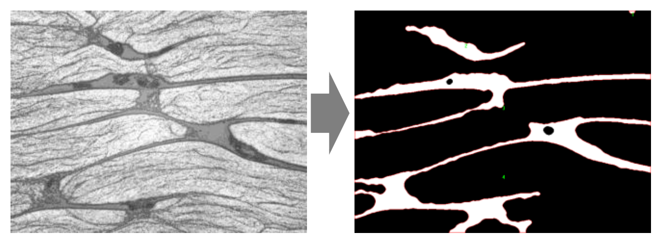
Non-uniformity of resin and fibre is a prominent feature of the infused laminate

Optical Comparison: Infusion vs. Prepreg

Infusion laminate morphology

- Distinct matrix boundaries between carbon fiber bundles
- Fiber and matrix rich areas result in fiber-volume variations over cross section
- Fiber bundles are deformed and possibly deflected in 90° direction
- Porosity is generally low, but some bigger pores are present





Matrix rich domains form ~15% of total

Infusion sample is less uniform: for fibre, fibre direction and matrix

Mechanical Properties Using Prepreg and Infusion

Glass

Glass: Materials

Infusion

- **Reinforcement: LT1218 (UD1200 + slight reinforcement in 90°)**
- **Resin: Epikote RIM 135**
- **Cure at 90°C**

Prepreg

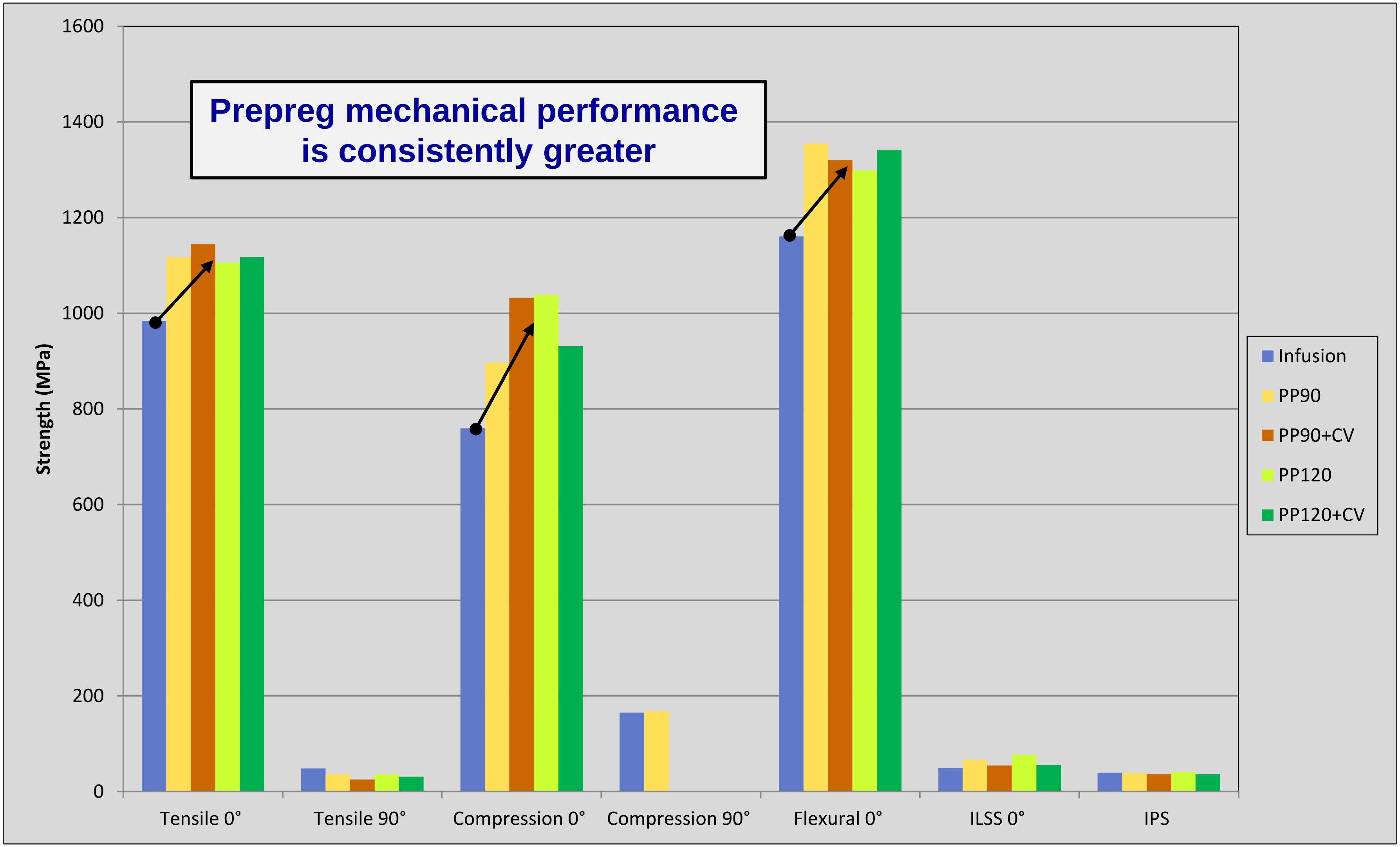
- **M9.6GLT/32%/1200(+CV)/G**
- **Cure at 90°C (‘PP90’) and 120°C (‘PP120’)**

Glass: Mechanical Properties

Property		Norm	Infusion	PP90	PP90+CV	PP120	PP120+CV
Tensile 0° *	Strength (MPa)	ISO527	984.3	1117.3	1144.2	1105.5	1117.1
	Modulus (GPa)		46.4	47.4	45.6	47.7	45.8
Tensile 90° *	Strength (MPa)		48.3	36.0	25.3	36.3	31.2
	Modulus (GPa)		9.66	12.7	8.87	10.7	12.2
Compression 0° *	Strength (MPa)	EN2850B	759.5	896.7	1032.6	1038.6	931.3
	Modulus (GPa)		47.1	48.7	49.0	49.0	48.3
Compression 90°	Strength (MPa)		165.4	168.0			
	Modulus (GPa)		13.9	15.9			
Flexural 0° *	Strength (MPa)	ISO14125	1160.5	1354.5	1320	1299	1341
	Modulus (GPa)		30.7	36.4	32.5	32.9	31
ILSS 0°	Strength (MPa)	ISO14130	48.7	66.2	54.7	77.3	55.8
IPS	Strength (MPa)	ISO14129	39.2	38.9	36.5	40.9	36.3
	Modulus (GPa)		3.40	4.50	4.2	3.9	4.2

