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Processing of Composite Materials for Large Structures in Marine Renewable Energy (Keynote Lecture)

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School of Engineering, University of Edinburgh, Scotland, UK

Flow Processes in Composite Materials 15, Purdue University, USA

June 28th 2023

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Processing of Composite Materials for Large Structures in Marine Renewable Energy

1. Tidal Stream Energy Blades – FastBlade Facility
2. Powder Epoxy Composites
3. Infusible Thermoplastic Composites
4. Future Plans and Conclusions

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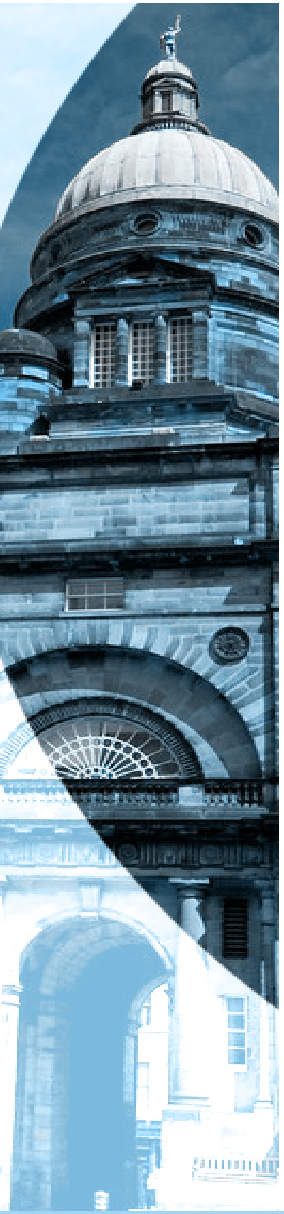
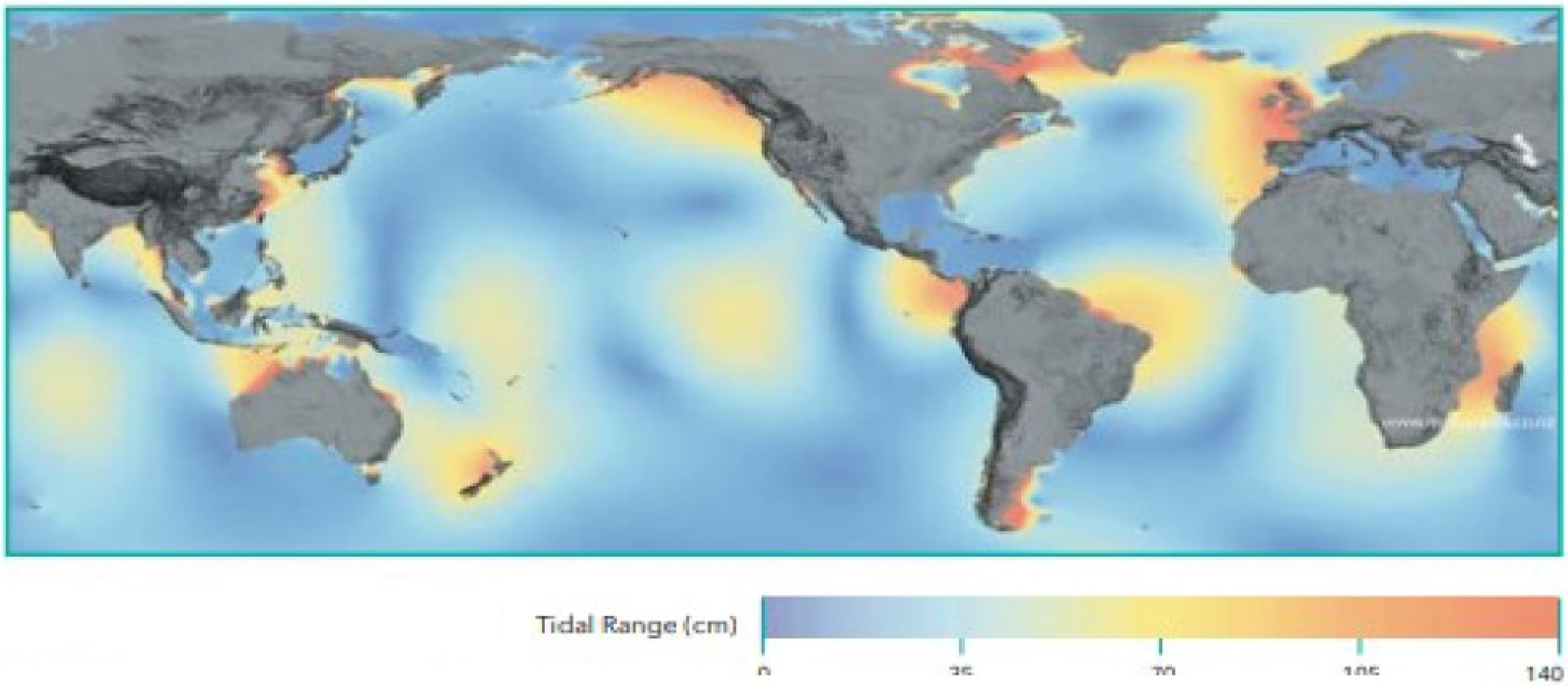


Wave and Tidal Stream Energy – Worldwide Potential Estimated at 300GW*

Tidal Stream Energy potential estimated at 40% or 120GW

The worldwide theoretical power of tidal energy, including tidal currents, has been estimated at around 1,200 TWh/year.

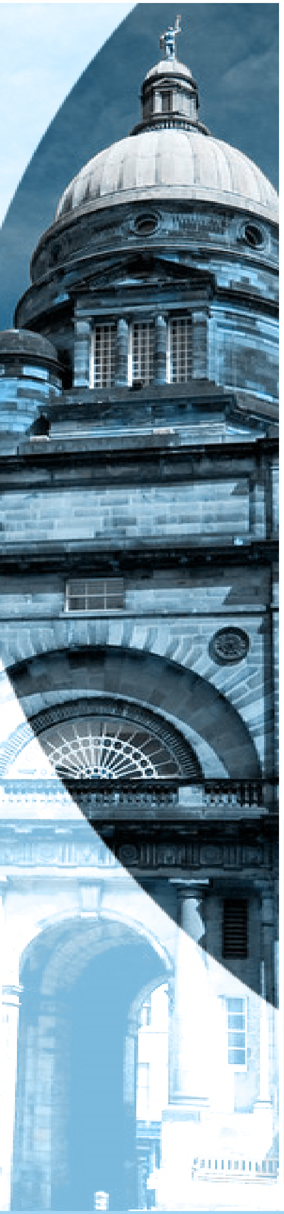


Context:

Total global installed wind energy capacity in 2021 was 837 GW.

But…..wind is intermittent.
Tidal energy is not !

**Ocean Energy Systems, "An International Vision for Ocean Energy 2017," International Energy Agency, 2017*
https://www.ocean-energy-systems.org/news/oes-vision-for-international-deployment-of-ocean-energy/



Tidal Stream Energy - Potential & Current

European Resource: >10GW deployable of highly predictable base load.

EU Target by 2030: 1GW installed.

Huge export potential

Current deployment in UK: ~20 MW

UK: 40 MW CfD Round awarded in 2022

10 MW CfD Round announced in 2023

EXISTING PROJECTS:

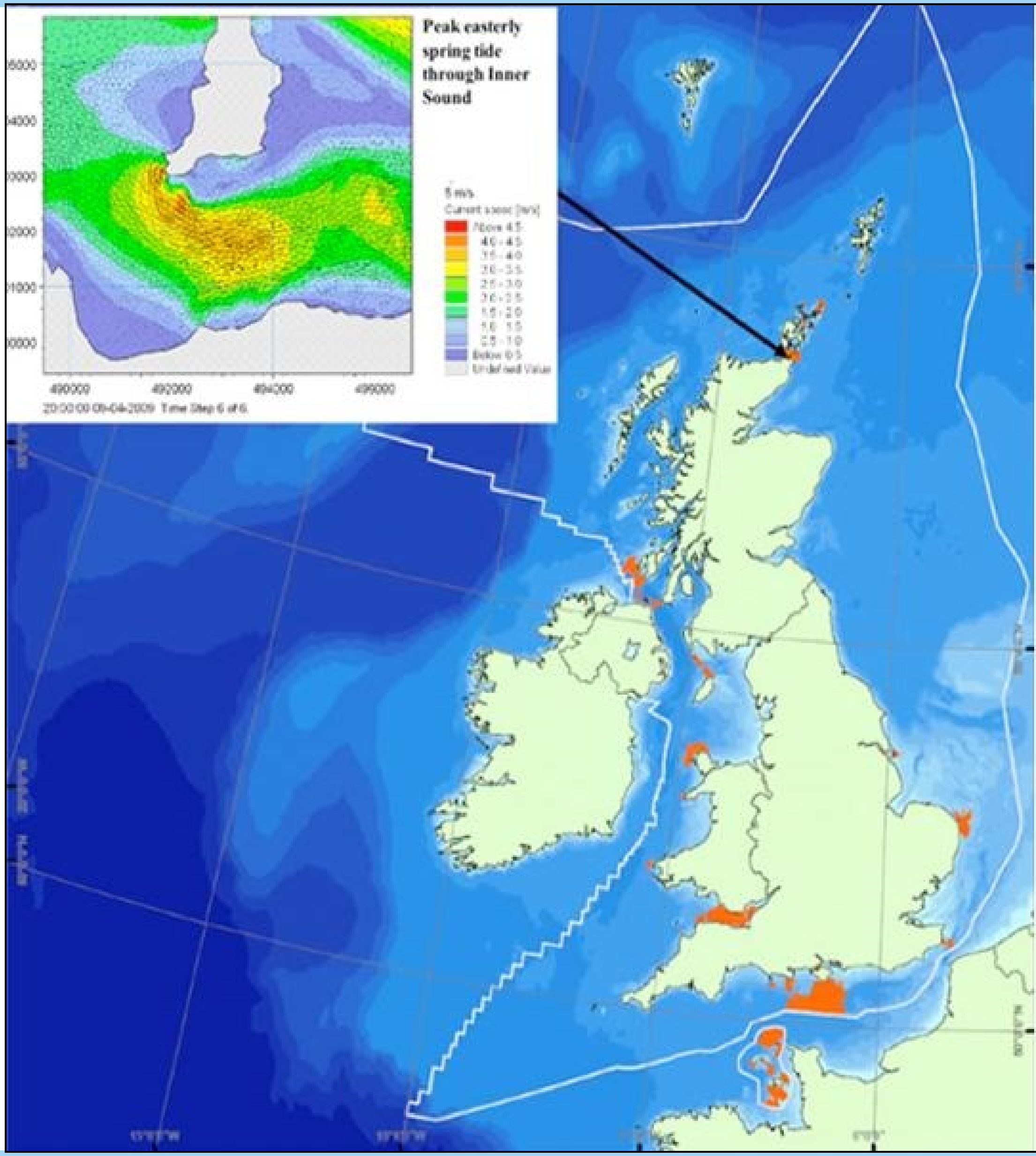
SIMEC ATLANTIS ENERGY, ANDRITZ Hydro Hammerfest: MEYGEN 1A, 6 MW, >22 GWh

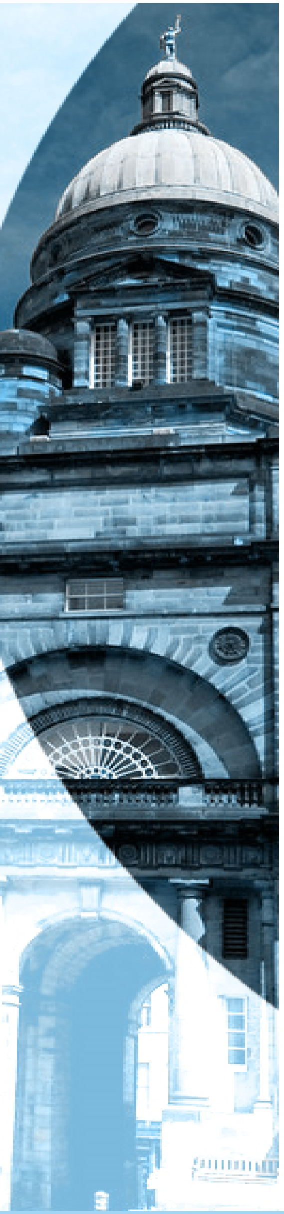
ORBITAL MARINE POWER: FALL OF WARNESS, 2 MW, >3 GWh

NOVA INNOVATION: BLUEMULL SOUND, 300 kW

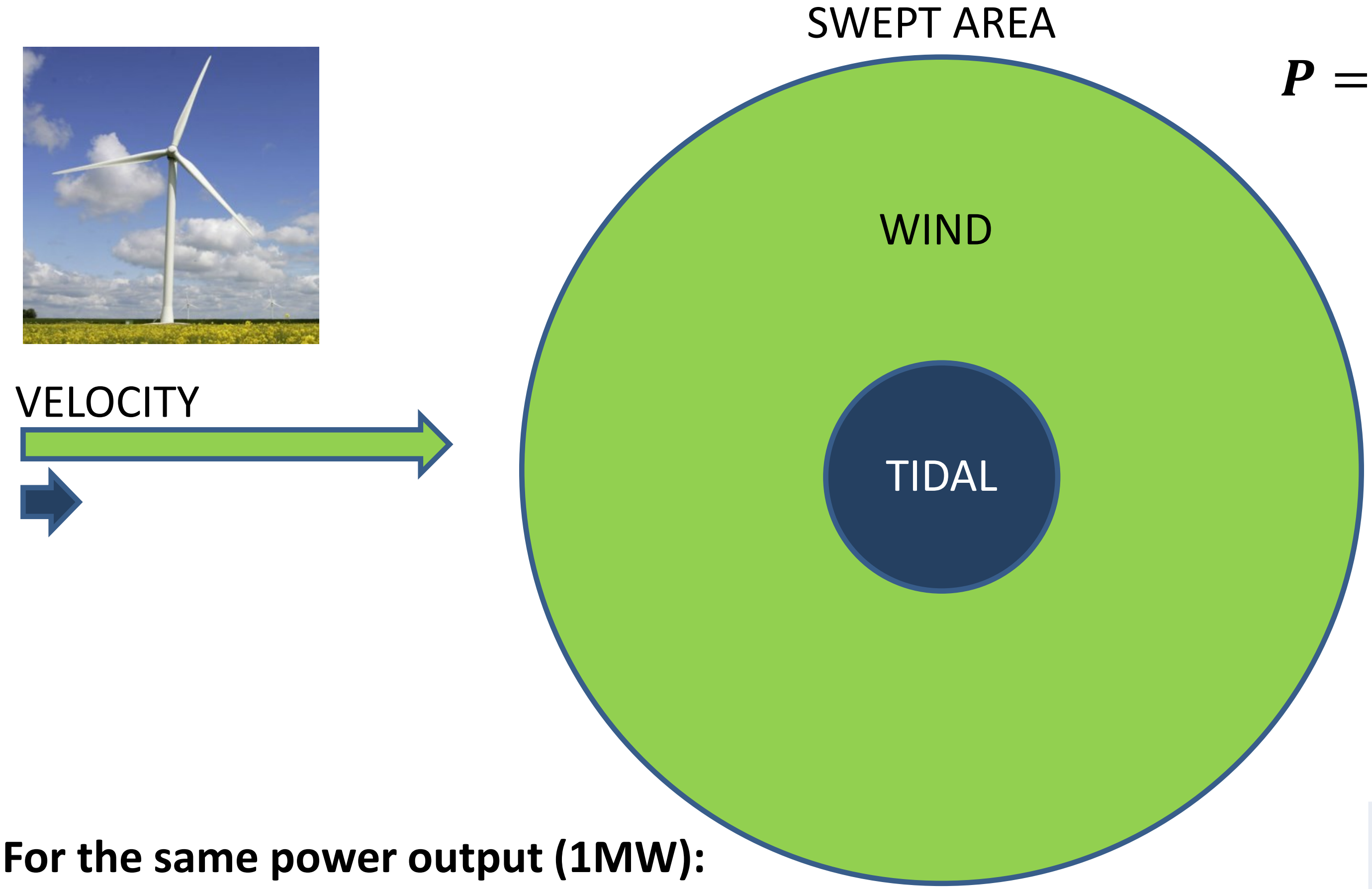
SUSTAINABLE MARINE ENERGY LTD, SCHOTTEL: GRAND PASSAGE, 280 kW

TOTAL ENERGY YIELD BEFORE 2017: >14 GWh, TOTAL ENERGY YIELD BETWEEN 2017-2019: >25 GWh

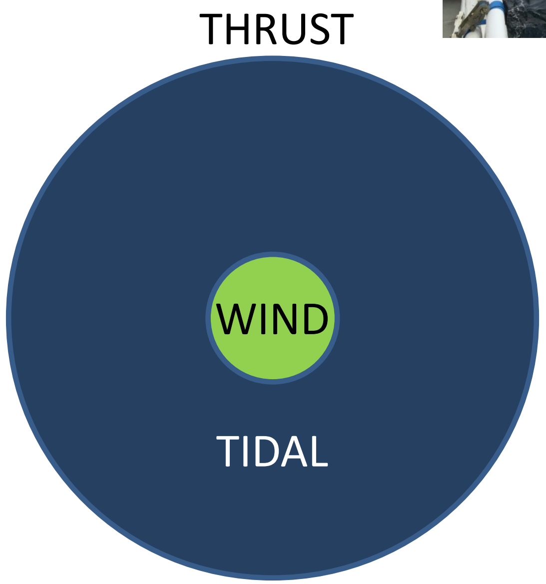




Wind Blades vs Tidal Blades (Equivalent Power)



$$P = \frac{1}{2}\, C_p\, \rho\, A\, v^3$$



For the same power output (1MW):

- **Tidal blades are approximately 4 times shorter than wind blades**
- **Tidal thrust is 4 times greater than for wind turbines (MN)**
- **Both systems react roughly the same moment (MNm)**

	Length (m)	Diameter (m)	Density (kg/m³)	Velocity (m/sec)	MW Extracted
Tidal	9.0	19.0	1025.0	2.5	1.0
Wind	32.6	67.3	1.3	10.0	1.0

Composite Tidal Turbine Blades

➢*Orbital Marine Power's 02 Blades*
(20m rotor diameter)

<u>Harsh marine environment</u>

- Blades carry 4x higher thrust loads than wind blades
- Tidal current velocities vary w. depth & location
- Erosion & wear (sand, ice, floating trees)
- Waves and storms (esp. for floating turbines)

<u>Blades require high strength (static and fatigue)</u>

- Thick composite sections (can be over 100mm)
- Glass fibre or carbon fibre ?
- Water ingress degradation important
- Can be very costly to repair, underwater access

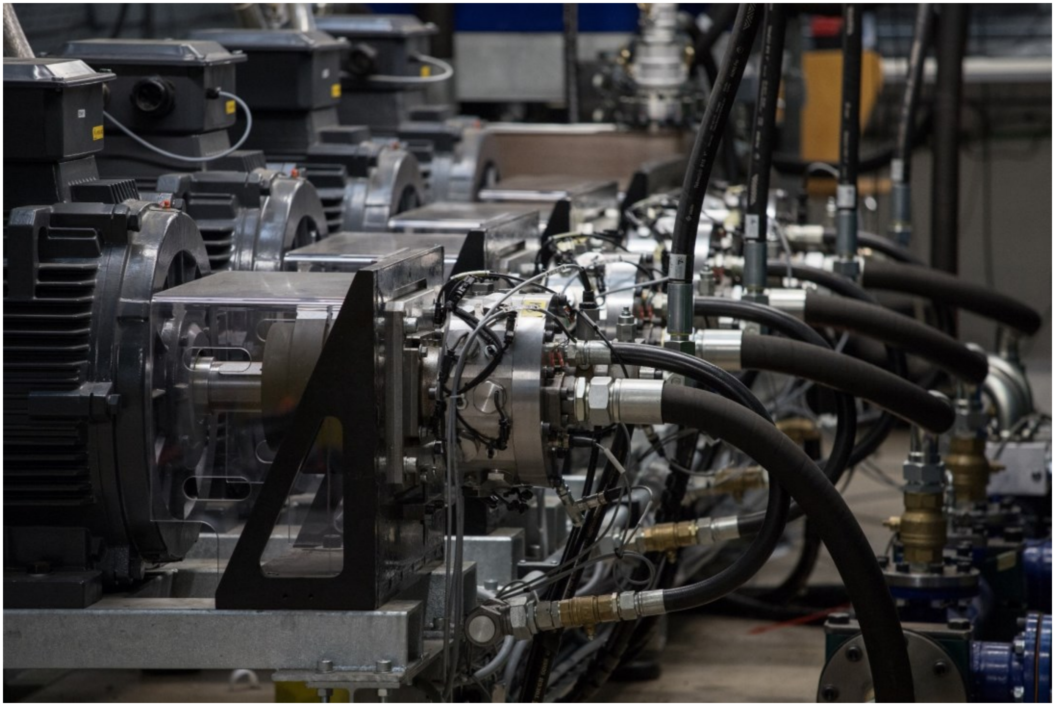
<u>Blades must be fatigue-tested hydraulically (v. slow)</u>

- Wind blades have low fundamental frequency & can be tested resonantly using motor/offset weight
- Tidal blades are more like aircraft wing boxes (stiff)

Regenerative Hydraulics - the USP

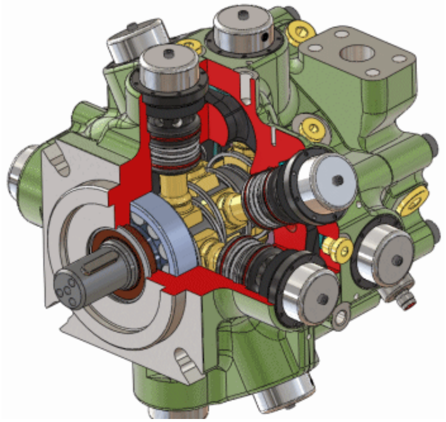
8 x
FASTER

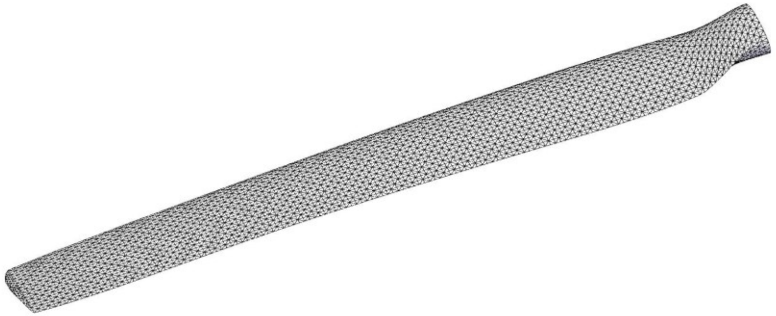
75%
Efficient



Energy transfer from kinetic to potential via hydraulic circuit

Using Digital Displacement Technology® from Danfoss.
https://digitaldisplacement.com/