*** Normalised at FV=60%**

Glass: Mechanical Properties



Mechanical Properties Using Prepreg and Infusion

Carbon

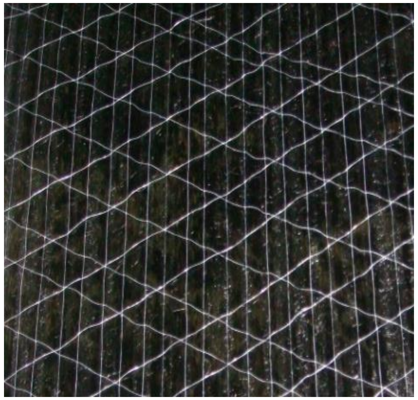
Carbon: Materials

Infusion

- Reinforcement: UD600 low crimp T620
- Resin: Epikote RIM135
- Cure at 90°C

Prepreg

- M9.6GLT/35%/UD600+2P/T620+PES
- Cure at 90°C and 120°C

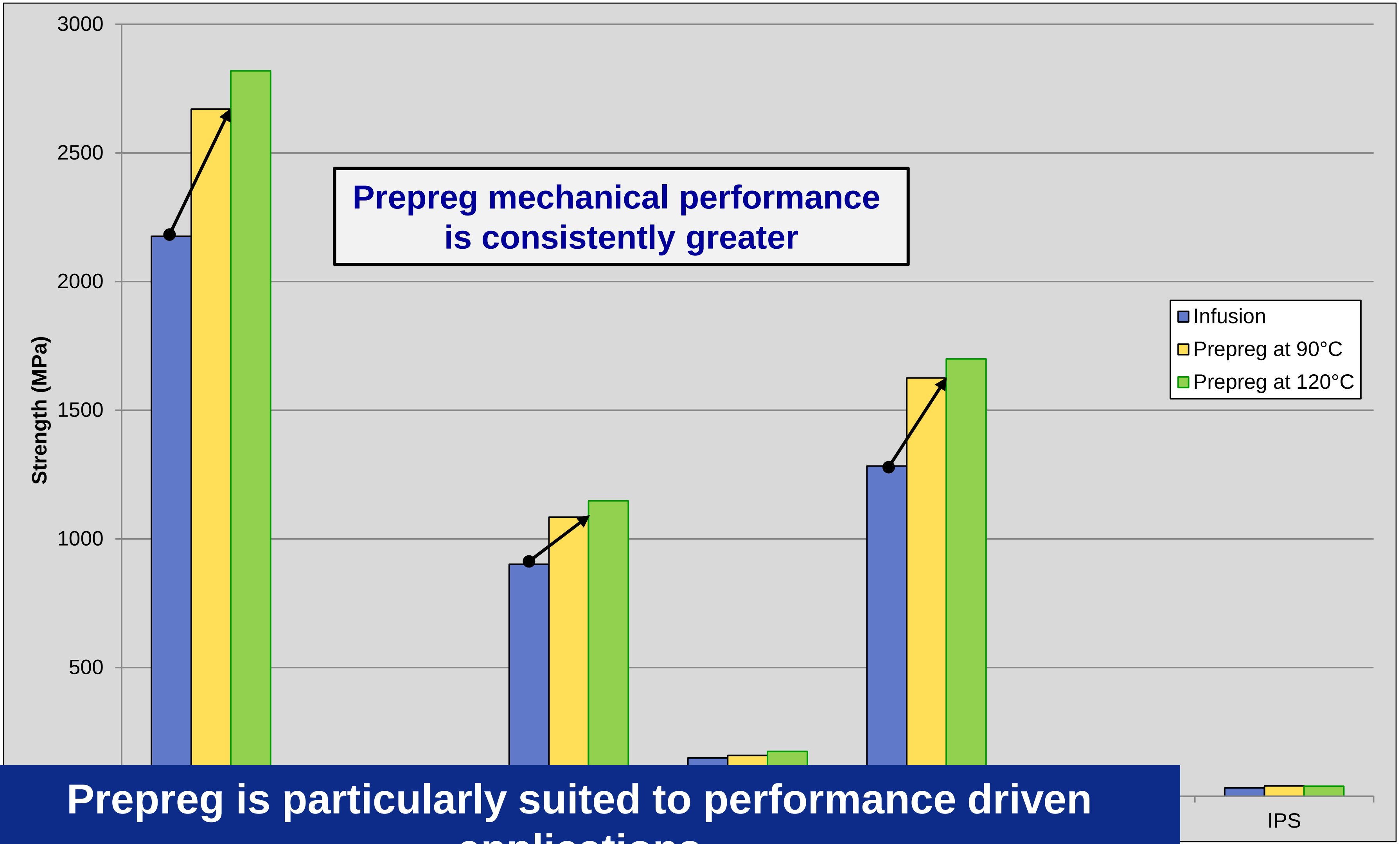


Carbon: Mechanical Properties

Property		Norm	Infusion	PP90	PP120
Tensile 0° *	Strength (MPa)	ISO527	2176,1	2670,2	2819,8
	Modulus (GPa)		130	125	128,4
Tensile 90°	Strength (MPa)		33	37,9	42,9
	Modulus (GPa)		8,4	8,2	7
Compression 0° *	Strength (MPa)	EN2850B	902	1085	1148
	Modulus (GPa)		128,5	125.1	119.8
Compression 90°	Strength (MPa)		148,6	158,3	173,6
	Modulus (GPa)		9	9,2	9,3
Flexural 0° *	Strength (MPa)	ISO14125	1283	1626	1700
	Modulus (GPa)		103,1	103,6	114,6
ILSS 0°	Strength (MPa)	ISO14130	60,6	66,7	67,6
IPS	Strength (MPa)	ISO14129	32,2	39,6	39,2
	Modulus (GPa)		4,2	4	3,9

* **Normalised at FV=60%**

Carbon: Mechanical Properties



Prepreg is particularly suited to performance driven applications

Prepreg and Infusion Matrices

M79: Eliminating the Gap Between Prepreg and Infusion

Typical Prepreg Systems in Wind Energy

Typical resin systems

M9G	310 J/g	Cure temperature ~100-120°C
M9GF	230 J/g	
M19G	160 J/g	

UD Products

Carbon 500-600 g/m^2

Glass 1000-3000 g/m^2

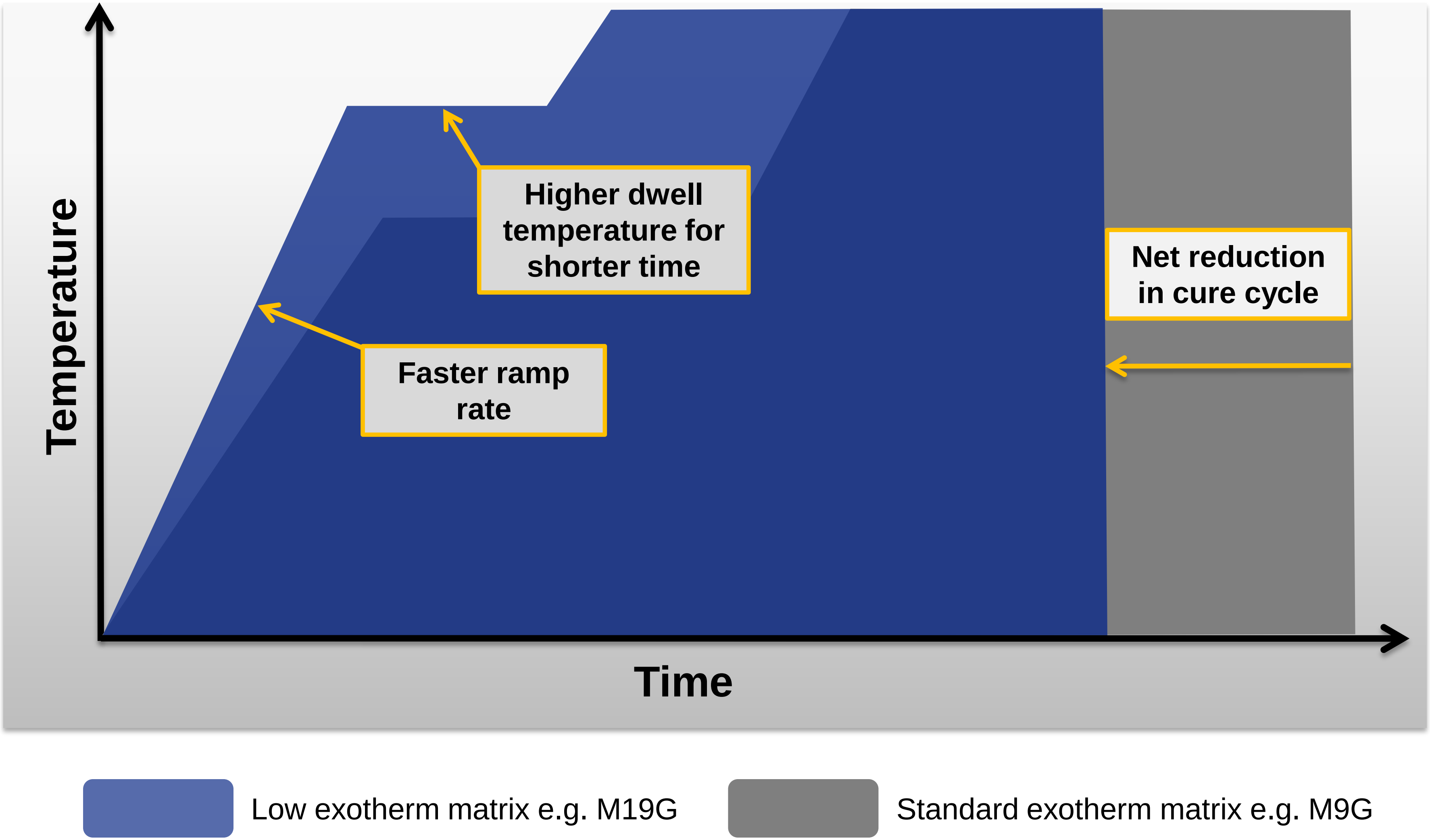
Overall cure cycles

~4 to ~8 hours (optimisation is key)

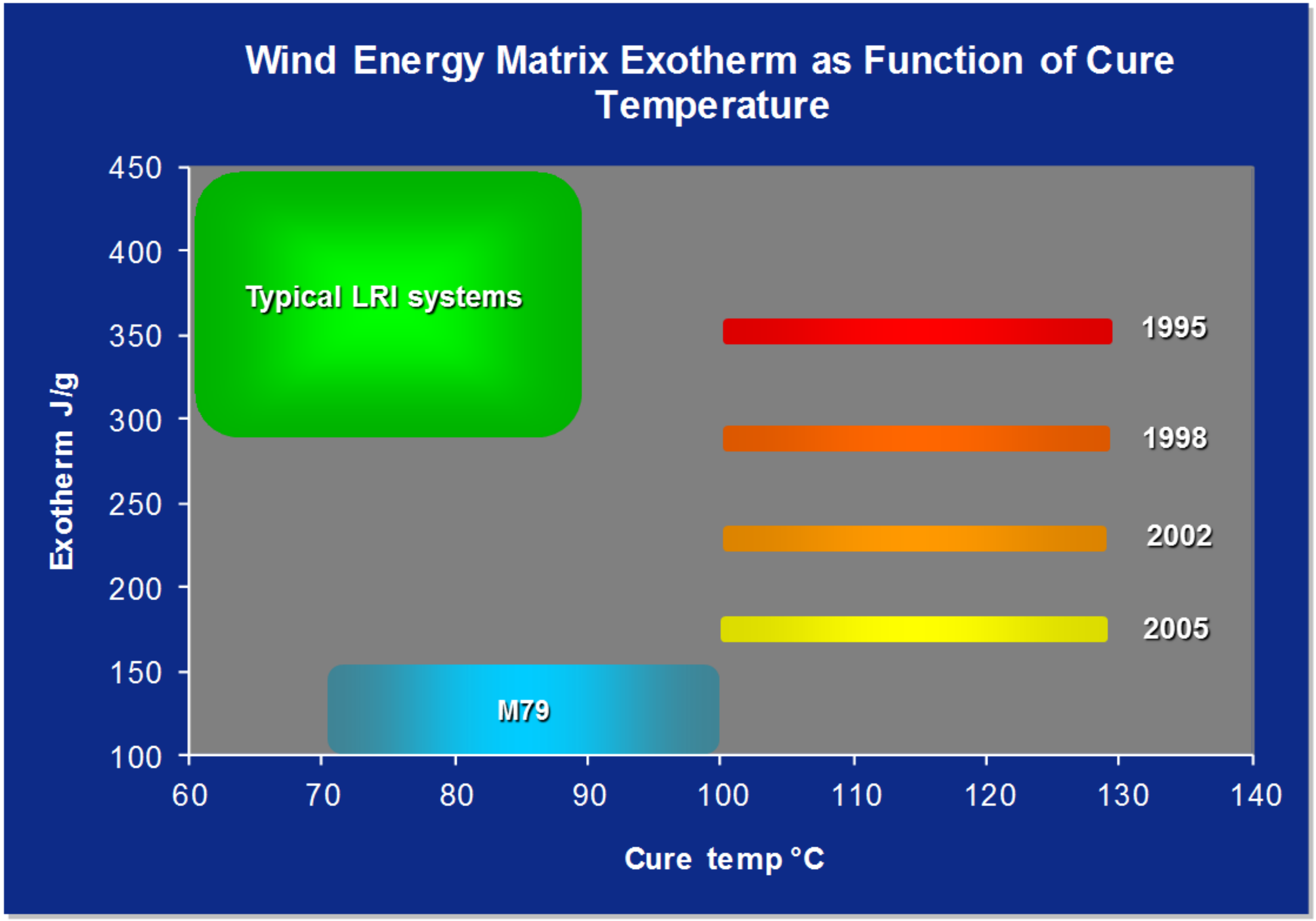
Typical prepregs
high areal weight + moderate cure temperature + low reaction enthalpy