FastBlade Tidal Blade Fatigue Test Facility- (Opened 2022)

Blades up to 13m long

Control room, teaching space and client rooms

Universal adaptor plate

Strong Wall

800 lpm regenerative pumping (under grating)

Hydraulic cylinders

12m x 2m loading area

Box beam reaction plane

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Fife Council

babcock™

Fife College

Scottish Enterprise

University of Strathclyde Glasgow

ARROL GIBB Innovation Campus

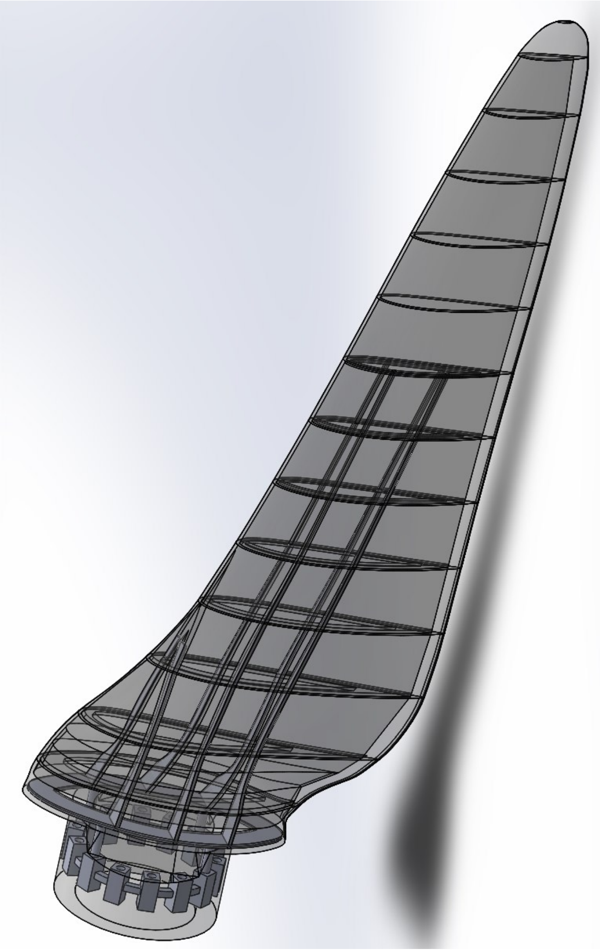
FASTBLADE Location

Fatigue Testing at 1Hz – 500 kW Tidal Blade

First structural test centre in the world to have regenerative hydraulics - proving to have c. 65% efficiency, compared to standard hydraulic system efficiency of c. 25%

Design and Manufacture of QED Tidal Rotor Blade

- New design
  - 2.8m in length
  - Skin- mainly CFRP with GFRP inner and outer layers
  - CFRP-GFRP-steel internal stiffeners
  - Stiffener thickness- 10mm steel+1mm GFRP+10mm CFRP
  - Skin thickness- 15mm
  - Monolithic fabrication using pre-pregs
  - Weight approx. 193 kg (200 kg weight saving)



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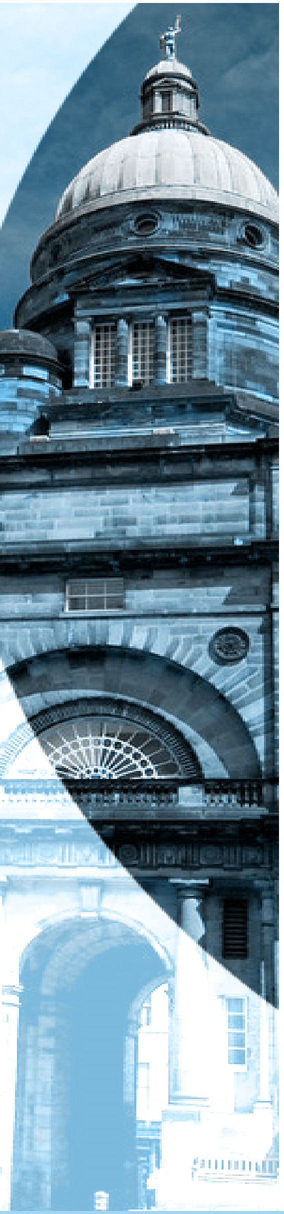
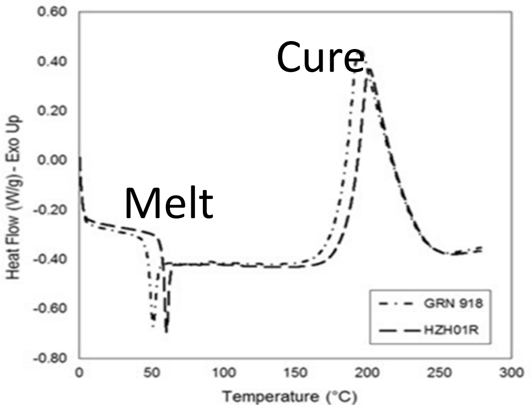
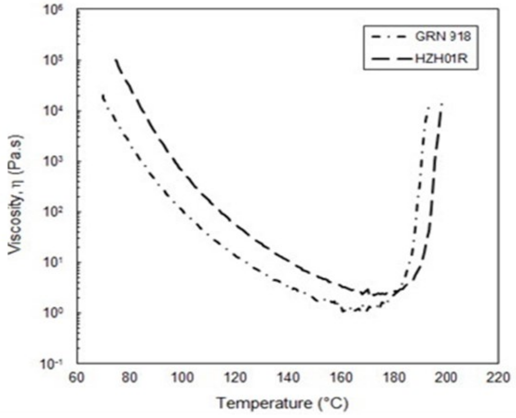


Powder Based Epoxy Composites

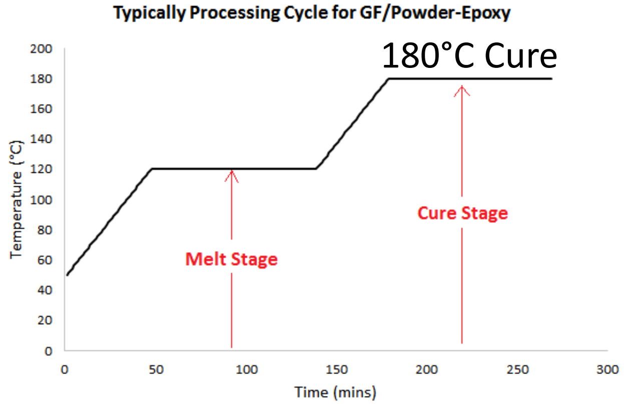
- Powder melts on fibres (towpreg) at low temperatures (c. 50˚C), then curing of the epoxy occurs at higher temperatures (heat activation).
- Low minimal viscosity (low molecular weight) during melting phase: easy to infiltrate and wet out thick fibre beds.
- Can also possess very high toughness (depends on formulation)*
- Low curing exotherm reducing the risk of thermal runaway in thick sections.
- Good potential for very thick composite sections (large wind blade sections - also tidal blades).



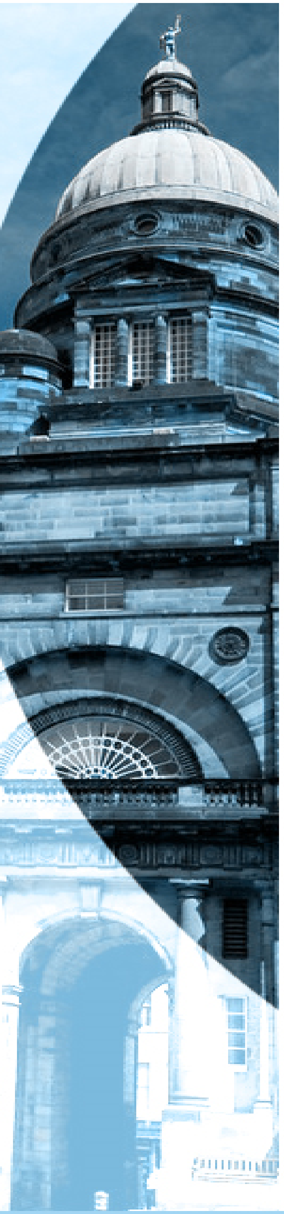
Differential Scanning Calorimetry



Parallel-plate Rheometry



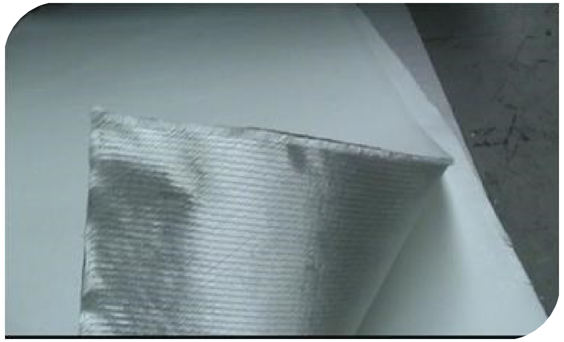
Floreani, C. et al., "Mixed-Mode Interlaminar Fracture Toughness of Glass and Carbon Fibre Powder Epoxy Composites—For Design of Wind and Tidal Turbine Blades", Materials, 2021, https://doi.org/10.3390/ma14092103



Powder Based Epoxy Composites

- Commodity materials
  - Widely available, relatively inexpensive
- Little or no VOCs produced during process
- Some unique processing advantages:
  - Low viscosity and low exotherm
  - Through-thickness infiltration – no dry spots
  - Heat-activated curing; melt and remelt without initiating significant cure
  - Consolidation of uncured structures, followed by assembly and co-curing

Epoxy resin system	Total enthalpy of reaction (J/g)
Powder coating	78.0 – 137.7
Powder coating	38.9
Powder coating	44.5
Resin transfer moulding (RTM)	441.0 – 469.0
Resin film infusion (RFI)	435.4
Infusion	425.3
Prepreg	560.0



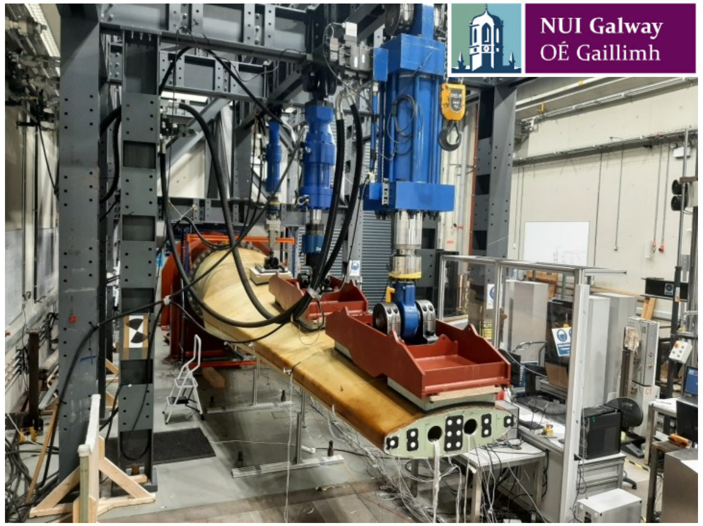
Wind turbine blade hub co-cured from 3 preconsolidated glass fabric/ powder epoxy semi-preg pieces

Maguire et al., Materials and Design, 2018. https://doi.org/10.1016/j.matdes.2017.10.068

Powder Based Epoxy Composite Blades

13.0m wind turbine blades manufactured by ÉireComposites (Ireland)

Electrically-heated ceramic mould tooling



Powder epoxy 5.0m tidal turbine blade under static testing at NUI Galway

Swiss CMT – Industrial Partner

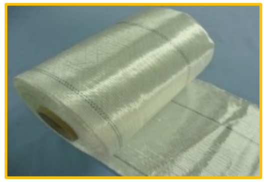
cmt
swiss composite materials & technologies

unique technologies for sustainable composite applications

reinforcements


natural fibers (e.g. Flax)


recycled fibers


virgin fibers (GF, CF, AF…)

+

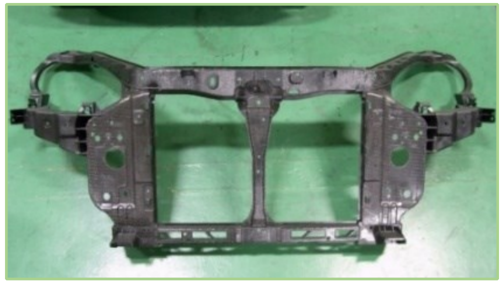
resins

Powder Resins
- innovative
- solvent-free
- none-hazardous
- infinite shelf life

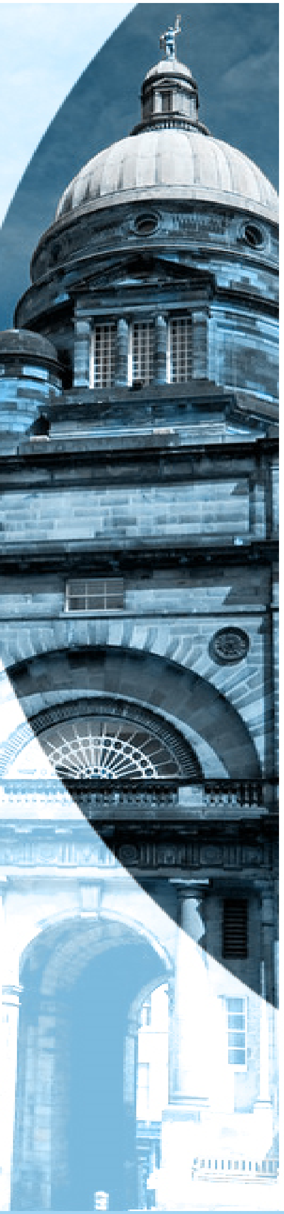
BIO Resins
- bio sourced or bio-degradable
- innovative
- customized

=

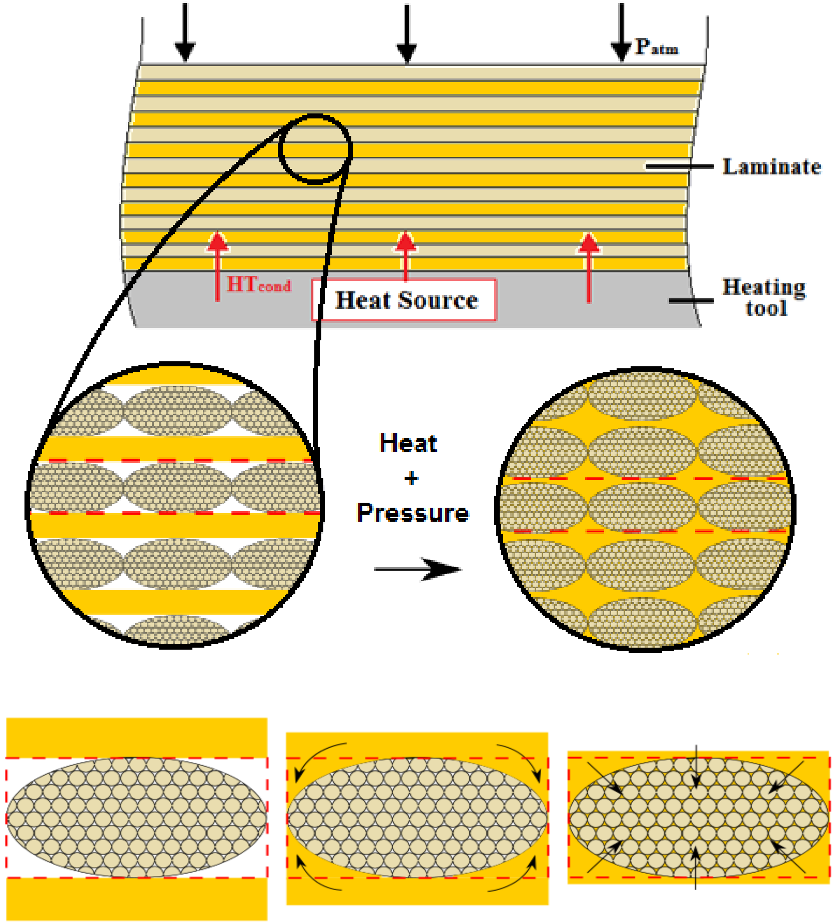


applications in…
construction, building, mobility, automotive, industry, renewables…



Thick Section Consolidation – 1D Modelling



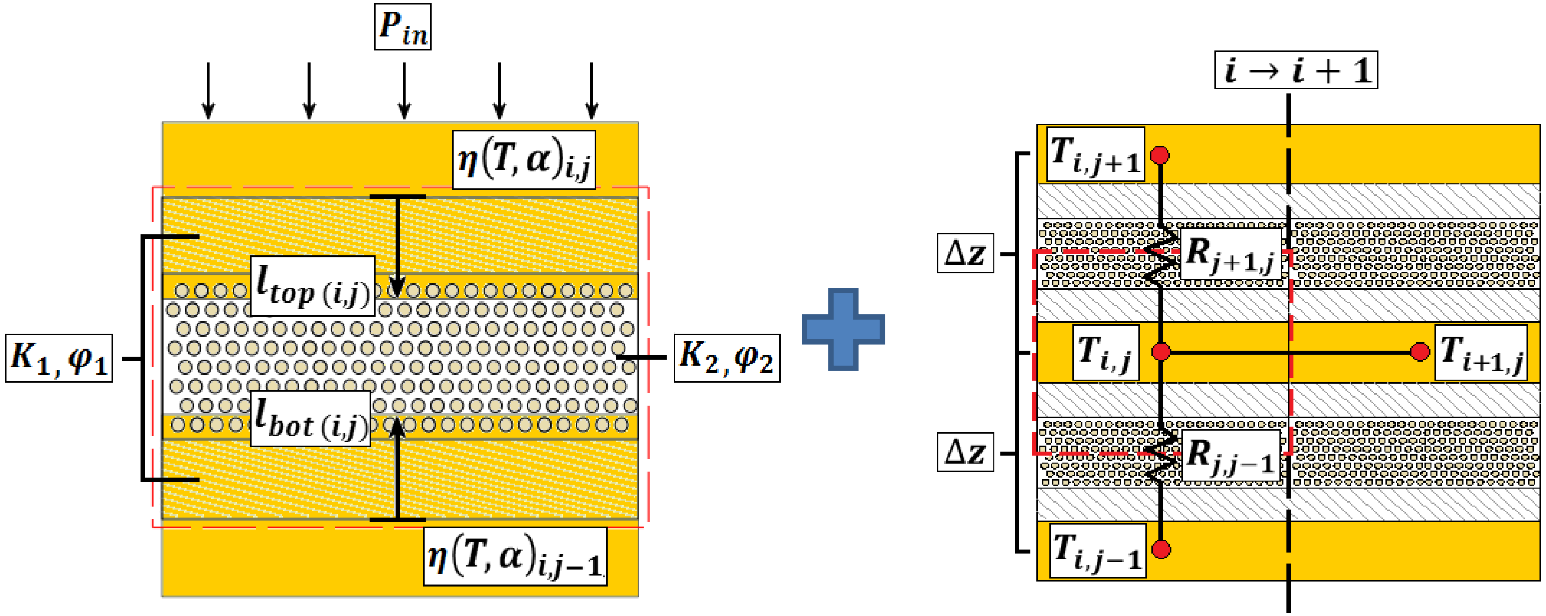
1. Inter-tow flow 2. Intra-tow flow

Dr. James Maguire
PhD 2019

Fundamental consolidation assumption is that inter-tow flow occurs before intra-tow flow – due to mismatch in permeabilities

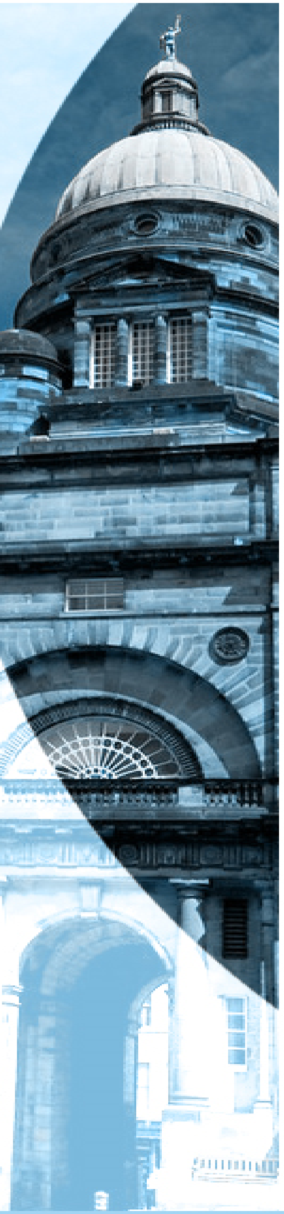
Thick Section Consolidation – 1D Modelling

- **Coupled resin flow model and heat transfer model (with Centre for Composite Materials, University of Delaware)**



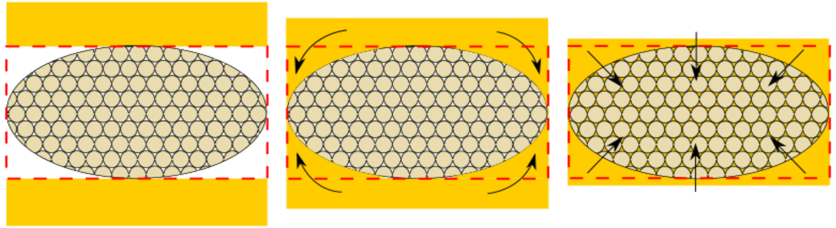
Flow Model **Heat Transfer Model**

Maguire et al., Part I, Composites Part A, 2020. https://doi.org/10.1016/j.compositesa.2020.105969