HEXCEL

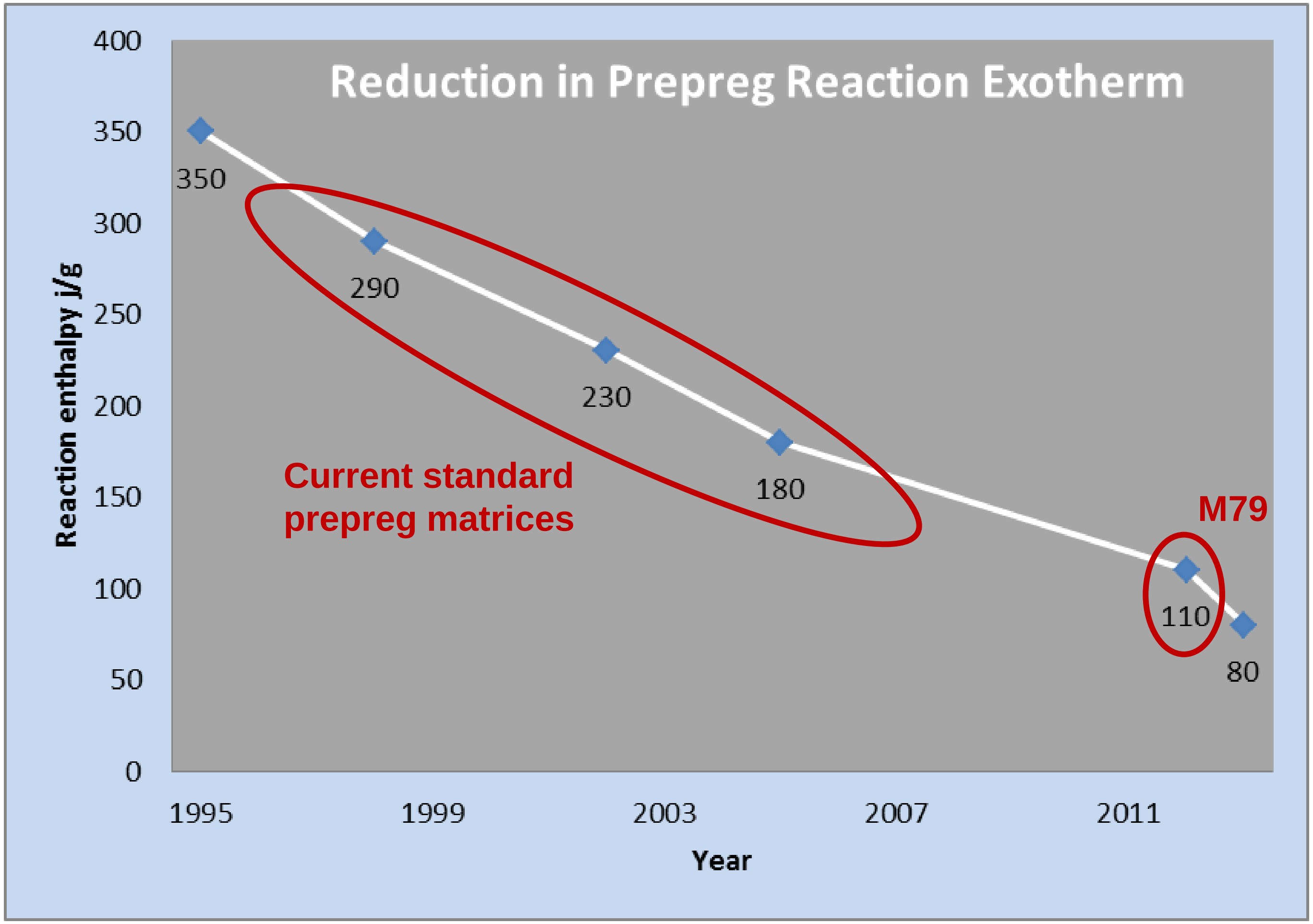
The Value of Low Exotherm in Thick Laminates



Prepreg and Infusion Matrix Systems



Reduction in Prepreg Exotherm, 1995-2013



M79 continues the trend: minimising reaction exotherm for short cure cycles of thick structures

M79

New generation prepreg system for large industrial structures (e.g. wind turbine blades)

Property	Value
Cure time at 70°C	10 hours
Cure time at 80°C	6 hours
Outlife	>2 months
Reaction enthalpy	100-120 J/g
Static mechanical properties	Similar to current M9 family
Product form	Same as current M9 family
Manufacturing process	Same as current M9 family

M79 extends performance envelope to lower temperatures and lower exotherm

HEXCEL

M79: Example of Mechanical Test Data (70°C cure)

Test & Direction	Measurement	70°C Cure				M9 Historical
		No. of specimens	Mean	SD	CV (%)	
Tensile 0°	Strength (MPa)	8	**469**	9.4	2.0	**445**
	Modulus (GPa)		**21.2**	0.5	2.5	**18.2**
Compression 0°	Strength (MPa)	10	**413**	20	4.9	**333**
	Modulus (GPa)		**21.0**	0.3	1.4	**19.5**
ILSS (45°, 4-ply)	Strength (MPa)	20	46.7	1.9	4.0	43.6

Normalized results are in bold

Test results for HexPly M79/43%/LBB1200+CV/G cured at 70 ºC

Overall, M79 mechanical test data compares favourably with conventional (M9) systems

M79: Example of Mechanical Test Data (80°C cure)

Test & Direction	Measurement	80 ° C Cure				M9 Historical
		No. of specimens	Mean	SD	CV (%)	
Tensile 0°	Strength (MPa)	20	**456**	16	3.6	**445**
	Modulus (GPa)		**19.1**	0.3	1.7	**18.2**
Compression 0°	Strength (MPa)	10	**394**	30	7.5	**333**
	Modulus (GPa)		**20.5**	1.0	4.7	**19.5**
ILSS (45° , 4-ply)	Strength (MPa)	20	39.5	1.1	2.7	43.6

Normalized results are in bold

Test results for HexPly M79/43%/LBB1200+CV/G cured at 80 ºC

Again overall, M79 mechanical test data favourably with conventional (M9) systems

HEXCEL®

Co-infusion

Combinations of Prepreg and Infusion

Co-infusion: an Introduction

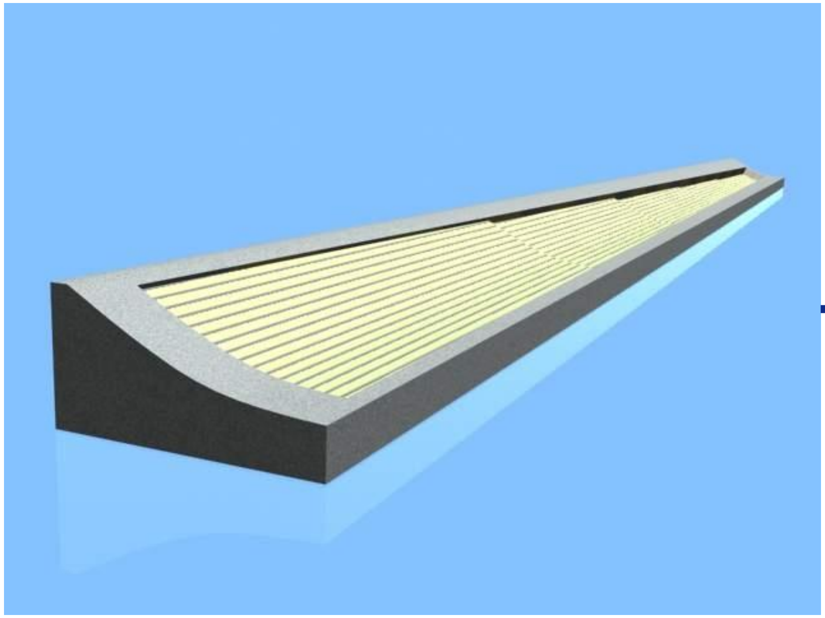
Co-infusion

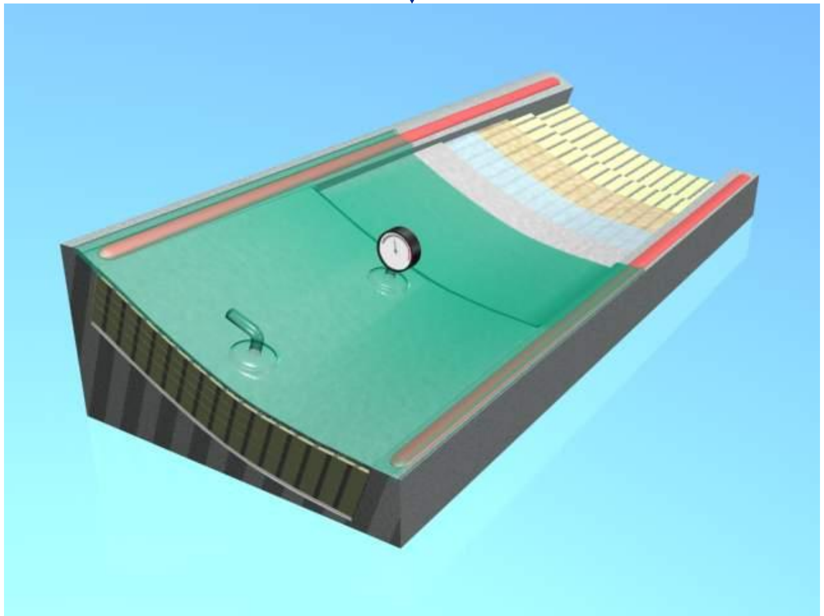
The use of prepreg and infusion technologies in the same laminate with co-cure

Typical configuration

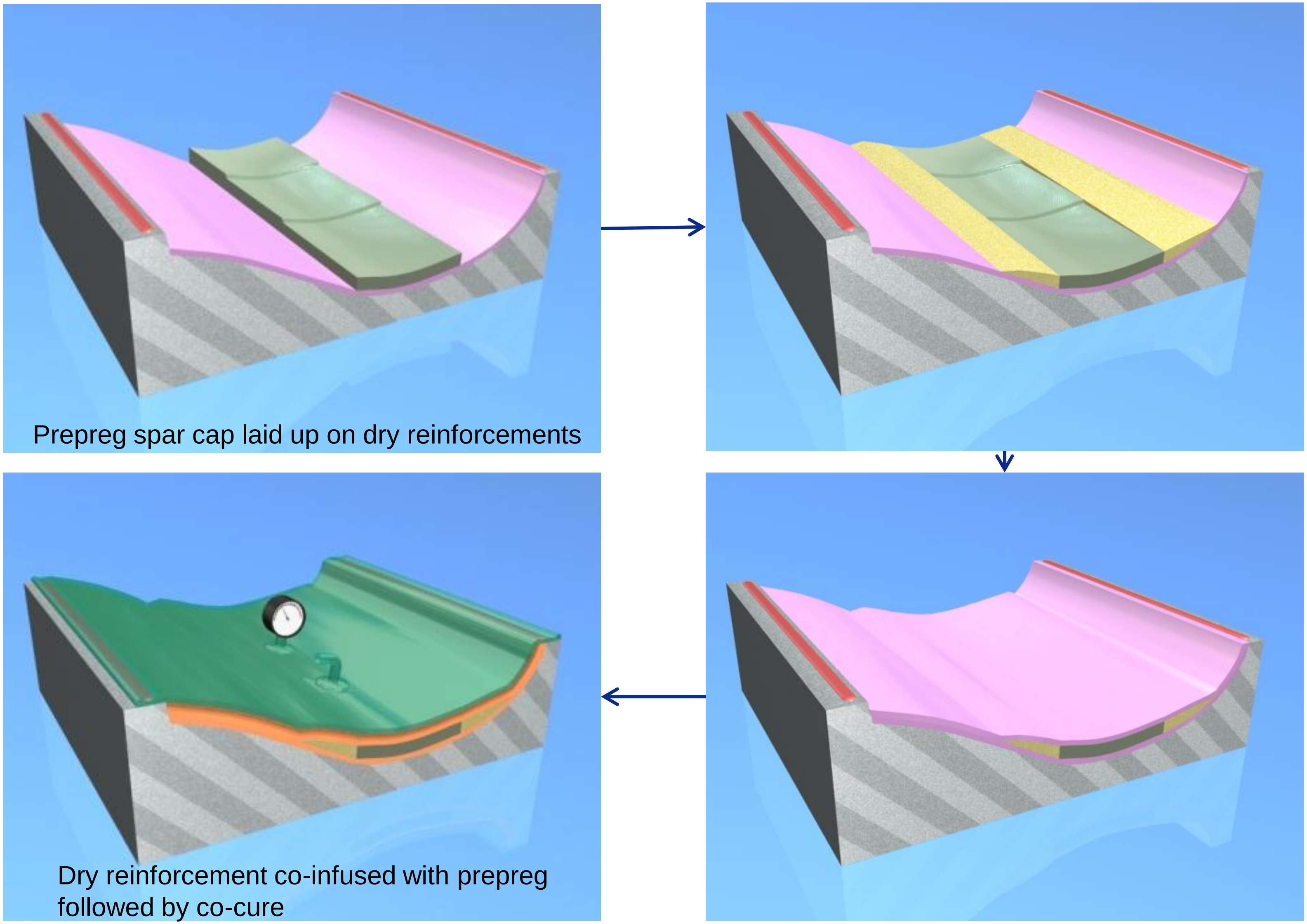
UD prepreg for the heavy load-carrying structure
Infusion of dry reinforcement for the remainder of the structure
Cure of the whole assembly at the same time and temperature