Thick Section Consolidation – 1D Modelling

Non-isothermal resin flow – Darcy's Law



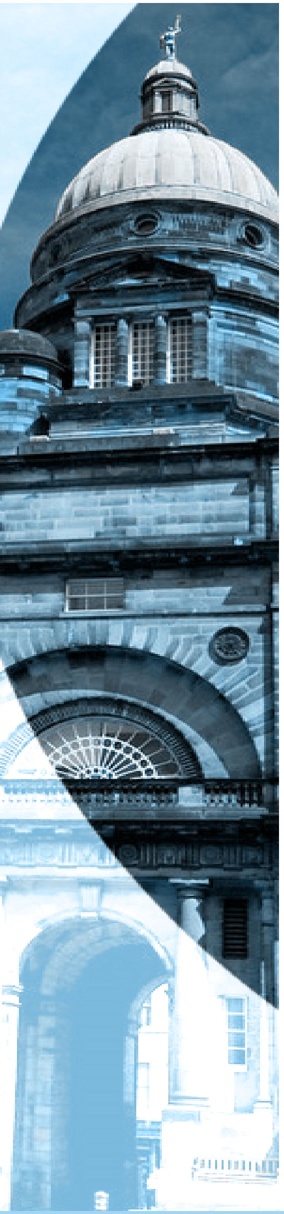
- **Inter-tow flow:**

$$\frac{dl}{dt} = \frac{K_1}{\varphi_1 \eta(T,\alpha)} \frac{P_{in}}{l} \quad , \qquad l < L_1$$

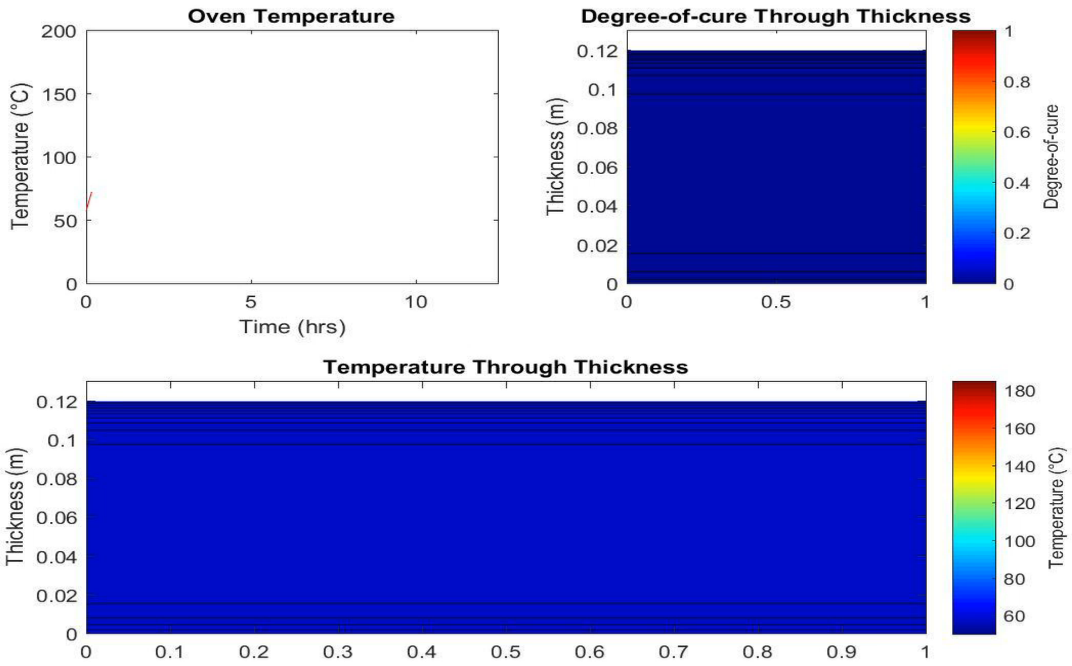
- **Intra-tow flow:**

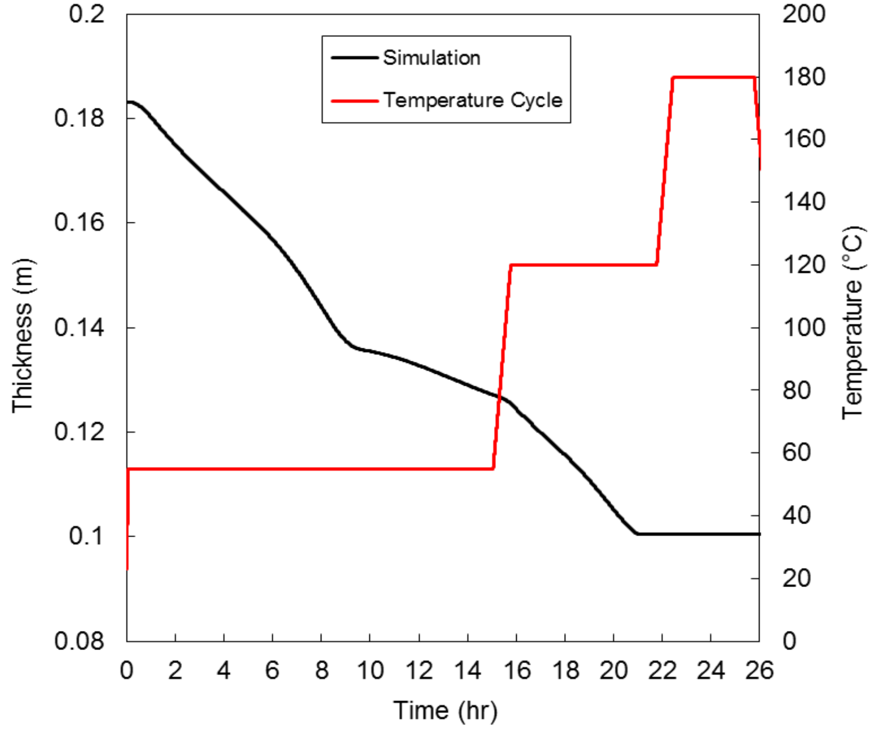
$$\frac{dl}{dt} = \frac{K_2}{\varphi_2 \eta(T,\alpha)} \cdot \frac{K_1 P_{in}}{K_2 L_1 + K_1 (l - L_1)} \quad , \qquad l \geq L_1$$

Maguire et al., Part I, Composites Part A, 2020. https://doi.org/10.1016/j.compositesa.2020.105969

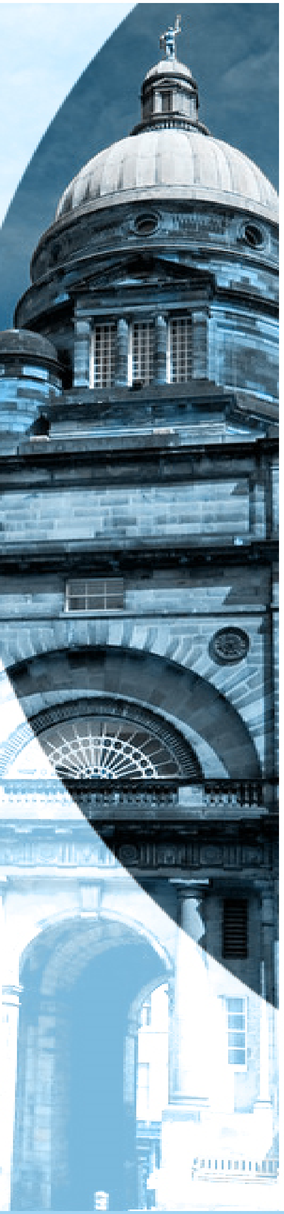


Thick Section Consolidation – 1D Modelling of 100-Ply Laminate



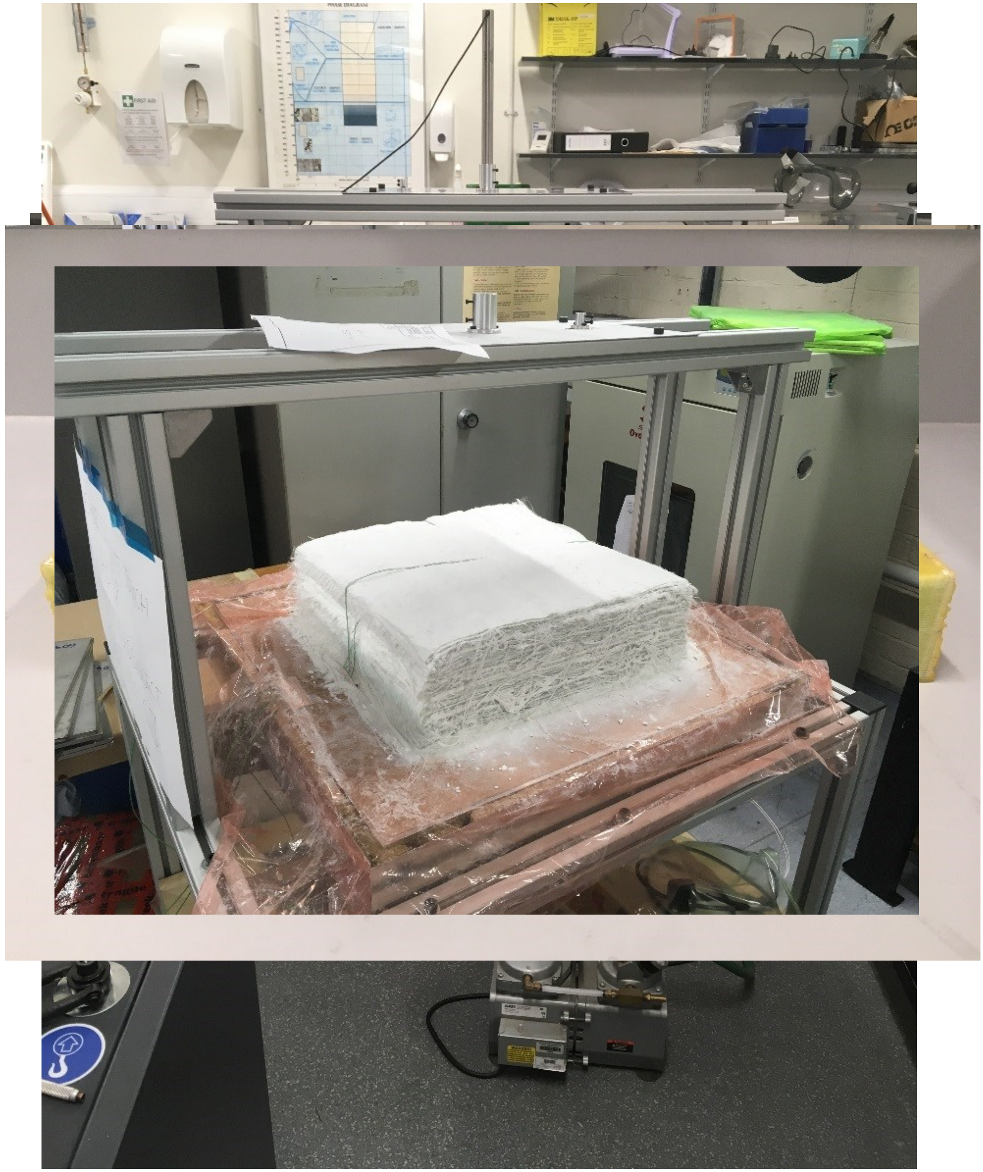


Maguire et al., Part I, Composites Part A, 2020. https://doi.org/10.1016/j.compositesa.2020.105969

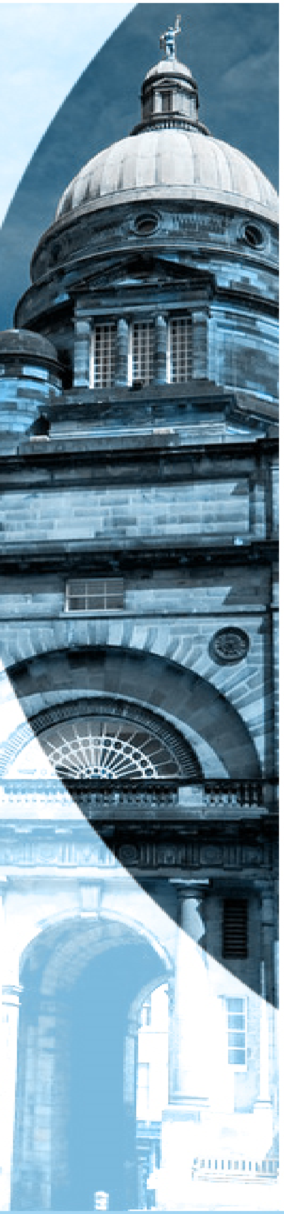


Experimental Validation

- **Three laminates manufactured**
  - **2 laminates with raw powder and UD glass-fibre**
  - **1 laminate with triaxial glass-fibre semi-preg**
- **Thickness change was measured by an LVDT**
  - **The LVDT was fixed on a supporting frame**
- **Temperature was measured in-plane and out-of-plane using K-type thermocouples**



Maguire et al., Part II, Composites Part A, 2020.
https://doi.org/10.1016/j.compositesa.2020.105970

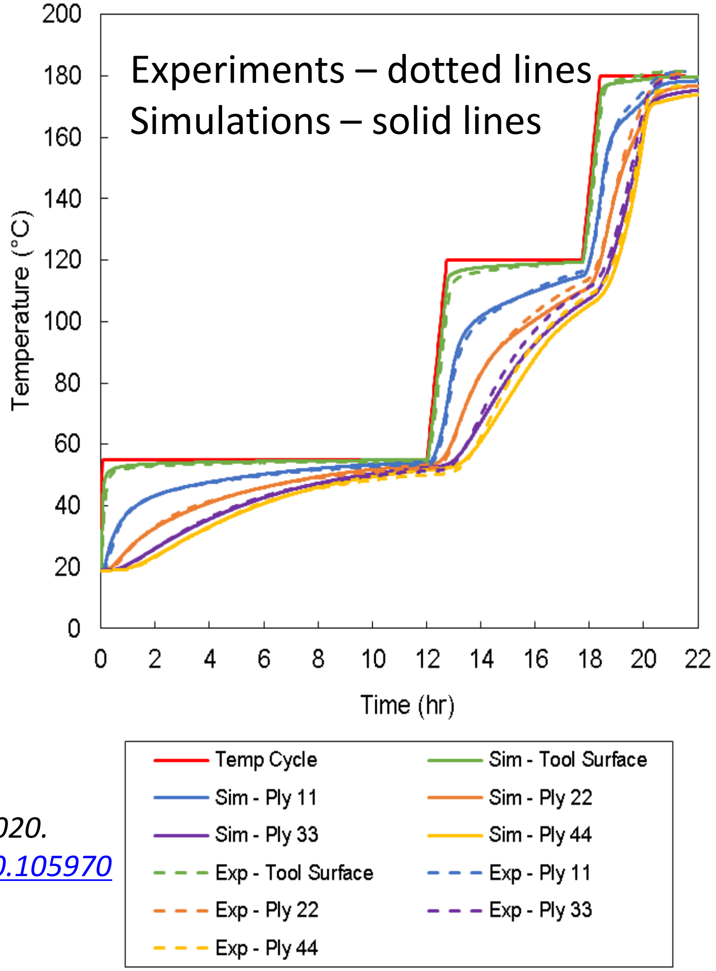


Experimental Validation

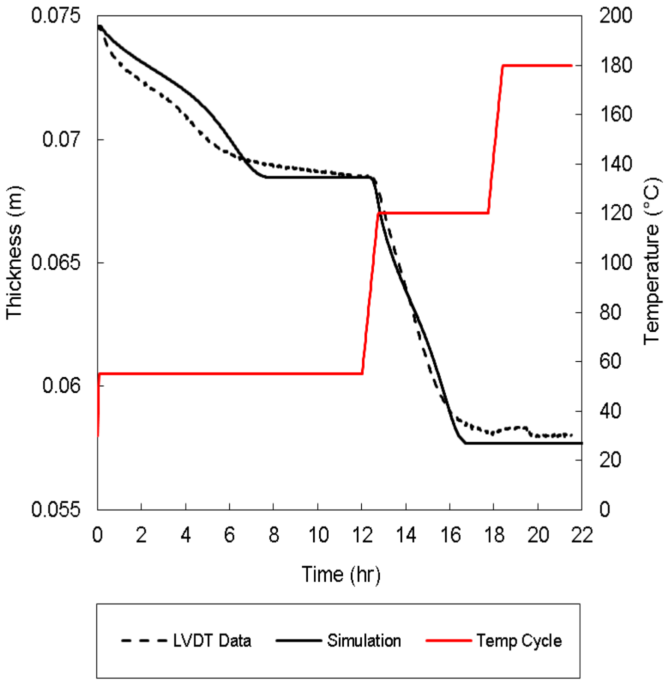
Agreement between experiments and simulations:

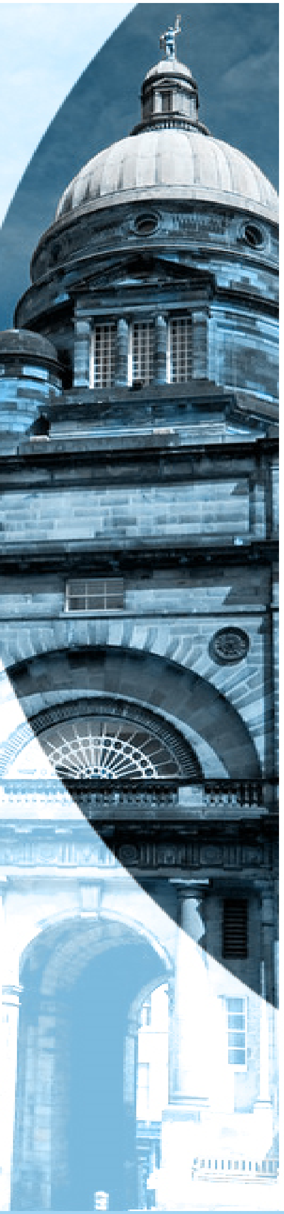
Thermal: Excellent

Consolidation: Good

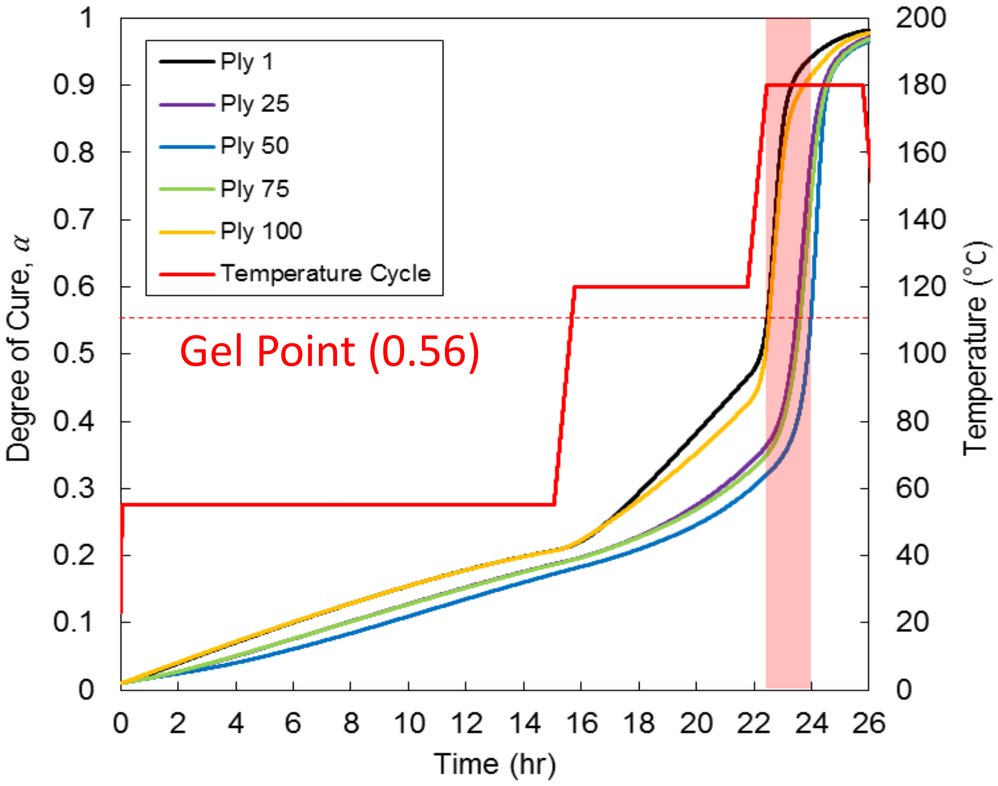


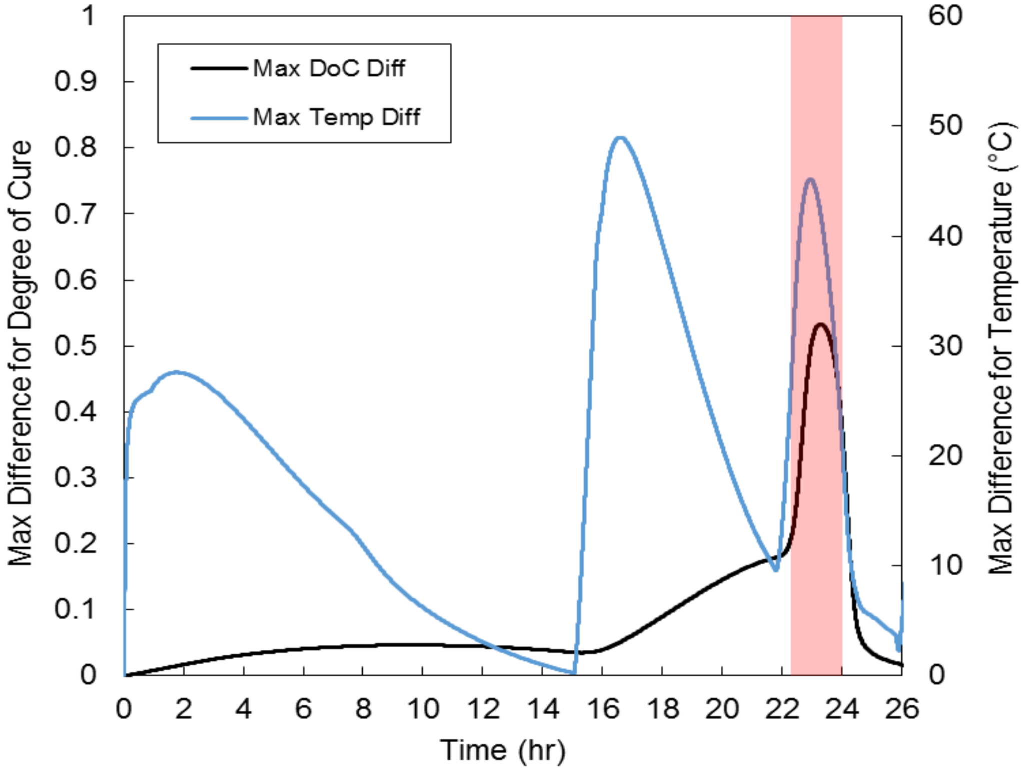
Maguire et al., Part II, Composites Part A, 2020.
https://doi.org/10.1016/j.compositesa.2020.105970