Spar Caps: Prepreg Layup and Cure



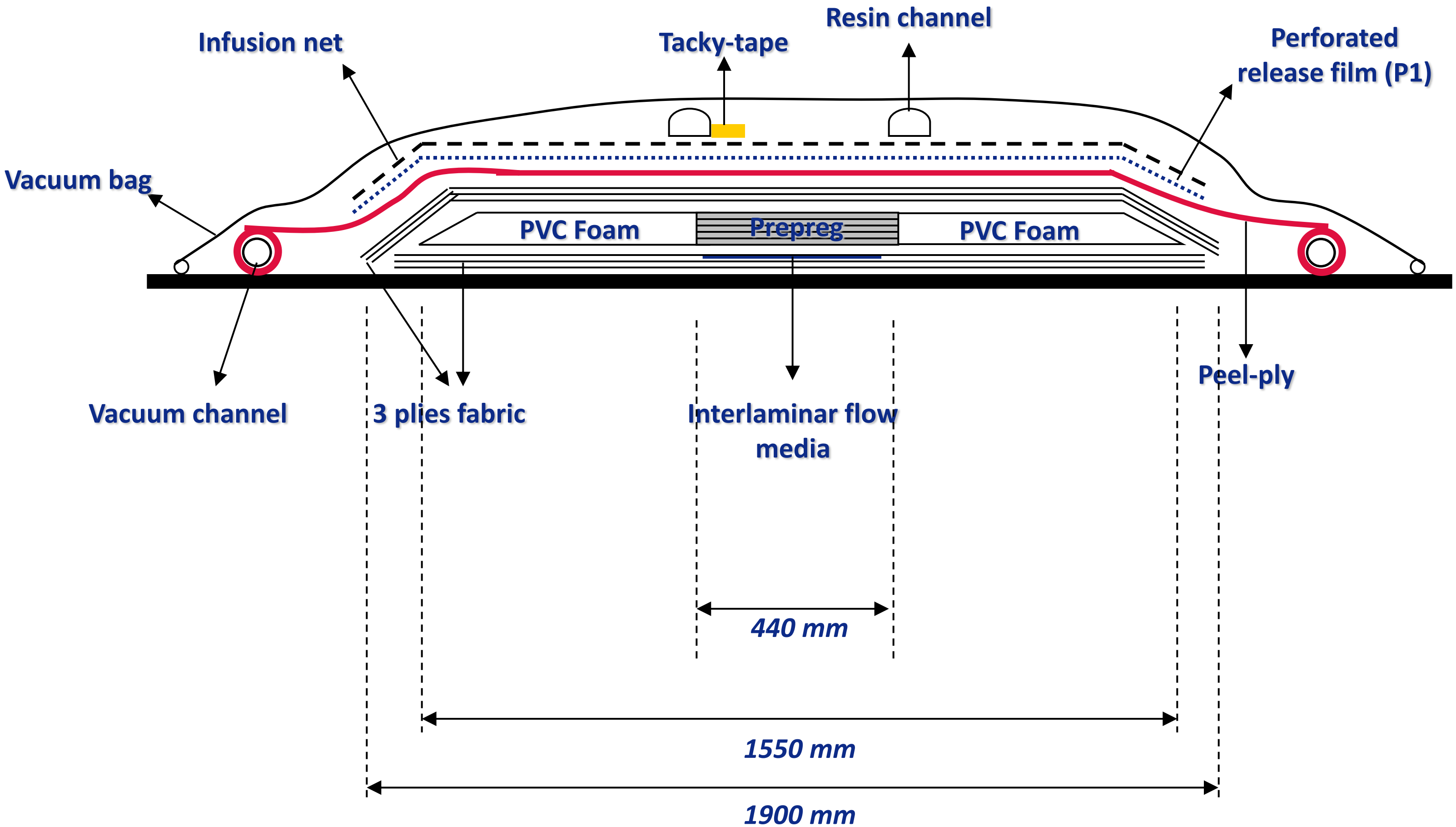


Wind Blades: M79 co-cured in an Infused Shell

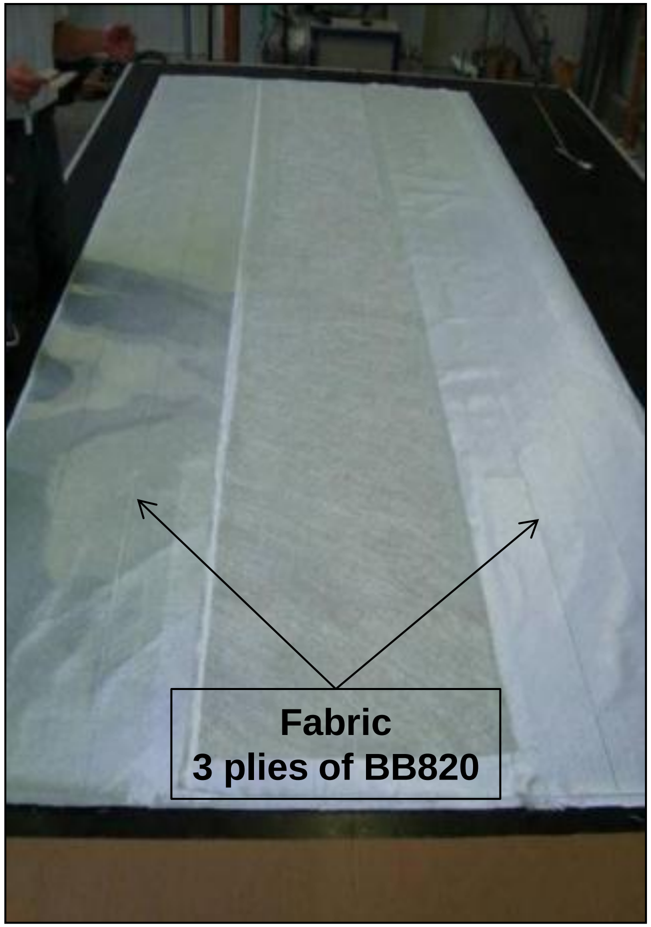


Co-infusion: Case Study, Construction

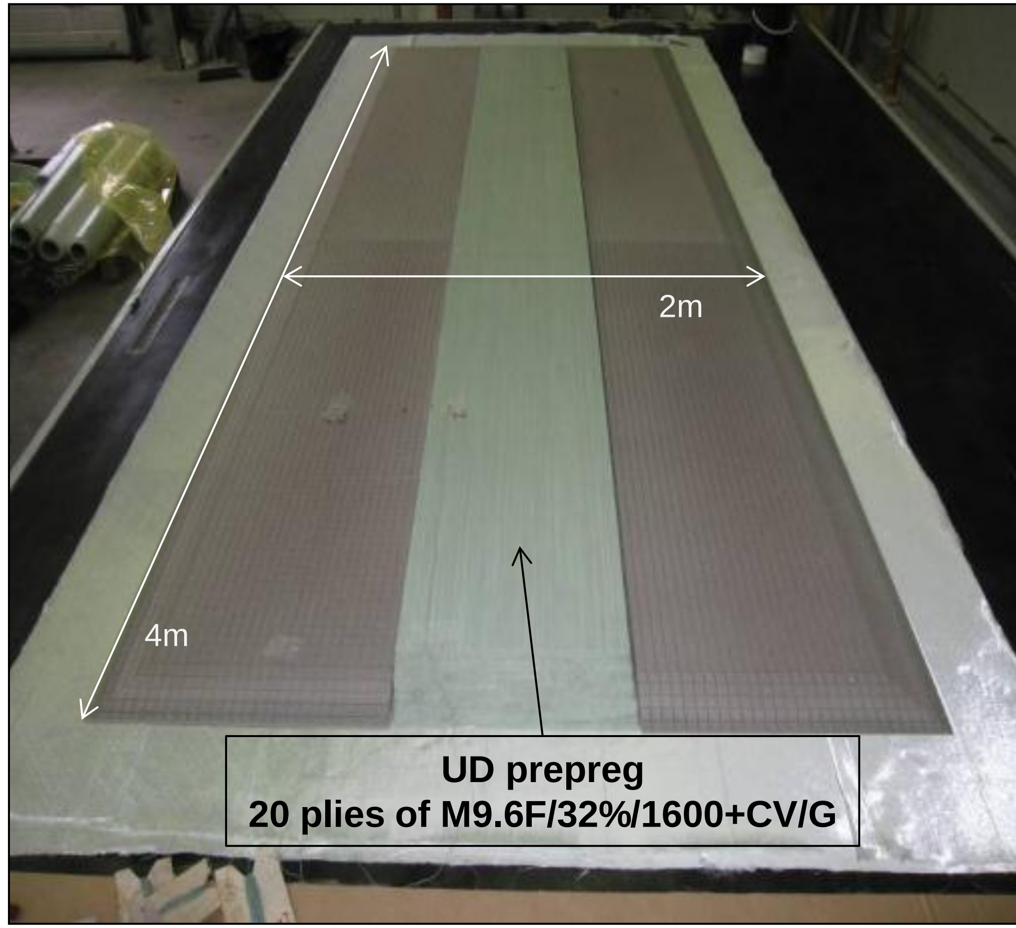
Demonstration on a 4 x 2m scale
UD prepreg with biax dry fabrics



Co-infusion: Case Study, Layup



Dry reinforcements

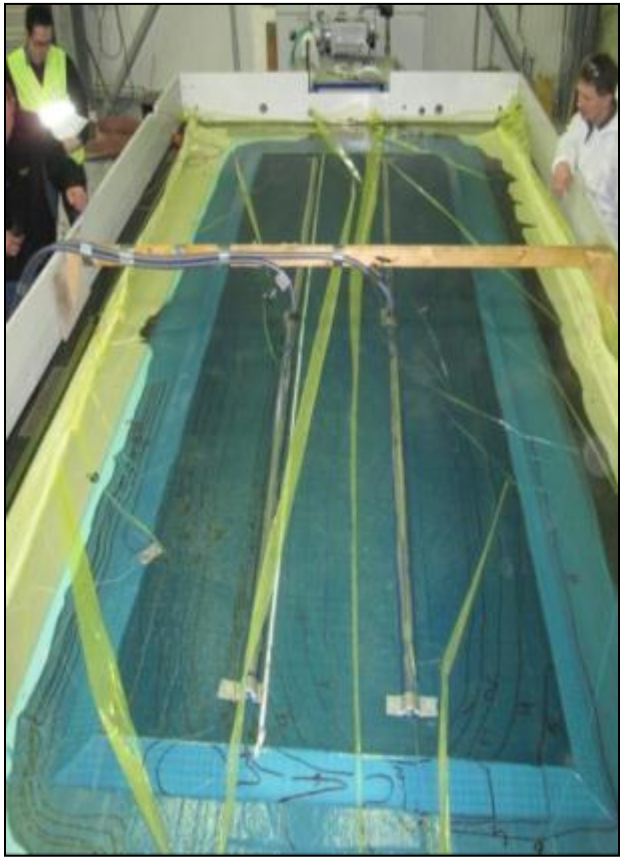


Foam and UD prepreg layers

Co-infusion: Case Study, Infusion Process

1 min

12 min



22 min

Infusion time: ~25 min
Resin consumption: ~34 kg, Epikote RIM 135

Co-infusion: Case Study after Demoulding

The finished 4x2m laminate

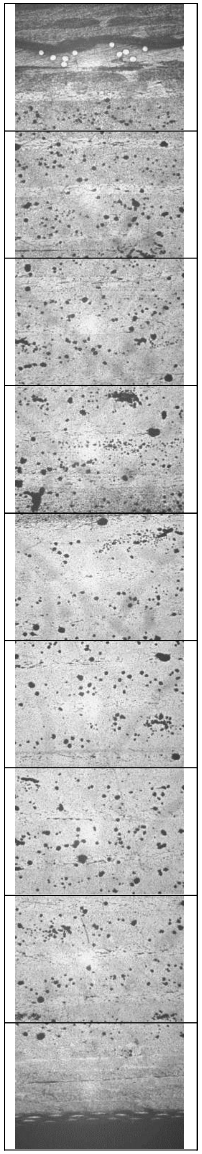
Low porosity, high Tg

FV (%)		50
Porosity (%)	Side	0,7
	Middle	1,5
Tg (°C)	Top	75
	Middle	120
	Bottom	75
Cure cycle		6hrs 90°C

Co-infusion simplifies the production process, combining the best features of prepreg and infusion materials