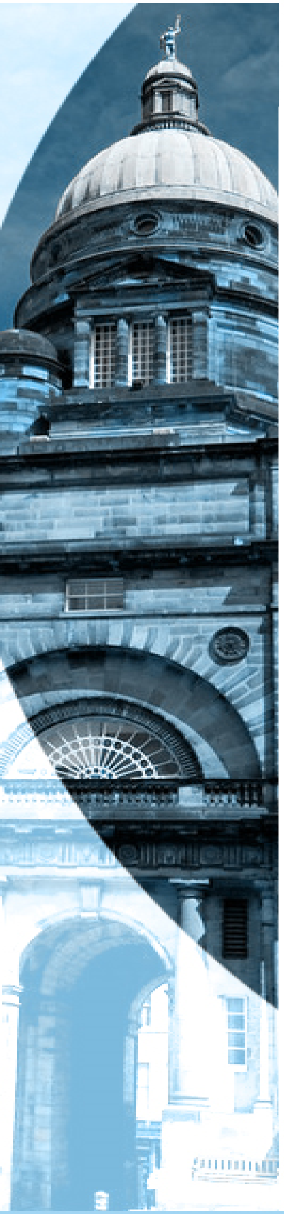
Thick-Section Simulation – Standard Cycle



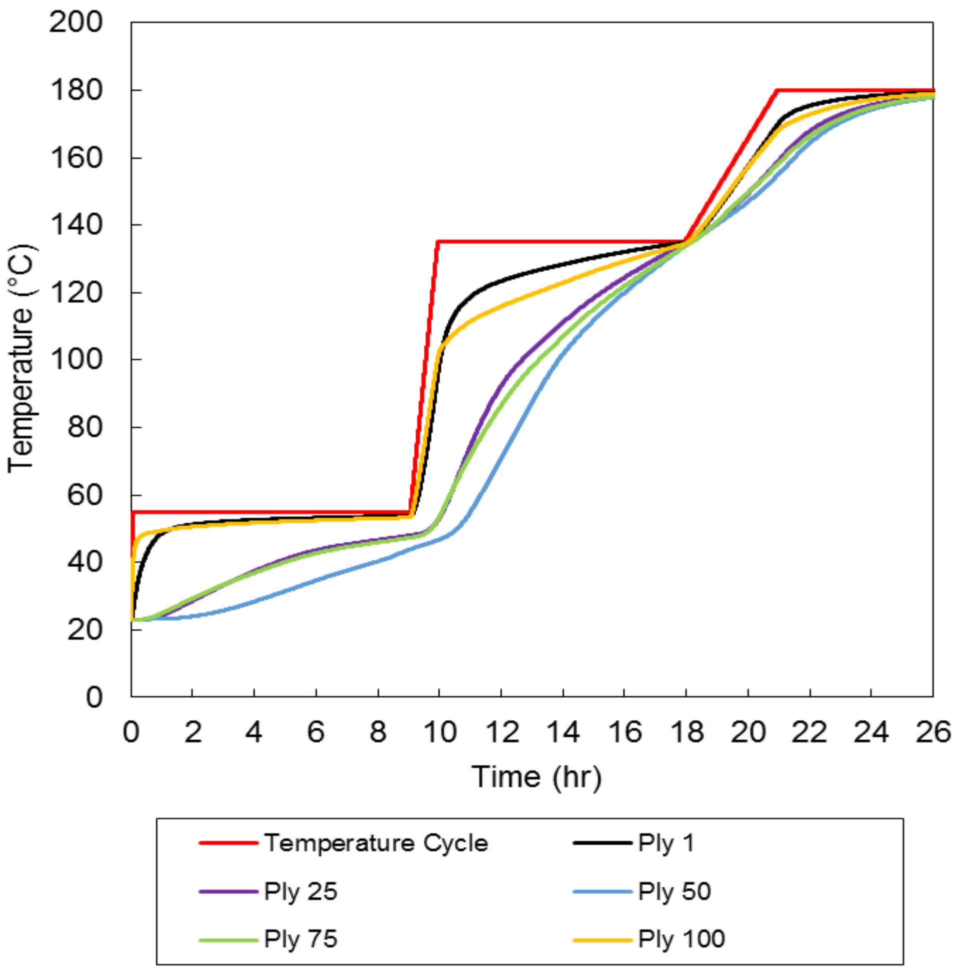


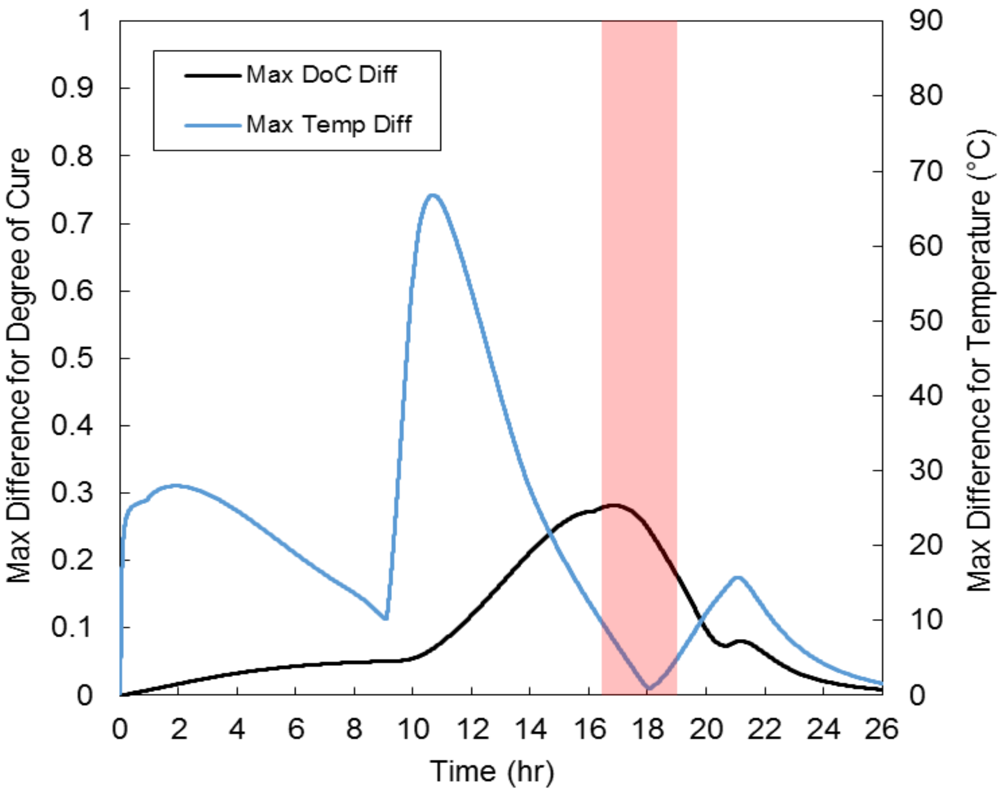
High thermal gradients and cure gradients still present through the thickness, especially around the gel point of the material.

Maguire et al., Part II, Composites Part A, 2020, https://doi.org/10.1016/j.compositesa.2020.105970



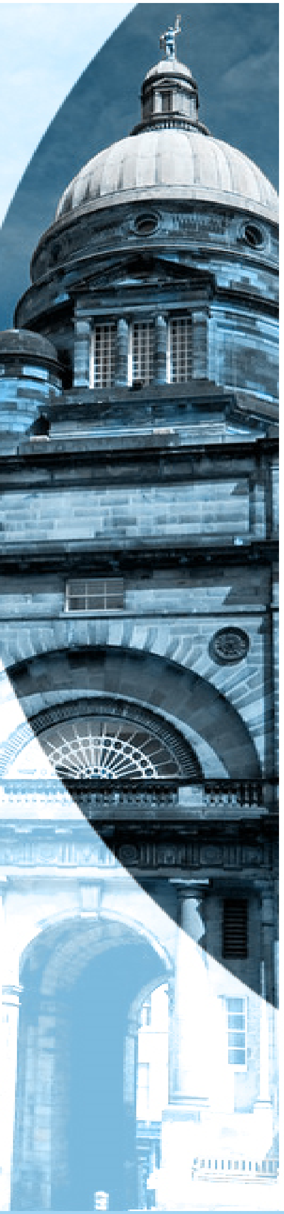
Thick-Section Simulation – Modified Thermal Cycle





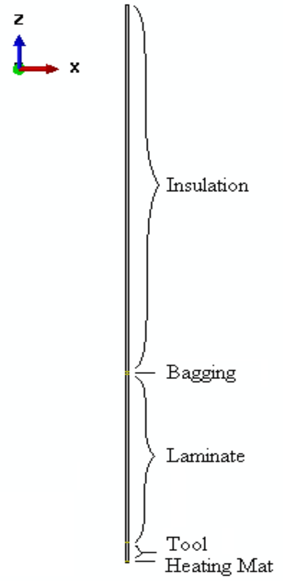
By modifying the process cycle, we can reduce these peaks significantly during the gelation period. Reduced drying time and increased ramp time.

Maguire et al., Part II, Composites Part A, 2020, https://doi.org/10.1016/j.compositesa.2020.105970

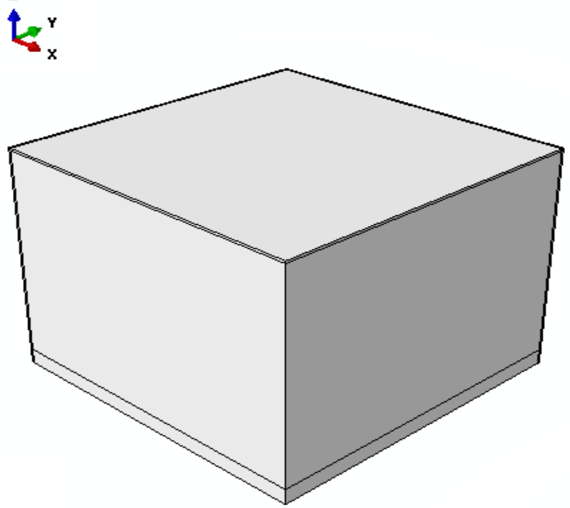


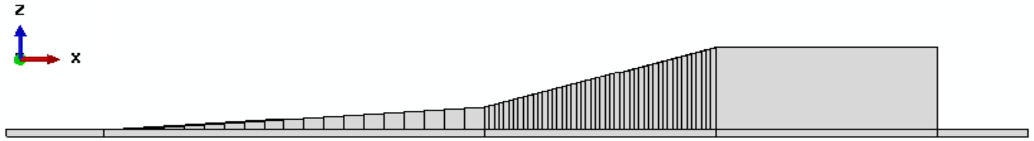
2.5D FEA Modelling of Consolidation of WT Blade Sections*

*1D Flow, but 3D heat transfer

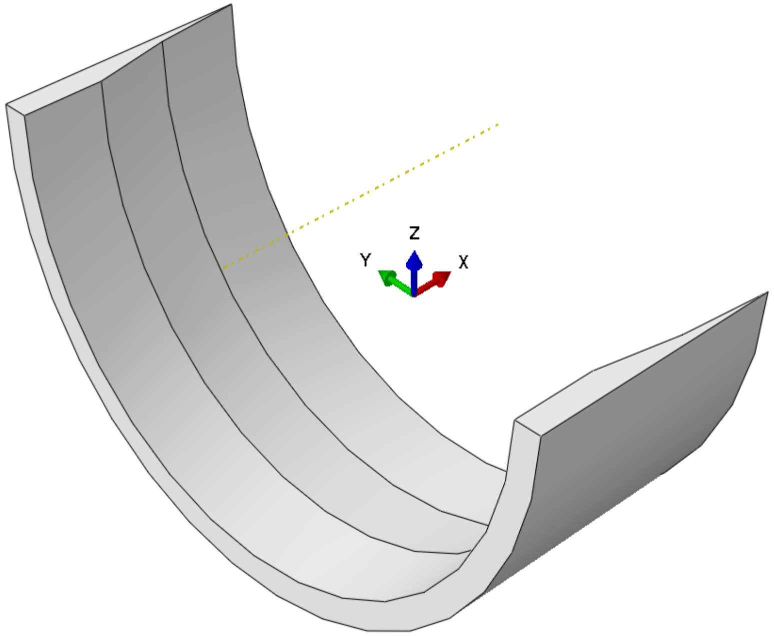


1D Flow "cube"



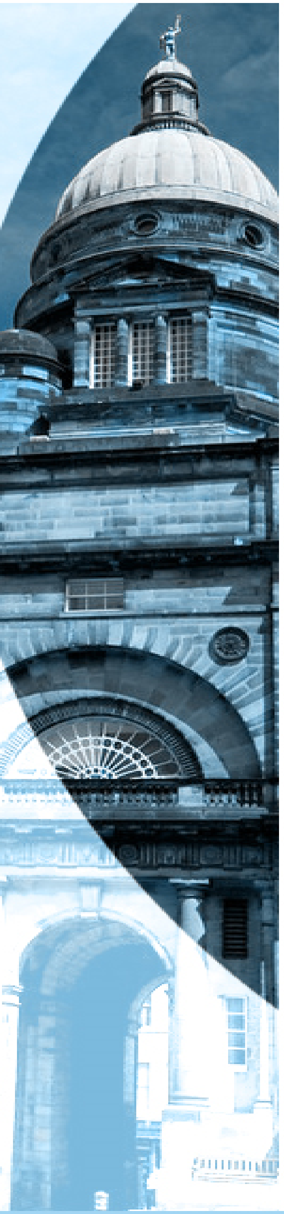


Section of blade root



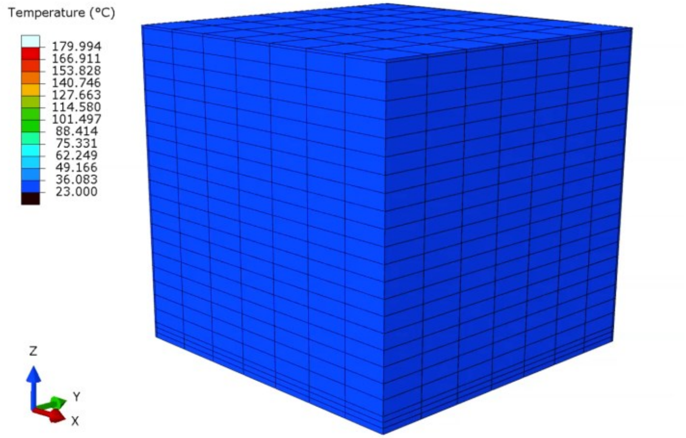
Root segment of WT blade with tapering thickness

Maguire et al., *Composites Part A*, *2022.* *https://doi.org/10.1016/j.compositesa.2022.107073*

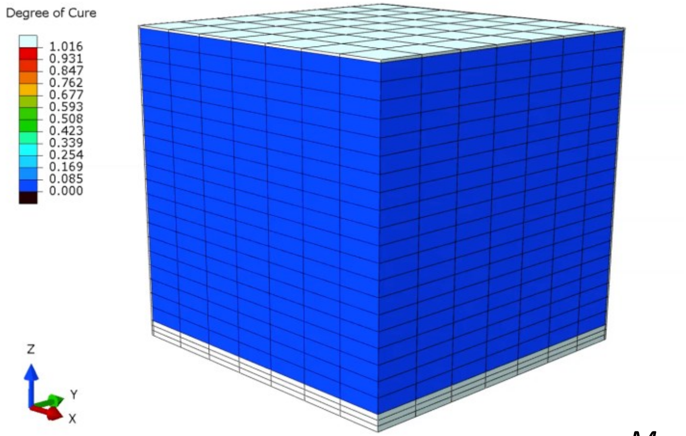


Thick Section Consolidation – 2.5D Modelling

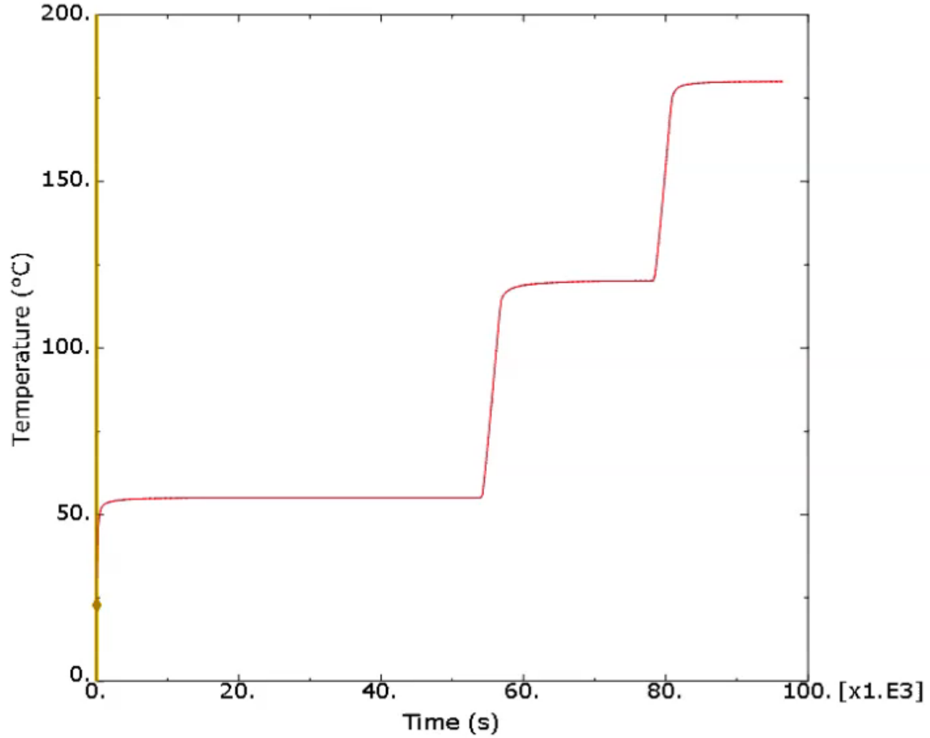
Temp.



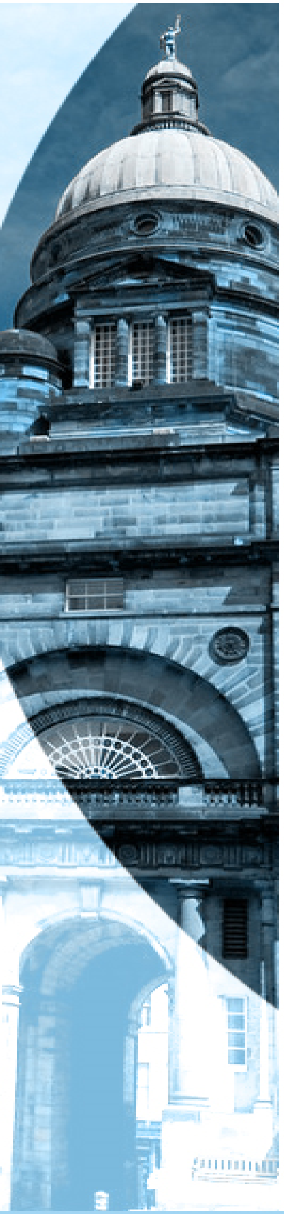
Degree of Cure



Convection Boundary Conditions on all surfaces (oven processing)

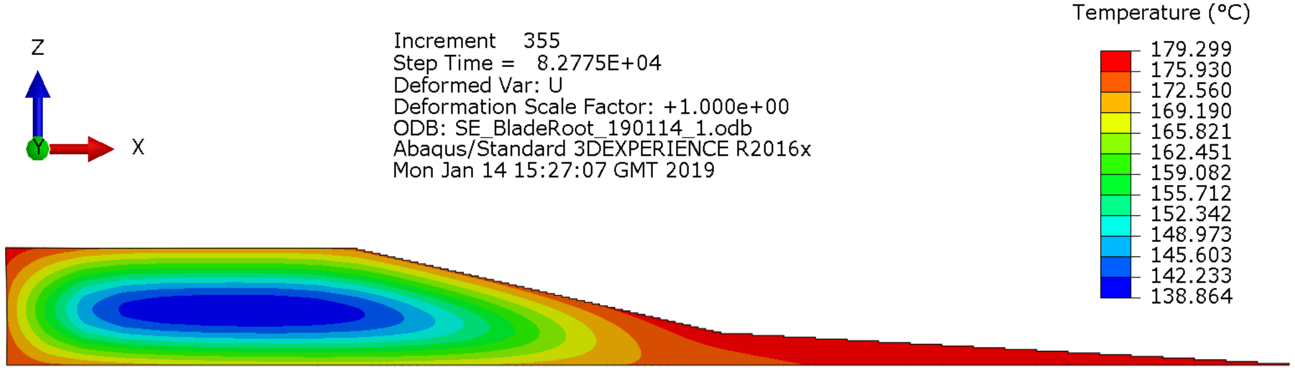


Maguire et al., Composites Part A, 2022. https://doi.org/10.1016/j.compositesa.2022.107073



2.5D Process Modelling by FEA (Standard Cycle)

Temp.