HEXCEL®

Co-infusion: Case Study, Porosity



3x Infusion fabrics

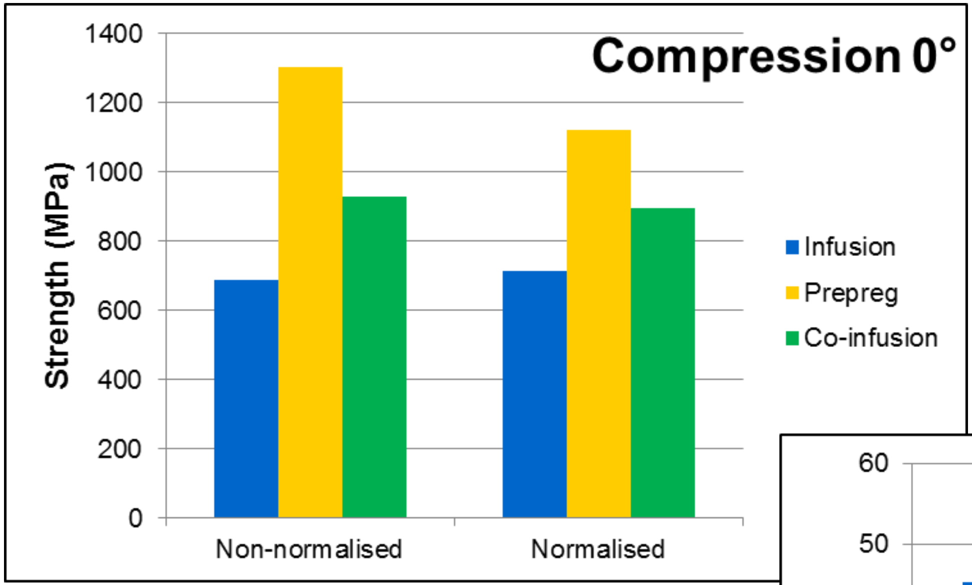
20x M9.6F/32%/1600+CV/G

3x Infusion fabrics

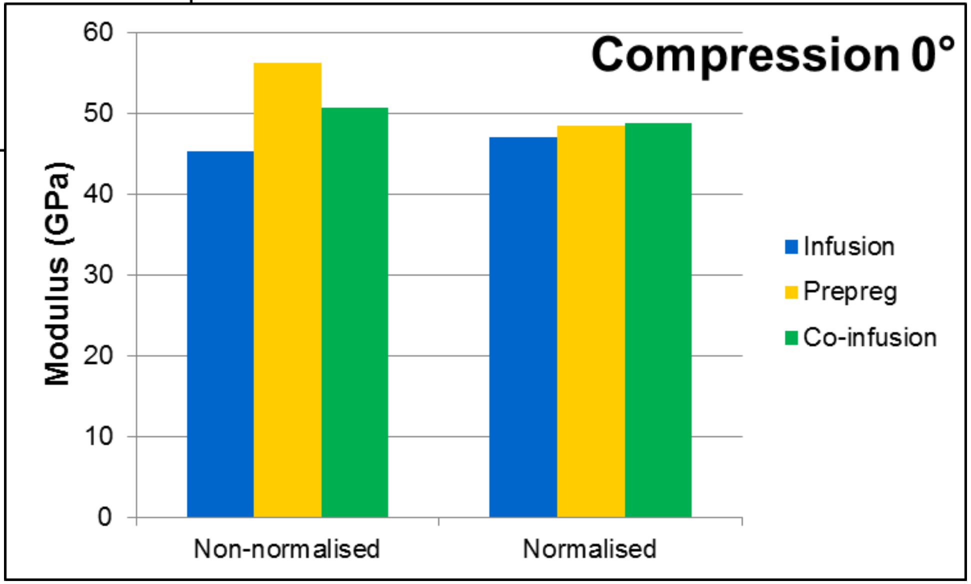
Porosity assessment	
Maximum void	<0.85 mm^2
Porosity	0.7-1.5%

HEXCEL

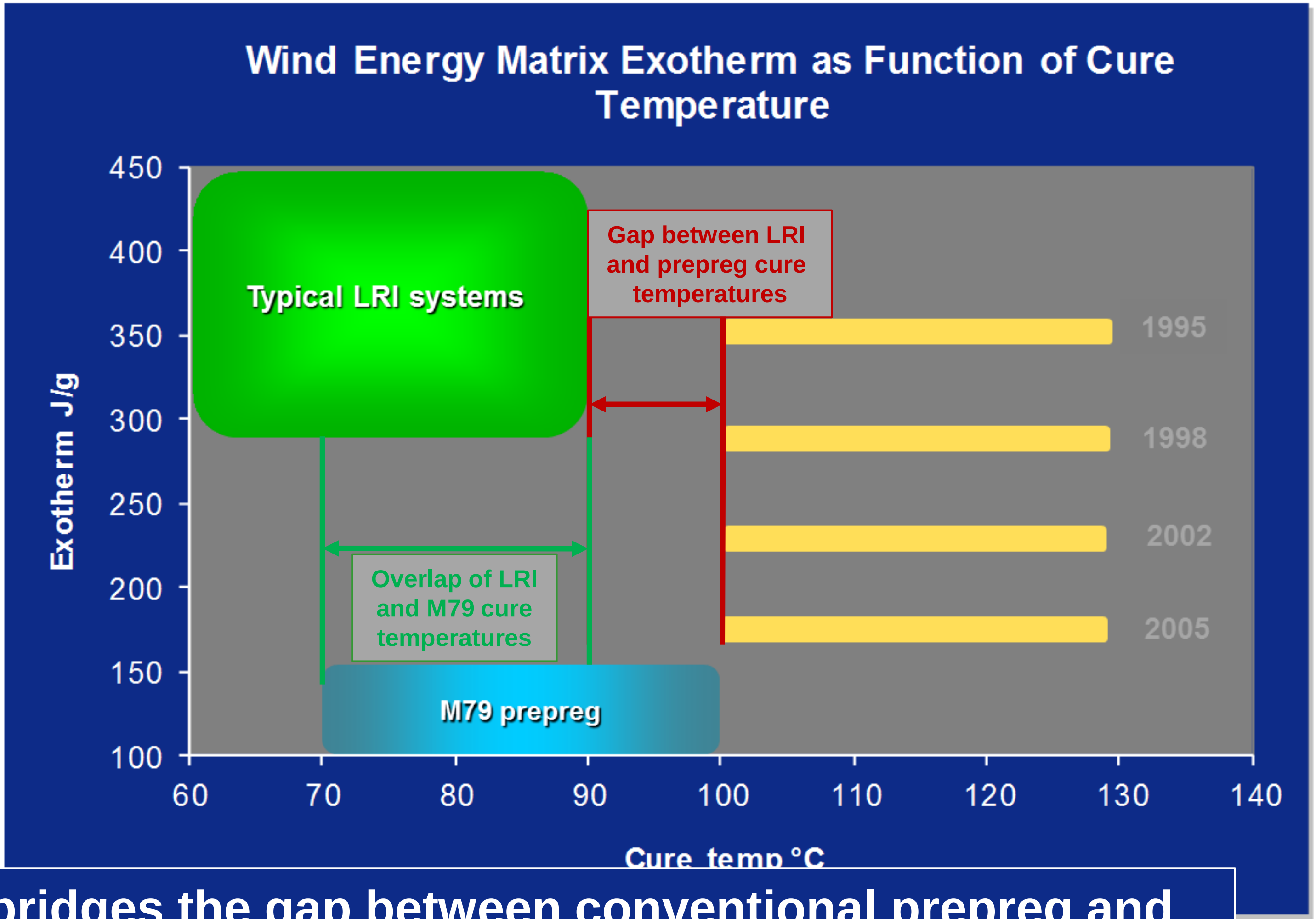
Co-infusion: Case Study, Compression



* ISO 14126



M79 Compared with Conventional Systems



M79 bridges the gap between conventional prepreg and infusion systems which facilitates co-infusion

Conclusions

Prepreg and Infusion Processes in Wind Energy

- **Different blade elements have different drivers, sometimes cost driven, sometimes performance driven**
- **Prepreg is particularly suited to performance driven applications, on glass and carbon**
  - Overall higher mechanical properties
  - Consistent low porosity when using appropriate architecture
  - Reliable impregnation, low exotherm, fast cure cycle
- **M79 offers prepreg quality at infusion cure temperatures**
- **Co-infusion can simplify the manufacturing process**
  - It can eliminate the separate steps in spar cap manufacture
  - M79 simplifies the process allowing prepreg cure at infusion cure temperatures

Maximum material performance is derived from prepreg which is particularly suited to performance applications

Disclaimer

This document and all information contained herein is the sole property of HEXCEL CORPORATION. No intellectual property rights are granted by the delivery of this document or the disclosure of its content.

This document shall not be reproduced or disclosed to a third party without the express written consent of HEXCEL. This document and its content shall not be used for any purpose other than that for which it is supplied.

The statements made herein do not constitute an offer. They are based on the mentioned assumptions and are expressed in good faith. Where the supporting grounds for these statements are not shown, HEXCEL will be pleased to explain the basis thereof.