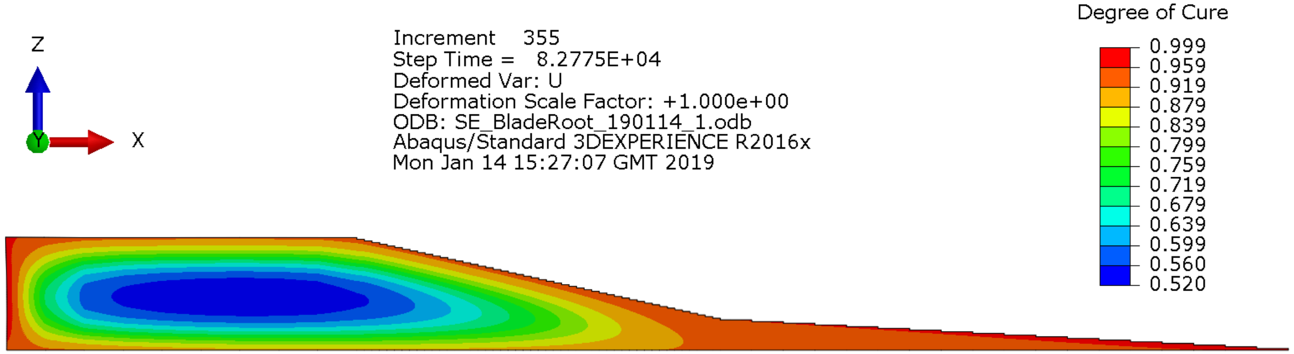


```
Increment    355
Step Time =   8.2775E+04
Deformed Var: U
Deformation Scale Factor: +1.000e+00
ODB: SE_BladeRoot_190114_1.odb
Abaqus/Standard 3DEXPERIENCE R2016x
Mon Jan 14 15:27:07 GMT 2019
```

Max Temp Diff.
> 40°C

Centre of thick section is just reaching gel-point when outer layers and thin section have fully cured

Degree of Cure



```
Increment    355
Step Time =   8.2775E+04
Deformed Var: U
Deformation Scale Factor: +1.000e+00
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Abaqus/Standard 3DEXPERIENCE R2016x
Mon Jan 14 15:27:07 GMT 2019
```
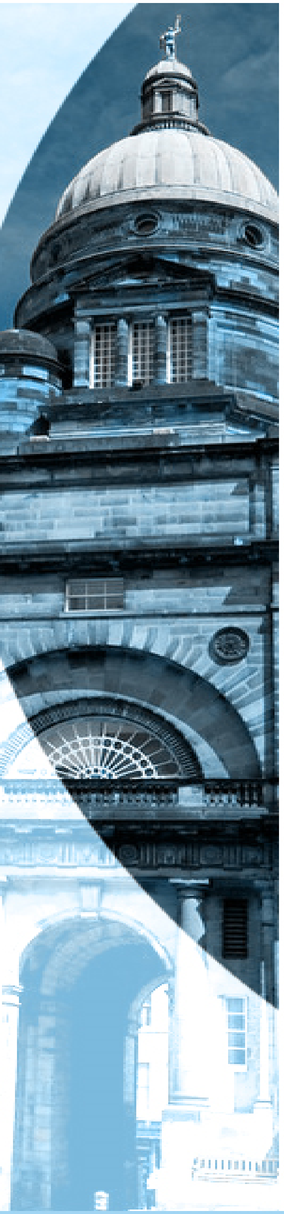
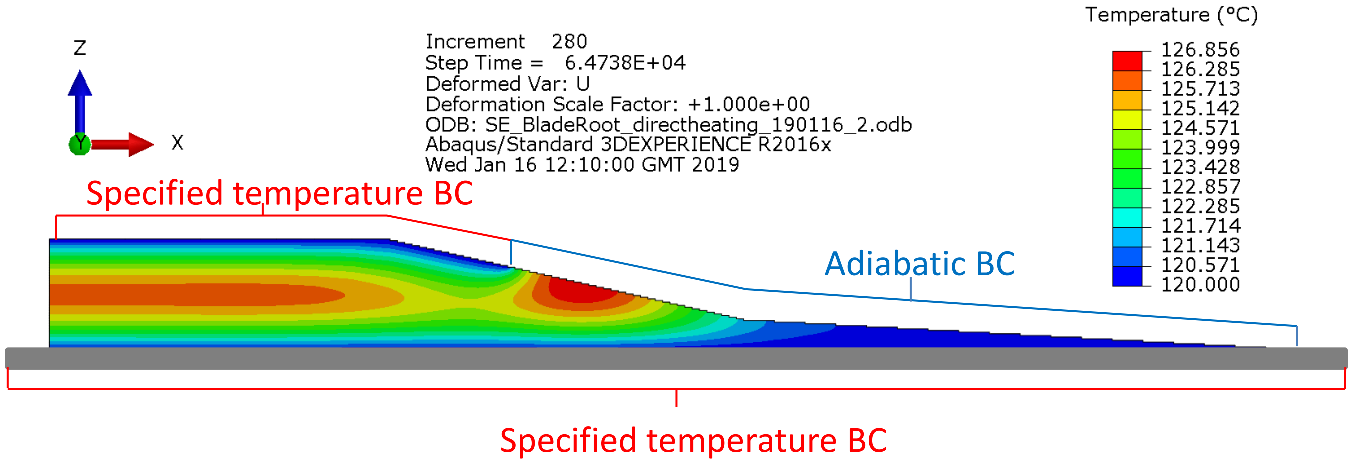

Max DOC Diff.
=0.48

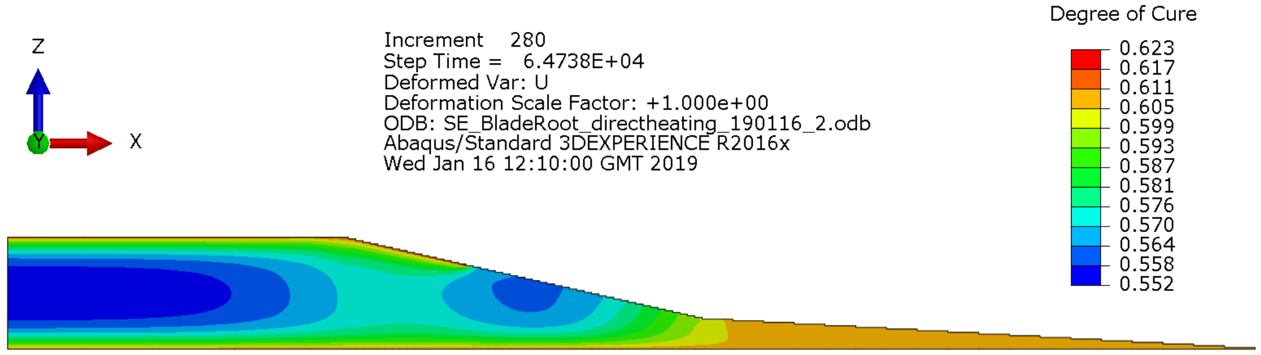


2.5D Process Modelling by FEA (Modified Cycle & BCs)

Temp.



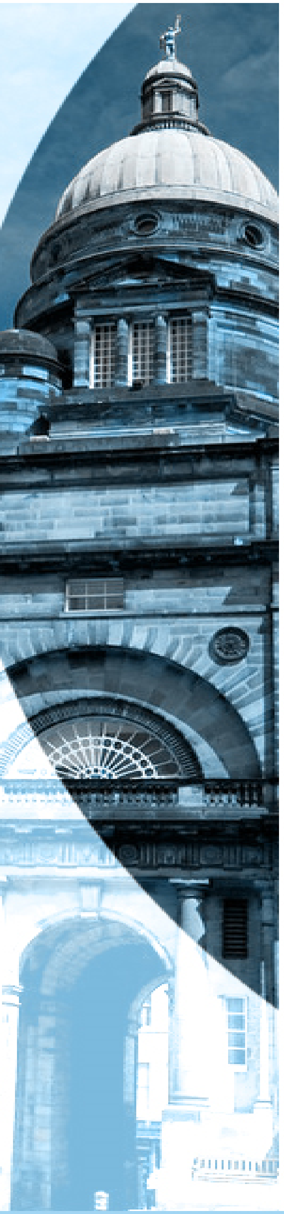
Degree of Cure



Max Temp Diff. < 7°C

Modified cycle and two-sided heating used to reduce gradients. Local heating can be used for thick sections, thus saving energy and cost.

Max DOC Diff. = 0.07



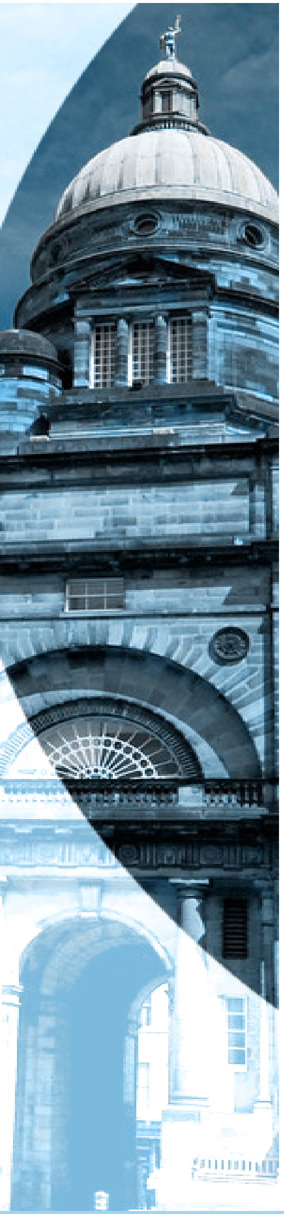
Outlook for Powder Epoxy Composites in Tidal Blade Structures

Several Advantages:

- One piece moulding - no gluing of spars to skins → one shot cure, cost savings
- Low exotherm: reduces risks and allows quicker manufacturing, cost reduction.
- Process modelling can reduce temp. and cure gradients.
- Powder and towpreg can be stored in a standard environment and ambient temperature for an extended amount of time.

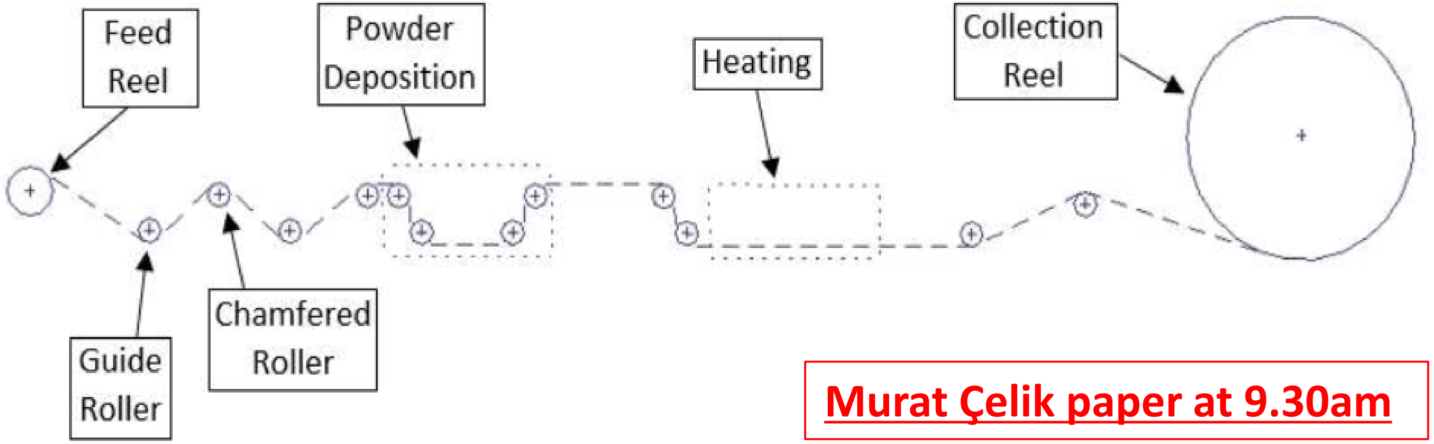
Major Disadvantage:

- Needs elevated cure (c. 180°C) – using ovens or electrically-heated tooling. Large blade manufacturers want lower processing temperatures (as close to room temperature as possible).



CF/Epoxy Towpreg Manufacturing

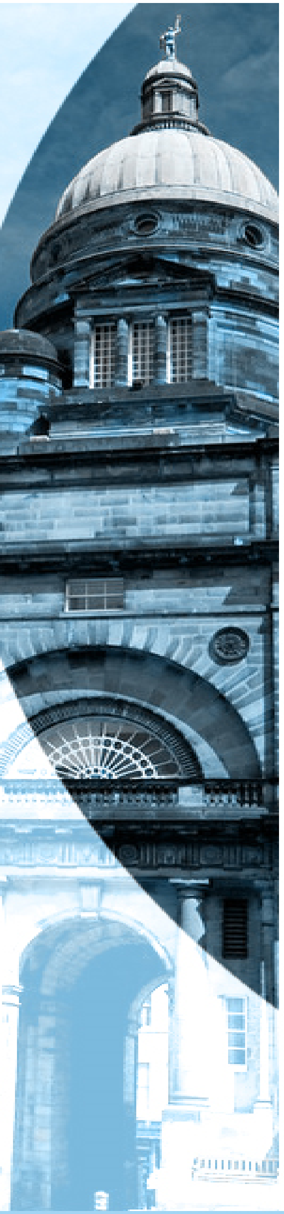
- **Towpreg manufacturing, then composite processing (AFP robot). Possibility for H_2 tanks, other tape structures.**
- **Tapeline: Dry tow fed through 1) electrostatic powder deposition, then 2) electrical heating for melting of powder into dry tow to produce towpreg.**



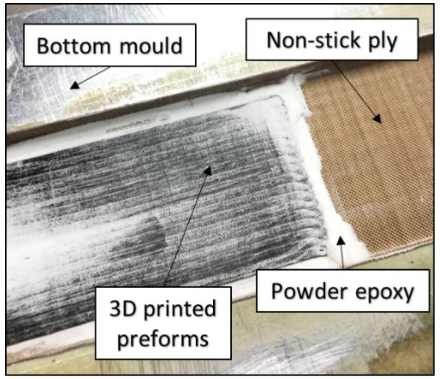
Murat Çelik paper at 9.30am

Robert et al., Composites Part B, 2020, https://doi.org/10.1016/j.compositesb.2020.108443

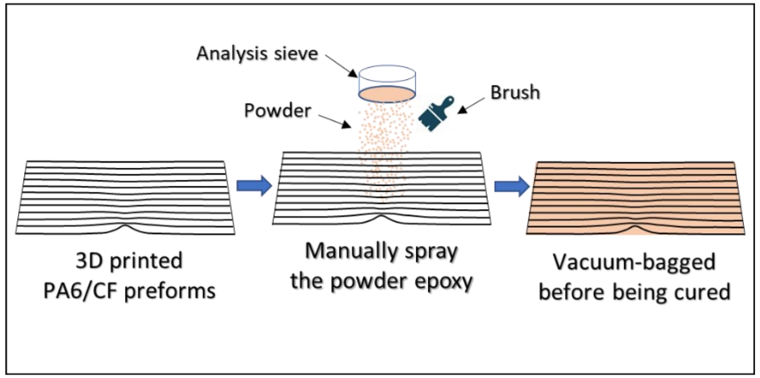
Çelik et al., Composites Part A: Applied Science and Manufacturing, 2023, https://doi.org/10.1016/j.compositesa.2022.107285



CF/Epoxy for “Dual Polymer” 3D Printing (with CF PA-6)

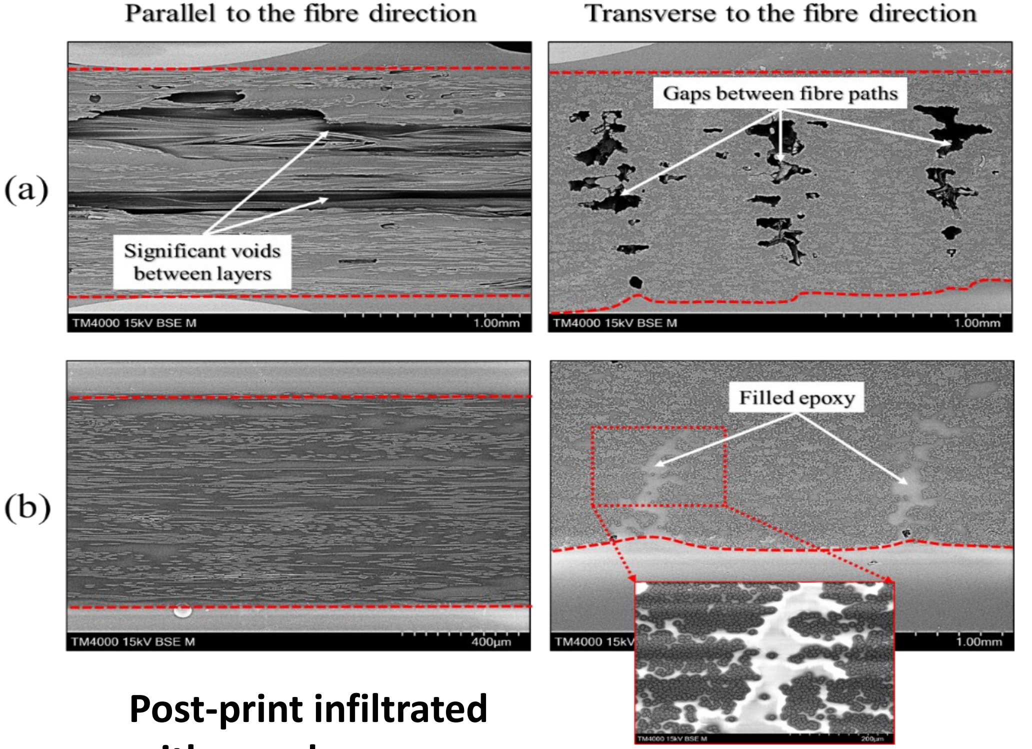


(a)

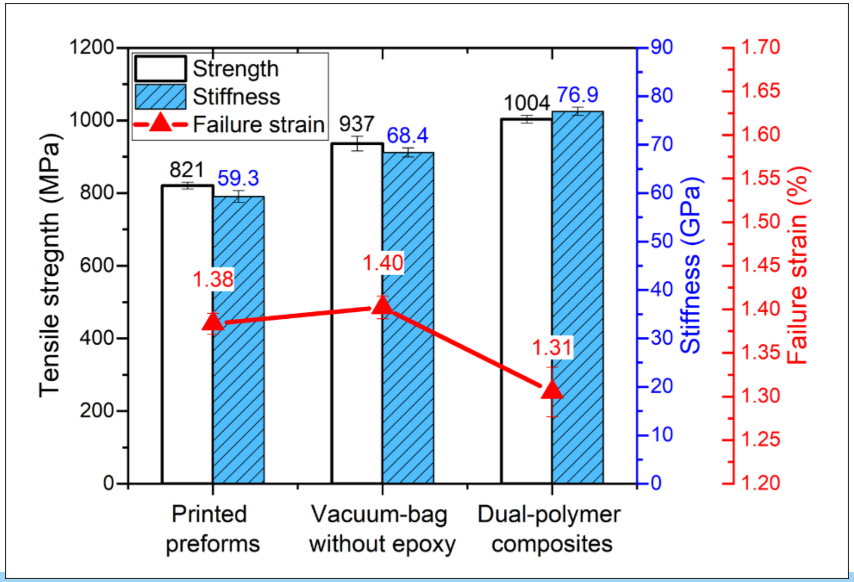


(b)

3D Printed CF/PA-6



Post-print infiltrated with powder epoxy



Jiang, H. et al., Composites Part B: Engineering, 2022
https://doi.org/10.1016/j.compositesb.2022.109687

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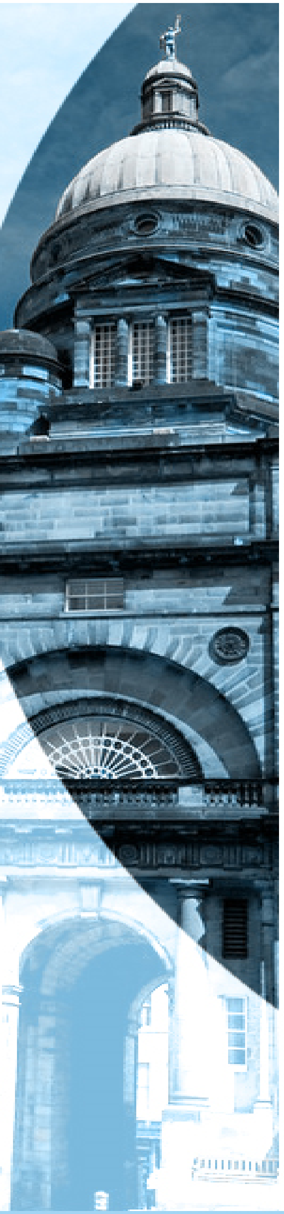
Processing of Composite Materials for Large Structures in Marine Renewable Energy

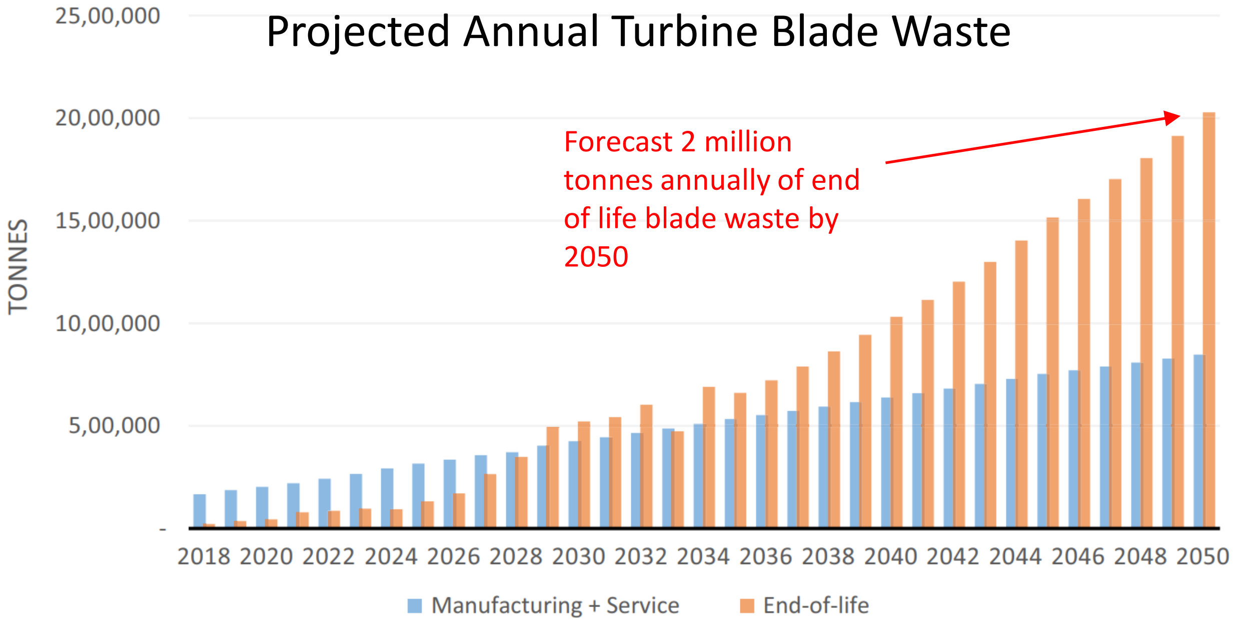
1. Tidal Stream Energy Blades – FastBlade Facility
2. Powder Epoxy Composites
3. Infusible Thermoplastic Composites
4. Future Plans and Conclusions



End of Life Problem for Wind Turbine Blade Composites

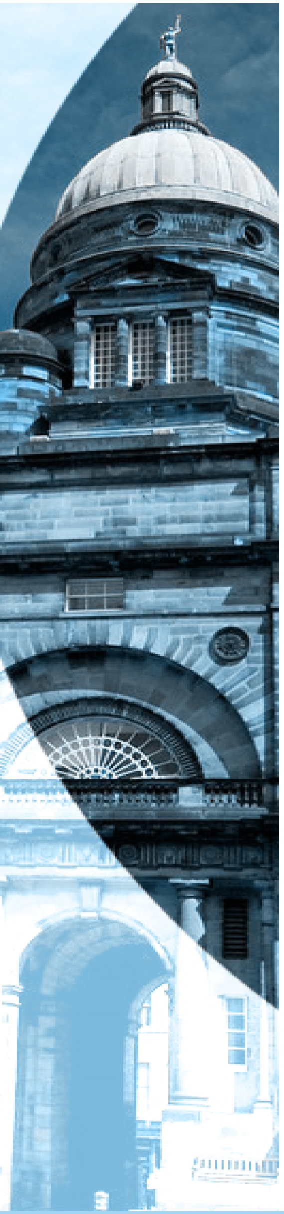
Wind turbine blades are currently manufactured from glass and carbon fibre epoxy, a thermoset polymer composite that cannot be recycled. With increased usage comes increased waste.

We mustn't repeat the same mistakes with tidal turbine blade composites.

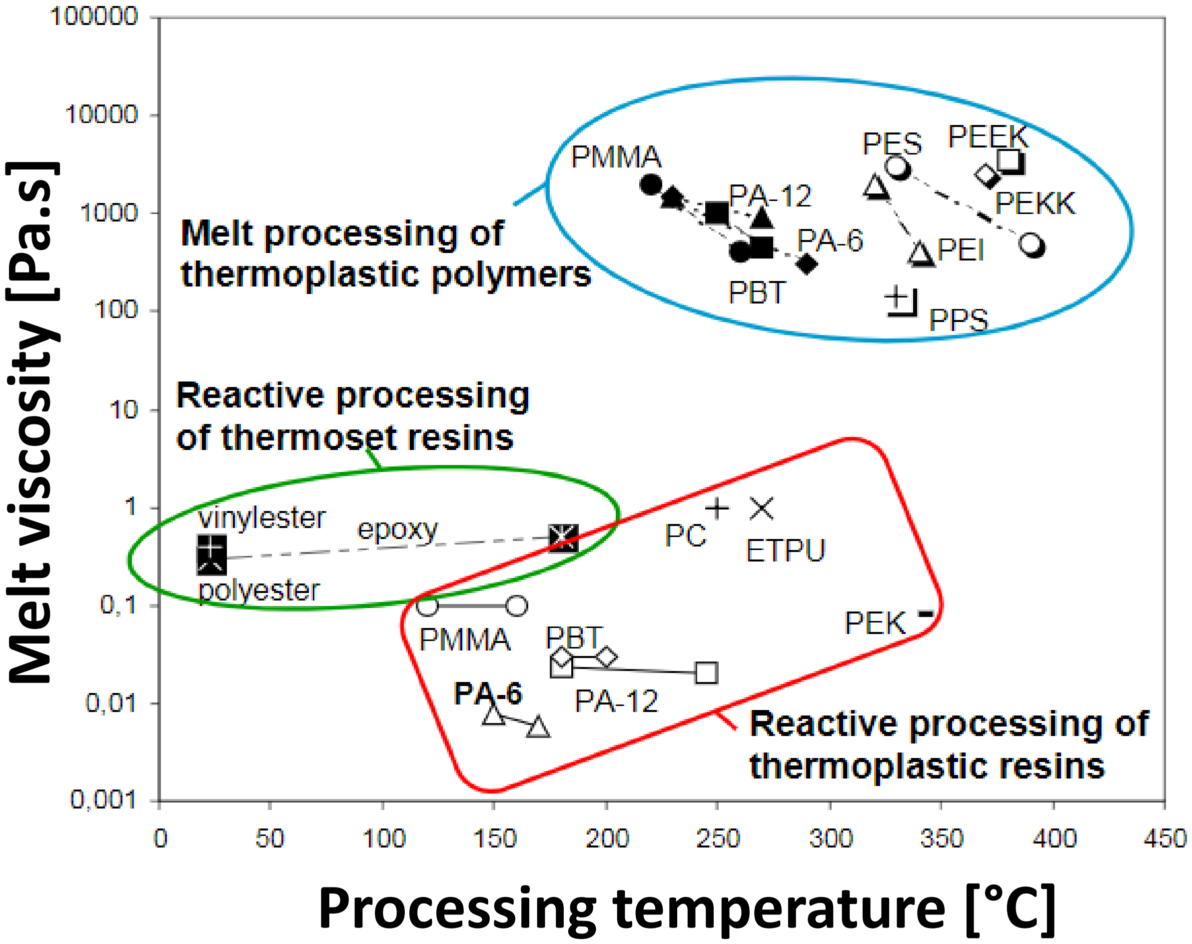


≈60,000 tonnes

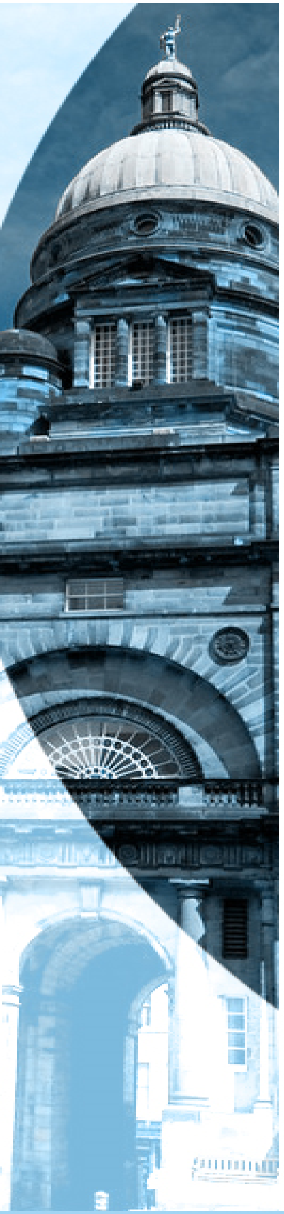
Liu, P. and C. Y. Barlow (2017). "Wind turbine blade waste in 2050." *Waste Management* ***62****: 229-240.*



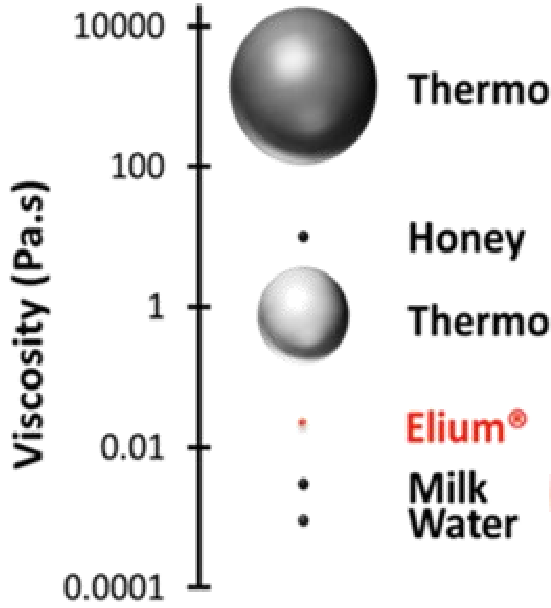
Reactive Processing of TPCs – “Infusible” Thermoplastics



K. Van Rijswijk, H. Bersee, “Thermoplastic composite wind turbine blades,” TU Delft, 2007



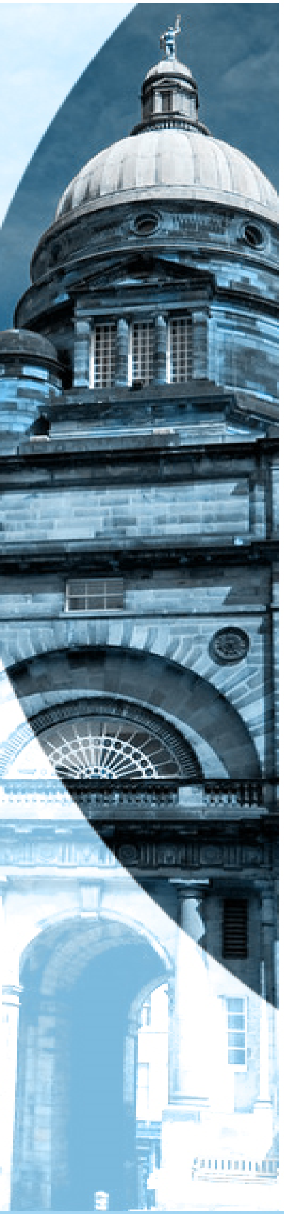
Liquid Thermoplastic (TP) Resin Technology



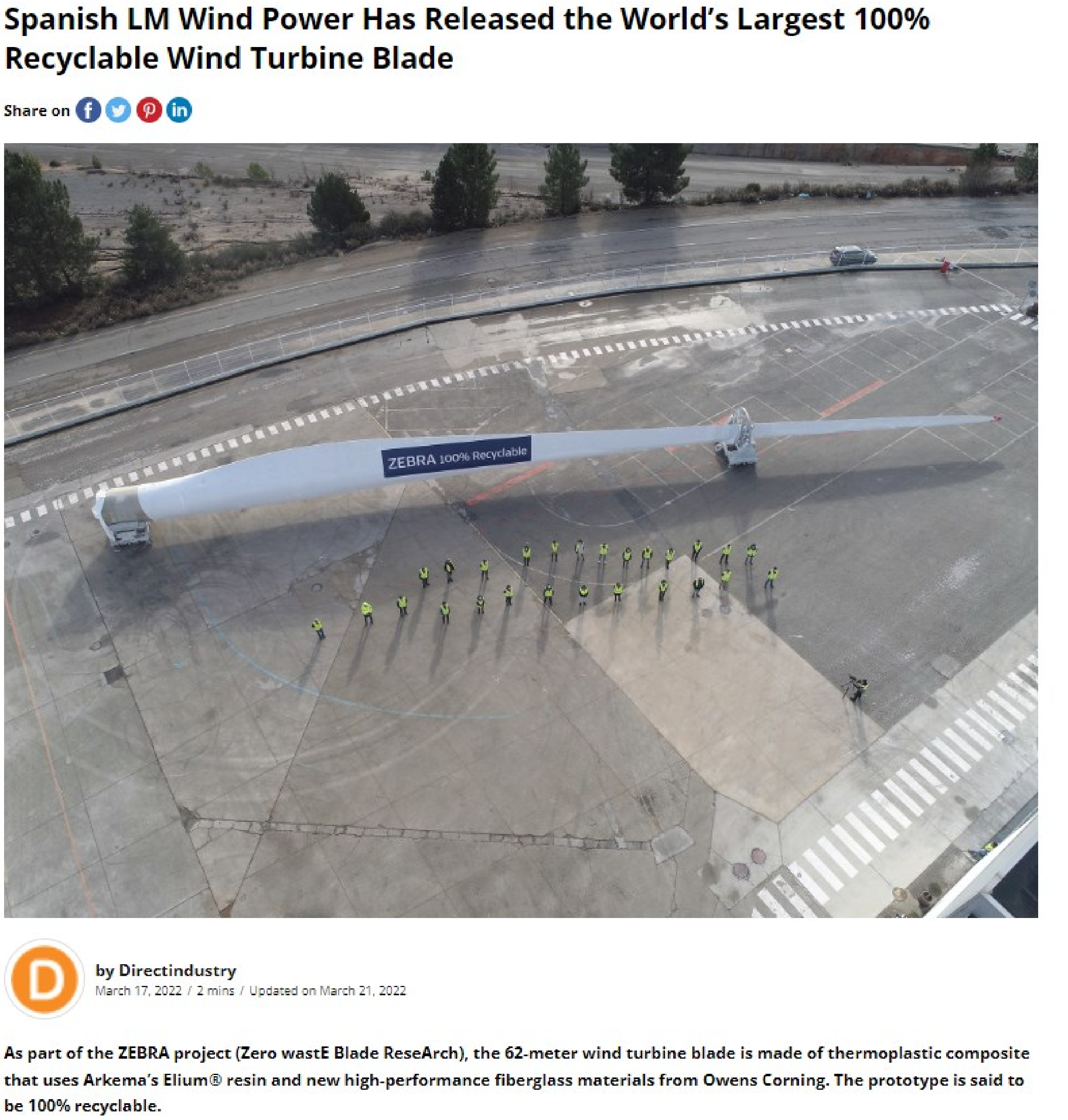
Advantages of Elium®:

- Reactive TP resin based on acrylic technology
- Low-viscosity (100-200 mPa.s)
- Suited to vacuum-assisted resin transfer moulding (VaRTM) and resin transfer moulding (RTM)
- Low-cost: ~£18 per kg

Acrylic is an amorphous TP, but can be alloyed with other TPs to improve solvent resistance



LM Wind Power Unveil 62m Thermoplastic Wind Blade (March 2022)

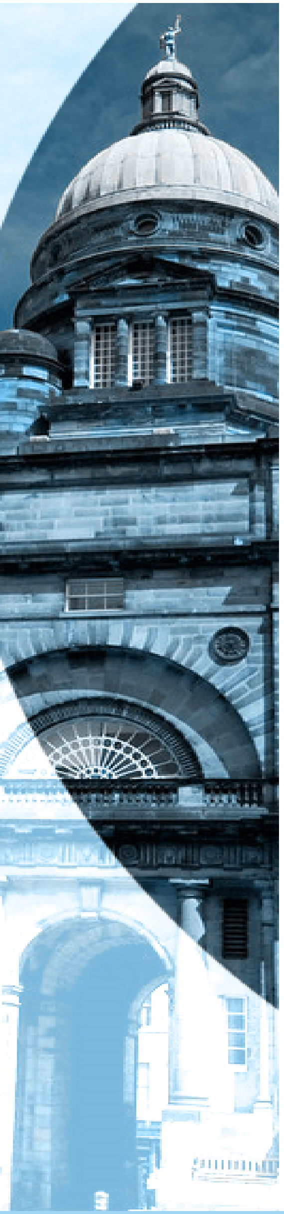


Spanish LM Wind Power Has Released the World's Largest 100% Recyclable Wind Turbine Blade

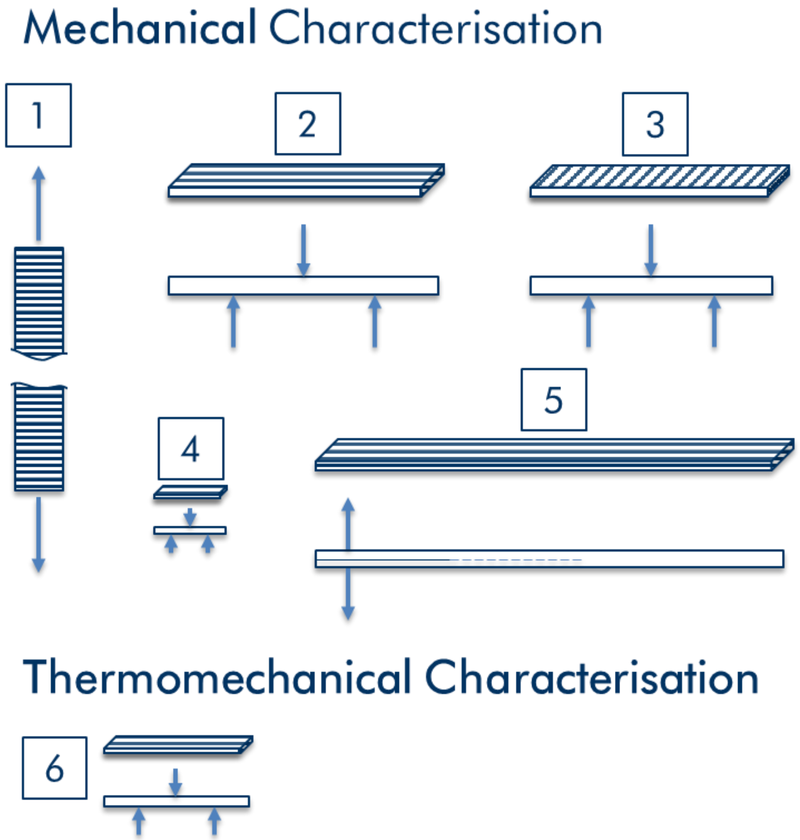
Share on

by Directindustry
March 17, 2022 / 2 mins / Updated on March 21, 2022

As part of the ZEBRA project (Zero wastE Blade ReseArch), the 62-meter wind turbine blade is made of thermoplastic composite that uses Arkema's Elium® resin and new high-performance fiberglass materials from Owens Corning. The prototype is said to be 100% recyclable.



Benchmarking Study – Acrylic/Glass fibre Composite vs Epoxy/Glass Fibre Composite



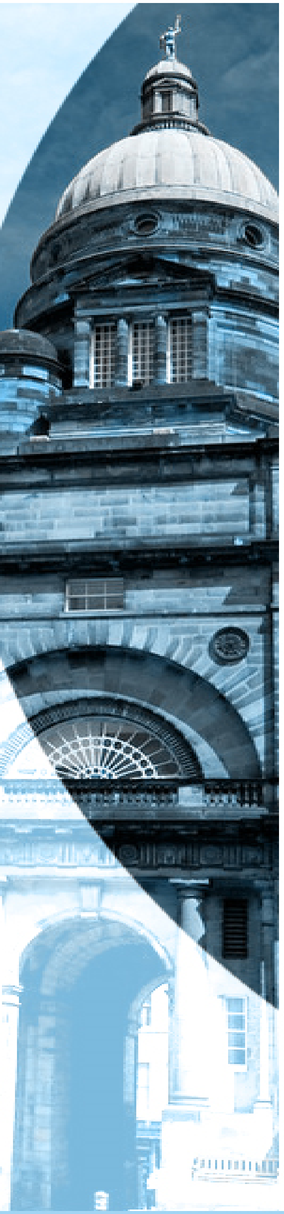
Mechanical Properties

1. Transverse tensile strength & modulus
2. Longitudinal flexural strength & modulus
3. Transverse flexural strength & modulus
4. Short beam shear strength
5. Mode-I interlaminar fracture toughness

Thermomechanical Properties

6. Damping capacity (tan delta) & glass transition temperature

Obande et al, Materials & Design, 175, (2019) 107828, https://doi.org/10.1016/j.matdes.2019.107828



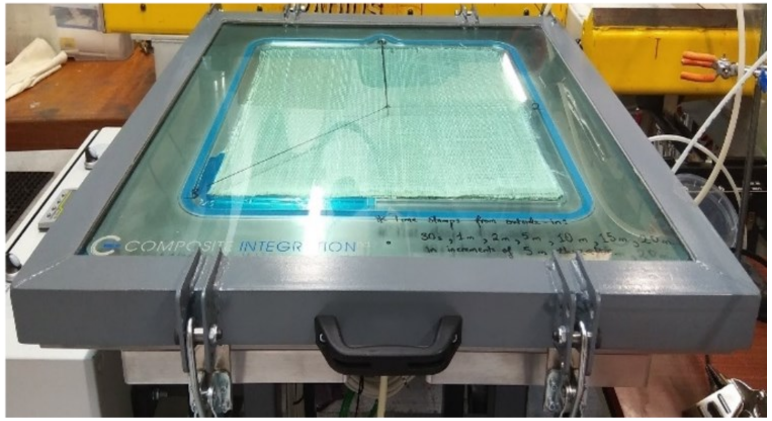
Materials & Fabrication Method

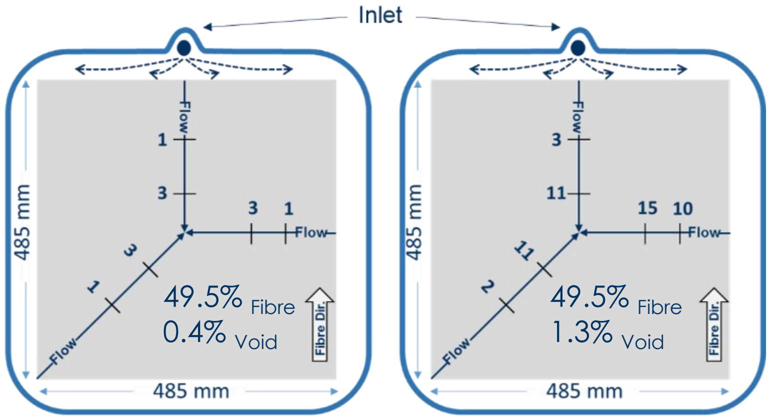
Materials:

- **Resins**
  - Elium®1880 (Arkema)
  - SR 1710 (Sicomin Epoxy Systems)
- **Reinforcement**
  - 646 gsm non-crimp glass fabric (Ahlstrom-Munksjö)

Method:

- **Technique**
  - Vacuum infusion at room temperature
- **Laminate specifications**
  - Size: *485 mm × 485 mm × 4 mm*
  - Stacking sequence: $[0]_8$
  - ID: *GF/Acrylic and GF/Epoxy*





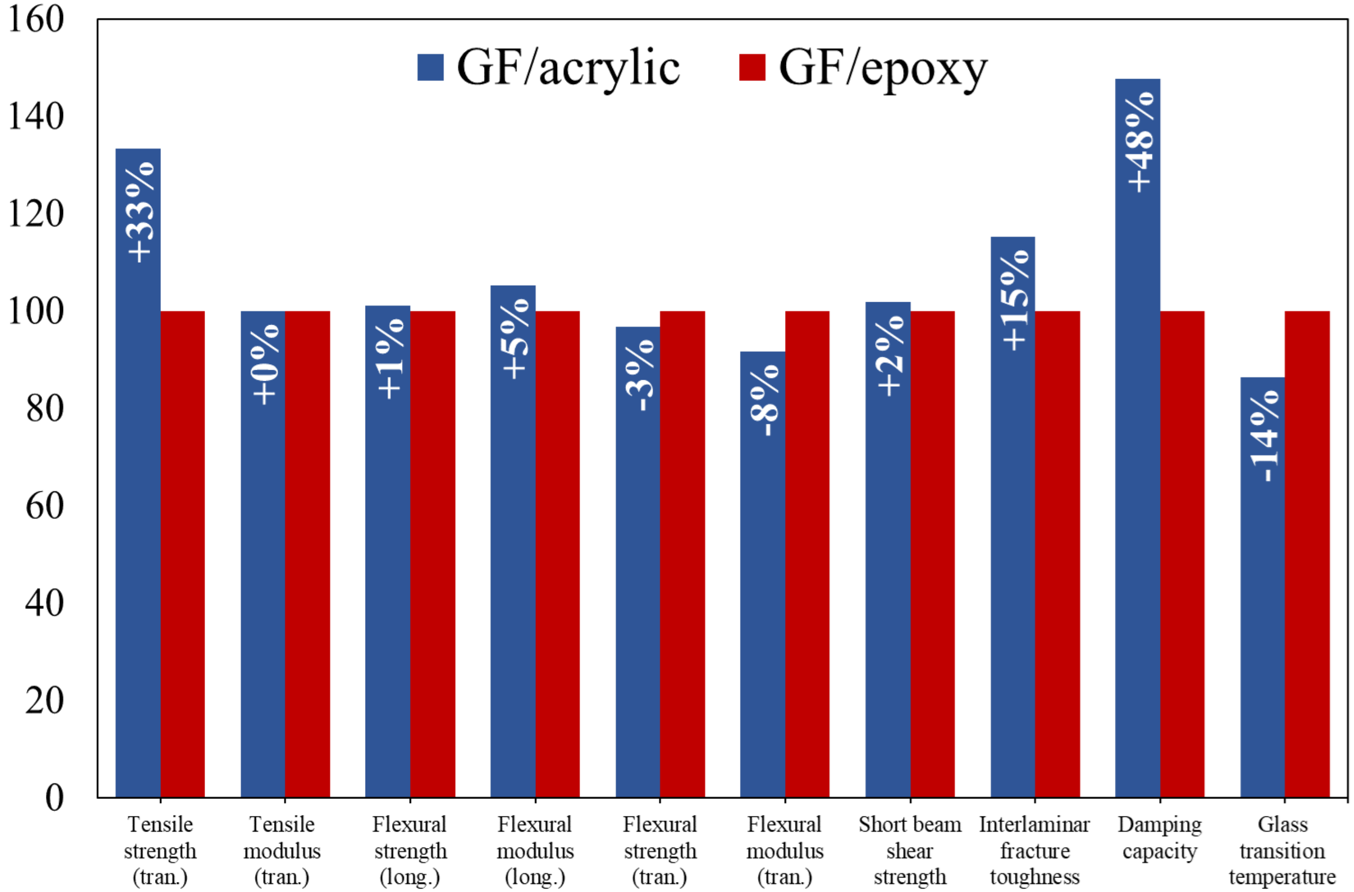
GF/Acrylic Infusion
Saturation time: 5.5 minutes

GF/Epoxy Infusion
Saturation time: 26.7 minutes

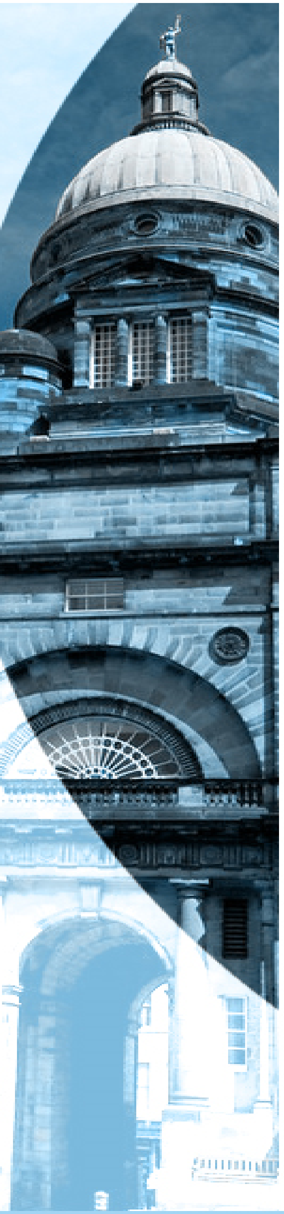
Note: Numbers represent time (min) at marked positions.

Obande et al, Materials & Design, 175, (2019) 107828, https://doi.org/10.1016/j.matdes.2019.107828

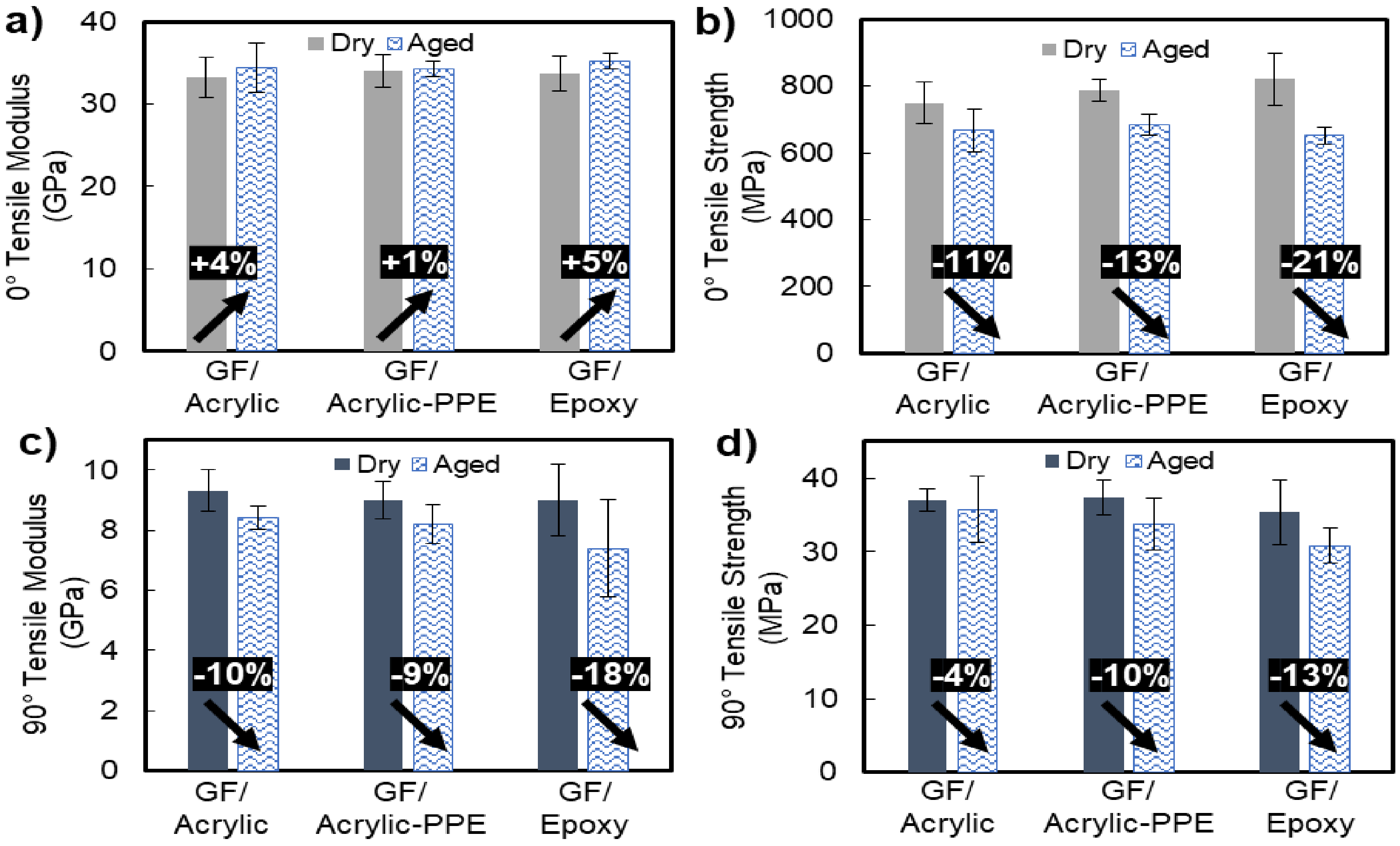
Benchmarking Study (Acrylic Composite vs Epoxy Composite)



Obande et al, Materials & Design, 175, (2019) 107828, https://doi.org/10.1016/j.matdes.2019.107828



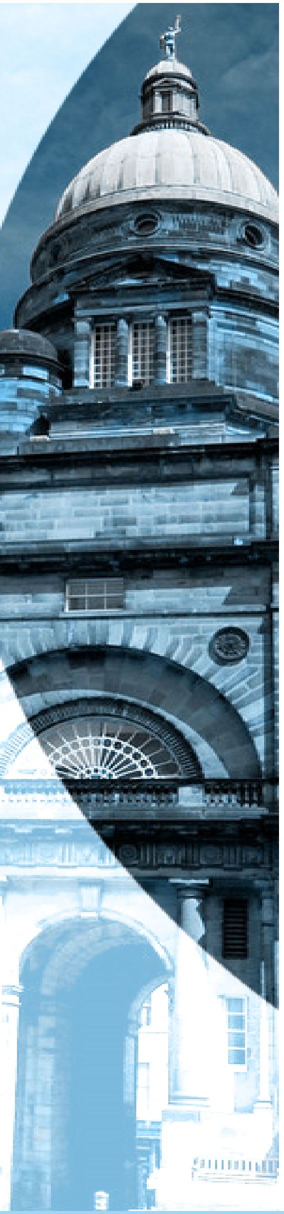
Water Absorption of GF/Acrylic Composites



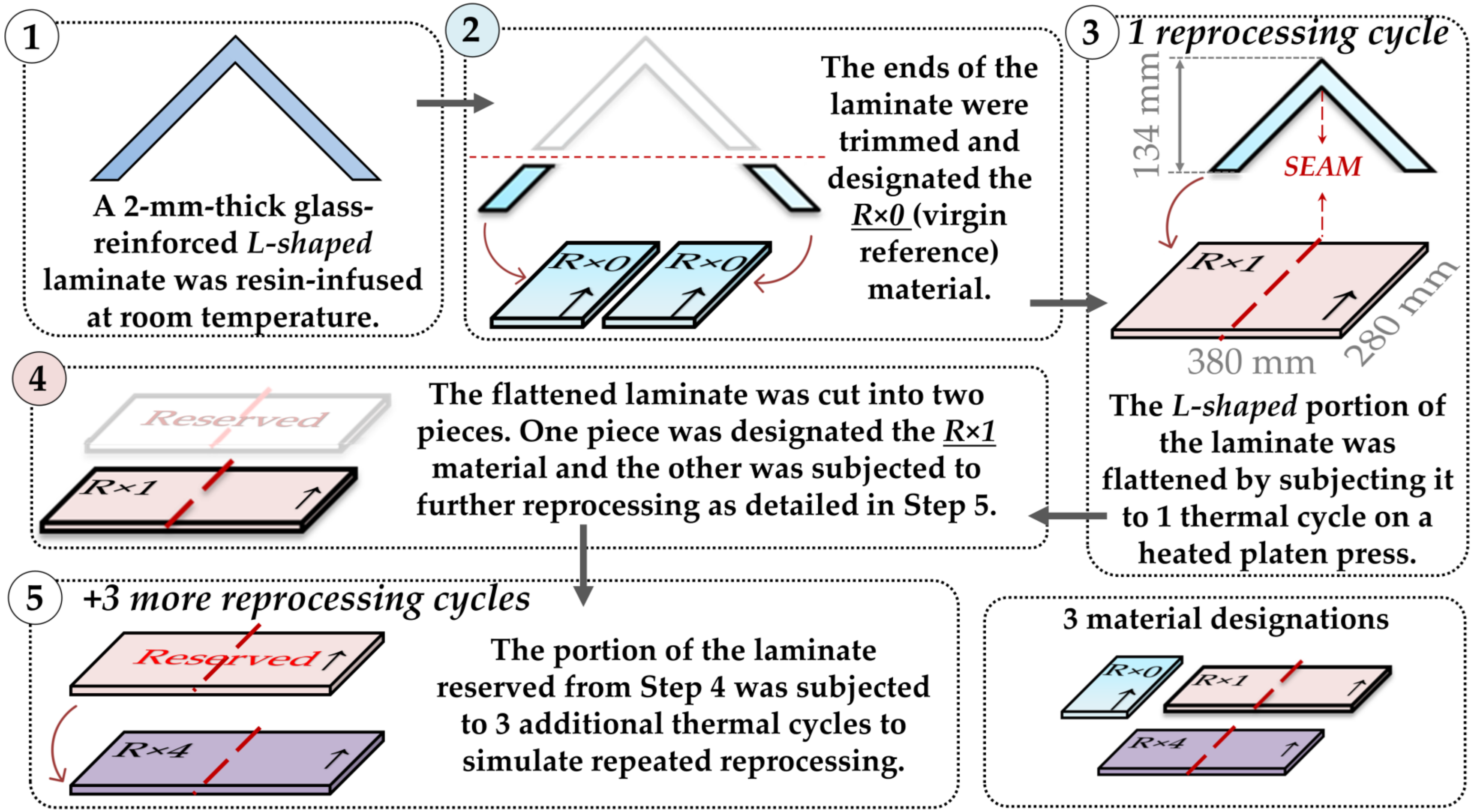
After 3 months immersion in sea water at 50˚C:

Both GF/Acrylic and GF/Acrylic-PPE outperform GF/Epoxy in terms of tensile strength retention, in both 0 ˚ and 90 ˚ directions.

Devine, M. et al., "Seawater Ageing of Thermoplastic Acrylic Hybrid Matrix Composites for Marine Applications", Composites Part B: Engineering, IN PRESS, June 2023



Thermal reshaping for reuse of acrylic composites



A 2-mm-thick glass-reinforced *L-shaped* laminate was resin-infused at room temperature.

The ends of the laminate were trimmed and designated the *R×0* (virgin reference) material.

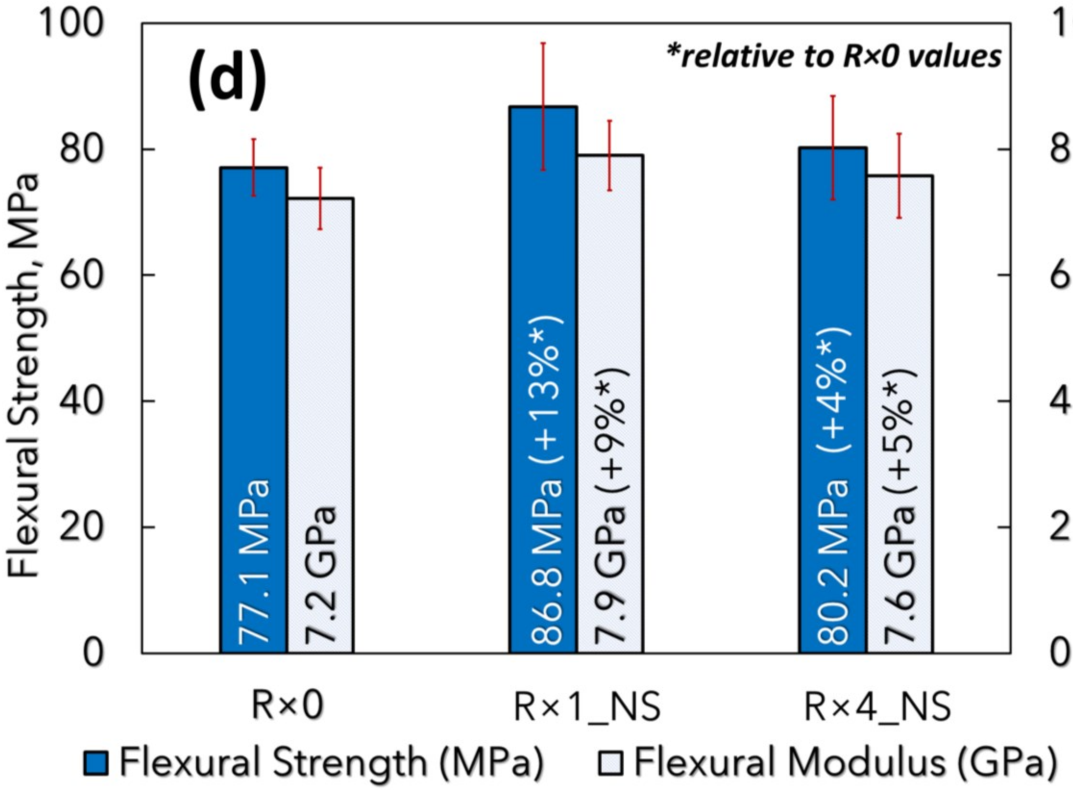
The *L-shaped* portion of the laminate was flattened by subjecting it to 1 thermal cycle on a heated platen press.

The flattened laminate was cut into two pieces. One piece was designated the *R×1* material and the other was subjected to further reprocessing as detailed in Step 5.

The portion of the laminate reserved from Step 4 was subjected to 3 additional thermal cycles to simulate repeated reprocessing.

Obande et al, Composites Part B: Engineering, 2023, https://doi.org/10.1016/j.compositesb.2023.110662

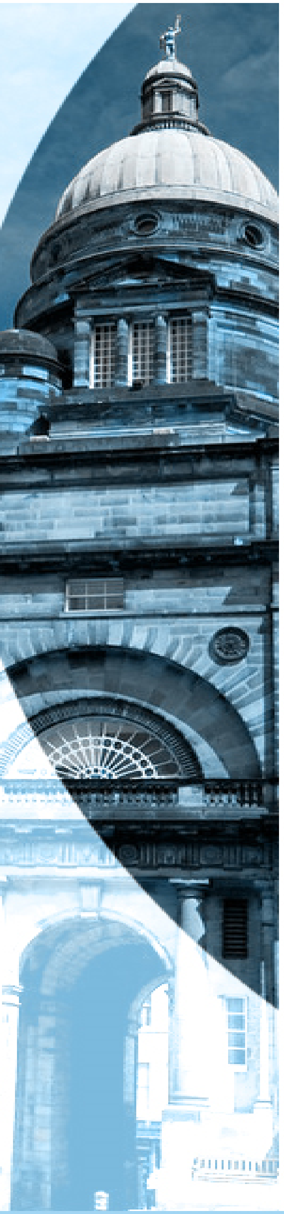
Thermal reshaping for reuse of acrylic composites



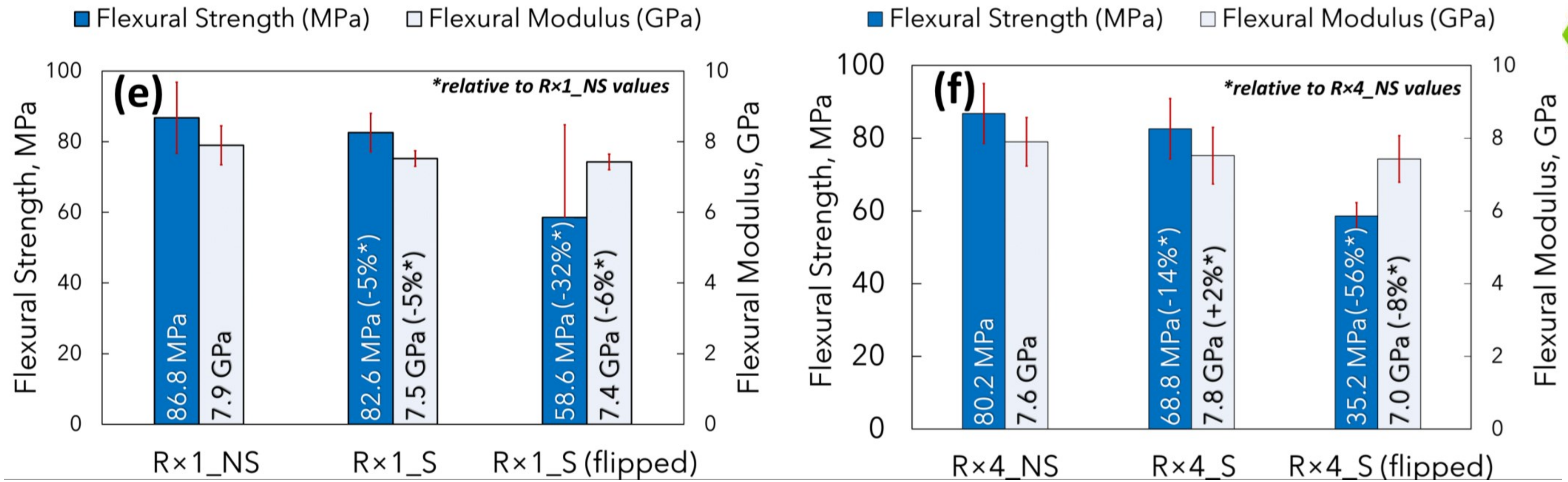
Flattening the 90° bend and re-processing actually increases the mechanical properties, when the “seam” is not included.

Rx0 means original props; Rx1_NS means flattened and reprocessed once with No Seam etc.

Obande et al, Composites Part B: Engineering, 2023, https://doi.org/10.1016/j.compositesb.2023.110662

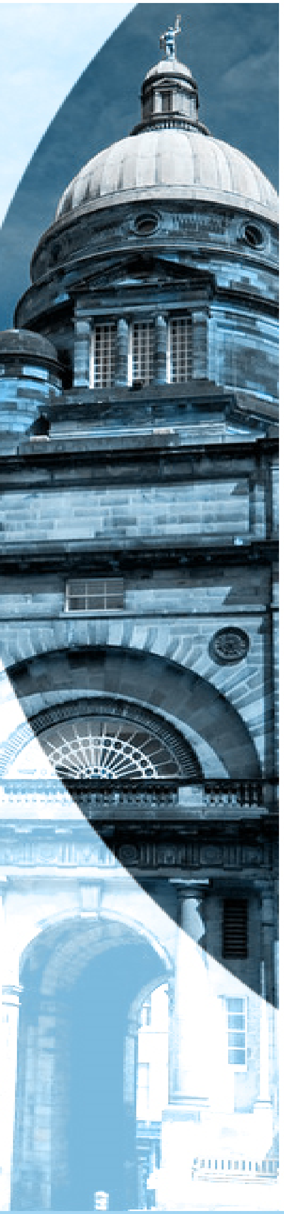


Thermal reshaping for reuse of acrylic composites



Flattening and re-processing reduces the mechanical properties by 5-10%, when the “seam” is included. “Flipping” the seam to the compression side of the specimen reduces the flexural strength by 30% after 1 cycle and by 60% after 4 cycles. Specimen modulus is not strongly affected by “flipping”.

Obande et al, Composites Part B: Engineering, 2023, https://doi.org/10.1016/j.compositesb.2023.110662



Outlook for Infusible Thermoplastic Composites in Tidal Blade Structures

Several Advantages:

- Room temperature infusion means that existing mould tooling and facilities can be used – no cost disadvantage.
- Should be a drop-in epoxy resin replacement.
- Thermal and other types of welding can replace adhesive bonding.
- Blades can be recycled by various methods at end of life.

Possible Disadvantage:

- Exotherm needs to be controlled especially in variable-thickness parts.
- Long-term durability under water needs to be verified and improved.

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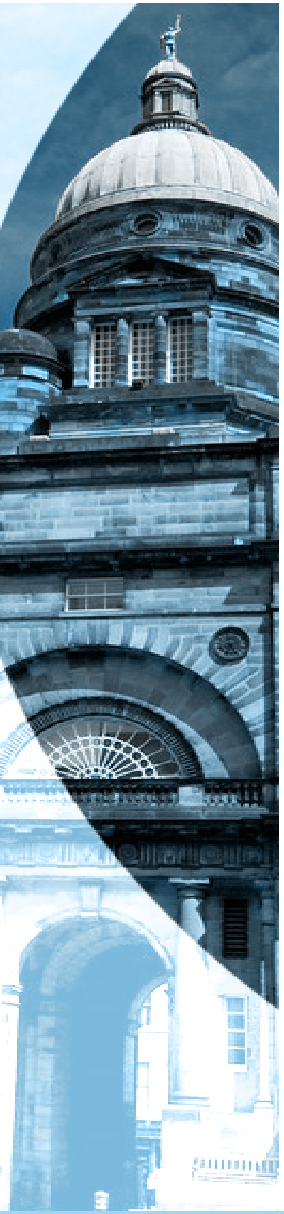
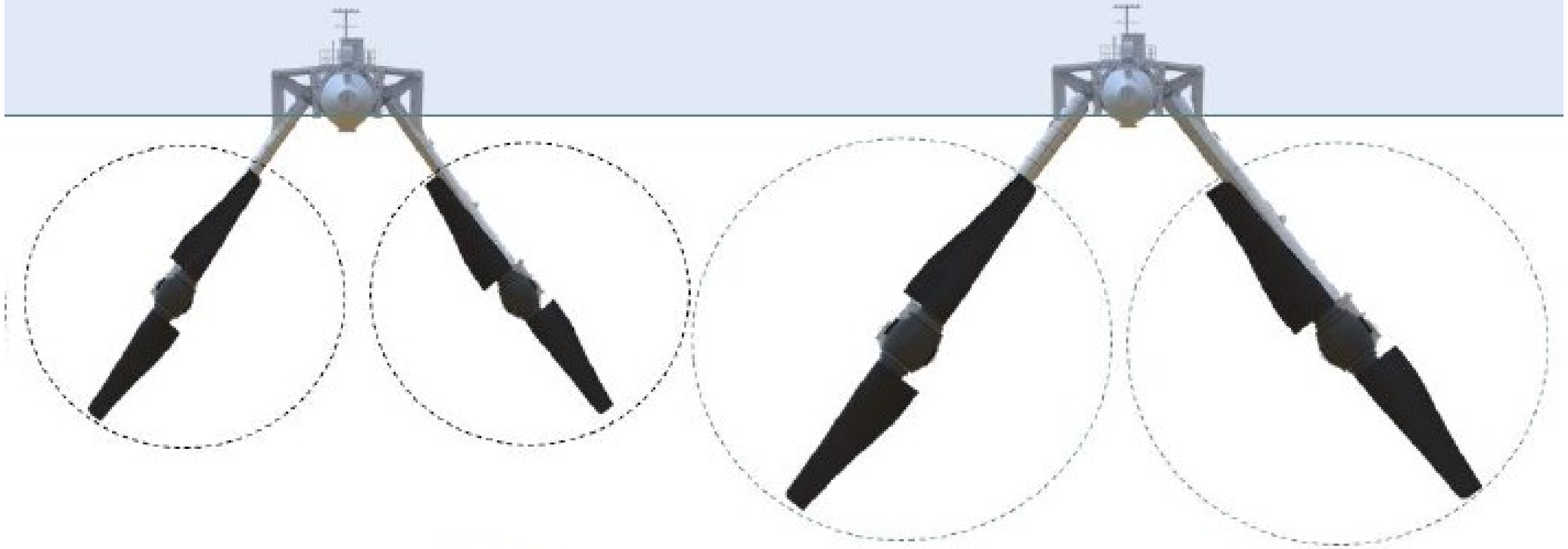


Maximising Tidal Energy Generation through Blade Scaling & Advanced Digital Engineering



O2 2 MW launched 2021
10m blade, 2 x 20m ⌀
628 m^2 swept area

€10M project funded for 66 months by Horizon Europe/UK Government. Project started in January 2023.

“The project aims to reduce the levelised cost of energy of Orbital’s tidal technology by 20% to €120 / MWh through a 70% increase in the rotor swept area with a reliable, cost-optimised 13m length blade.”

CoTide Programme Grant EPSRC (2023-2028)

Will develop and demonstrate **holistic integrated co-design processes** for tidal stream energy, that **will evolve** as we develop under-standing of sensitivity to design drivers.

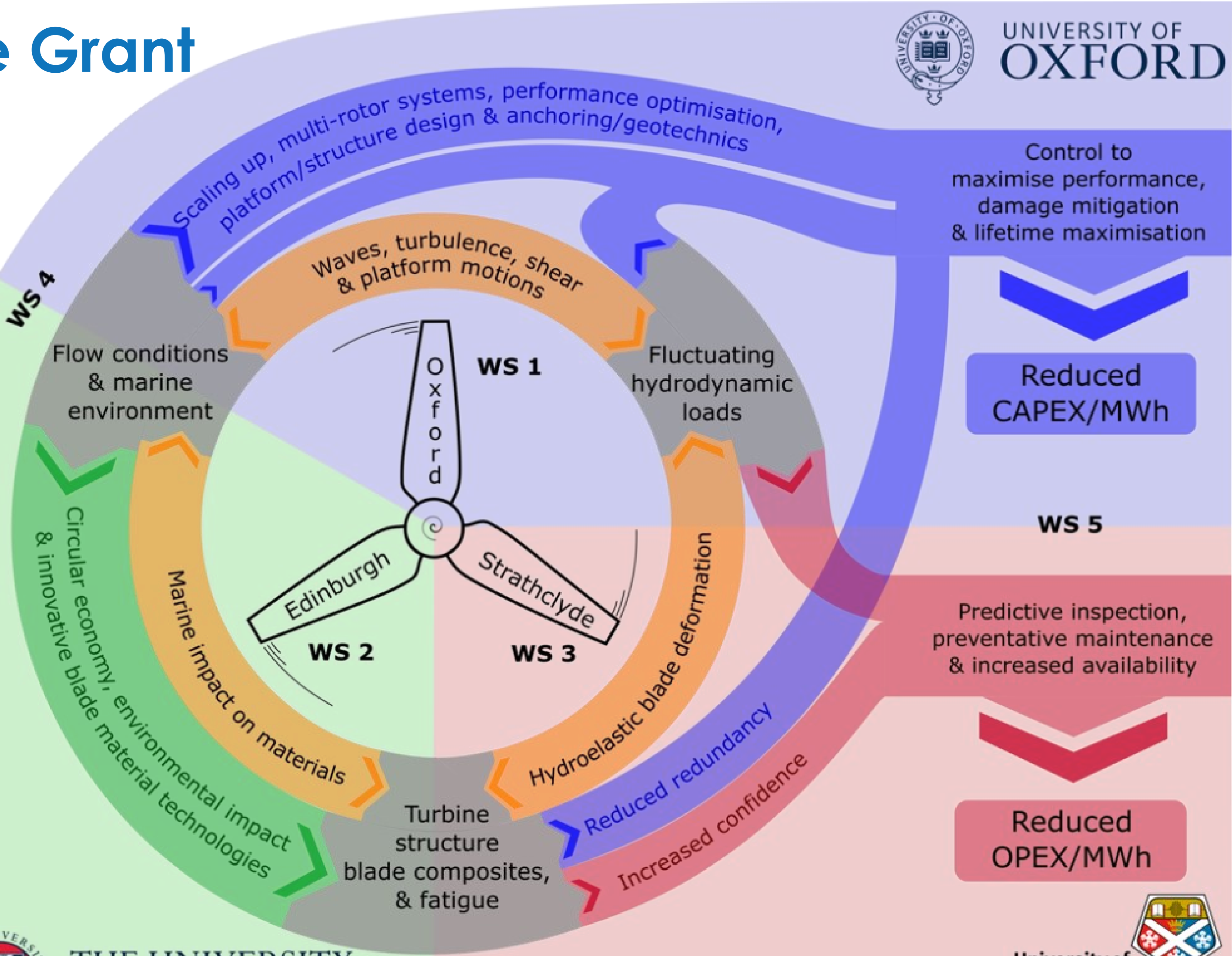
Objectives

We will **answer questions of how to**

- achieve scalability of tidal stream energy on the 2030 (100MW) and 2040 (>1GW) time scales,
- embed the concepts of whole system or co-design in design processes,
- ensure that tidal energy innovation is sustainable and responsible.

Five Work Streams

WS 1 – Device Hydrodynamics
WS 2 – Composites & Rotor Materials
WS 3 – Structures & Reliability
WS 4 – Metocean, Resource & Environment
WS 5 – Co-design & Optimisation



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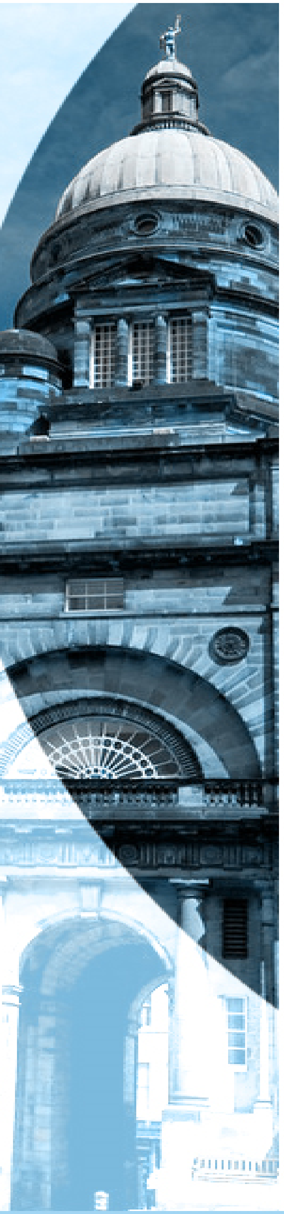
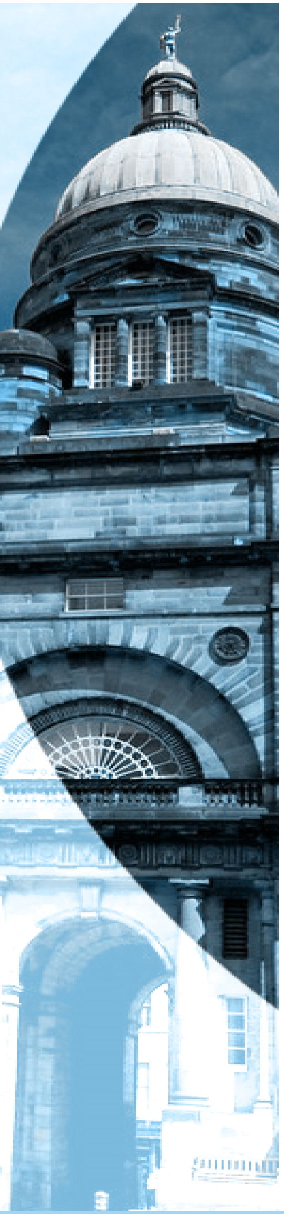


Conclusions

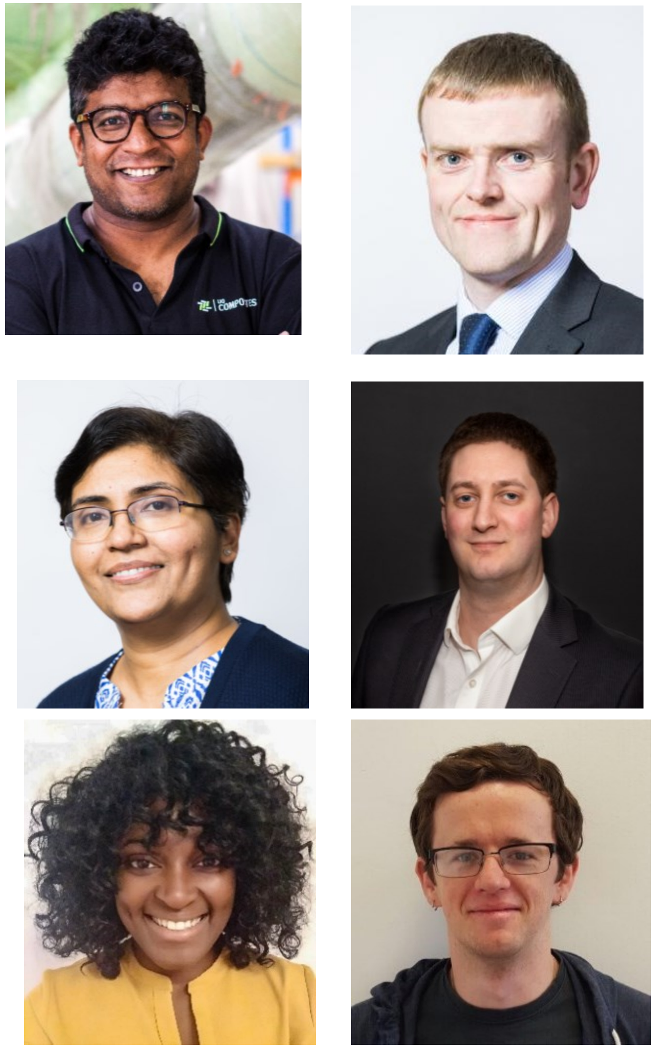
- Tidal stream energy is an emerging source of predictable renewable energy – new test facilities (FastBlade) and design methods needed.
- Powder epoxy composites are an advantageous material for processing of thick section structures, but high temperature processing may limit their use in large blade structures.
- Infusible room temperature acrylic thermoplastics are an alternative to epoxy for large-scale blade structures, with the improved potential for recycling and re-use at end of life.
- New UK and EU research projects are focussed on development of larger tidal energy blades, new more sustainable composite processes and improved design software.



Acknowledgements

- Prof Dilum Fernando, University of Edinburgh
- Dr Dipa Roy, Reader, University of Edinburgh
- Dr Eddie McCarthy, Senior Lecturer, University of Edinburgh
- Dr Fergus Cuthill, FastBlade Manager, 2021-
- Dr Sergio Lopez-Dubon, EU CoFund Fellow, 2020-
- Dr James Maguire, PhD student 2013-18
- Dr Winifred Obande, PDRA and PhD student, 2017-2021, Elizabeth Georgeson Fellow, 2023-
- Dr Ankur Bajpai, PDRA, 2020-2022

- Johns Manville, Arkema (industrial sponsors)
- EPSRC Future Composites Manufacturing Hub
- EPSRC Supergen Offshore Renewable Energy Hub
- European Union Horizon Europe Programme, 2023-2028



UKRI Engineering and Physical Sciences Research Council

Johns Manville

ARKEMA

Supergen Offshore Renewable Energy

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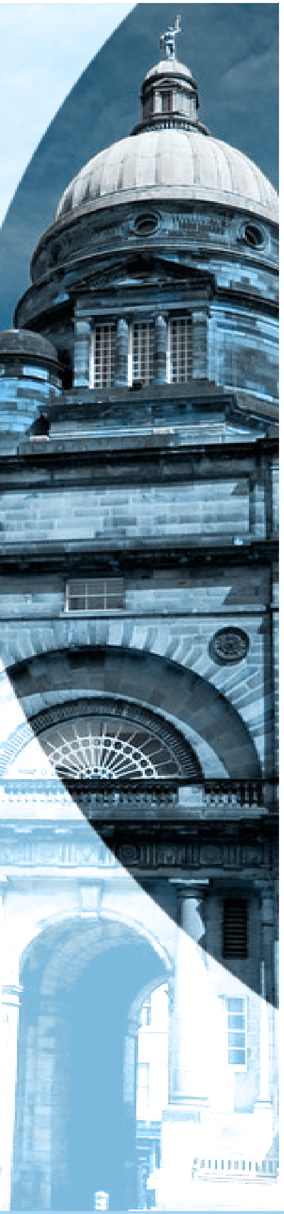
Processing of Composite Materials for Large Structures in Marine Renewable Energy (Keynote Lecture)

Prof. Conchúr M. Ó Brádaigh

School of Engineering, University of Edinburgh, Scotland, UK

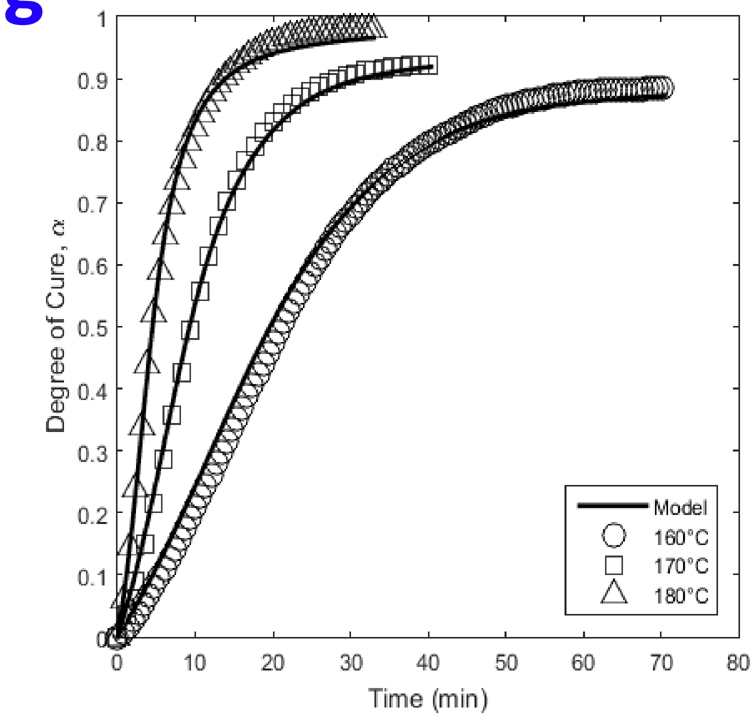
Flow Processes in Composite Materials 15, Purdue University, USA

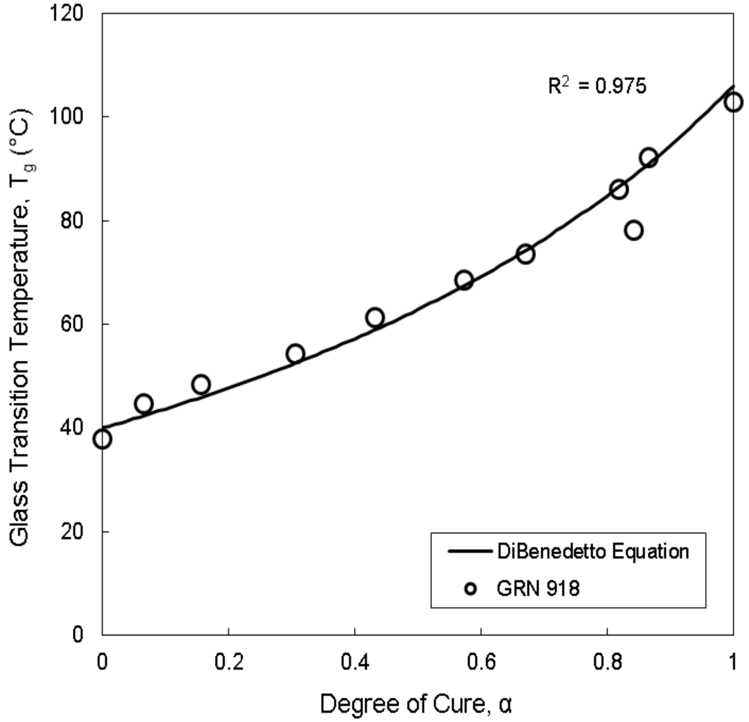
June 28th 2023



Material Modelling

- **Cure Kinetics**
- **Relationship of T_g and degree of cure**
- **Powder Sintering**
- **Chemorheology**





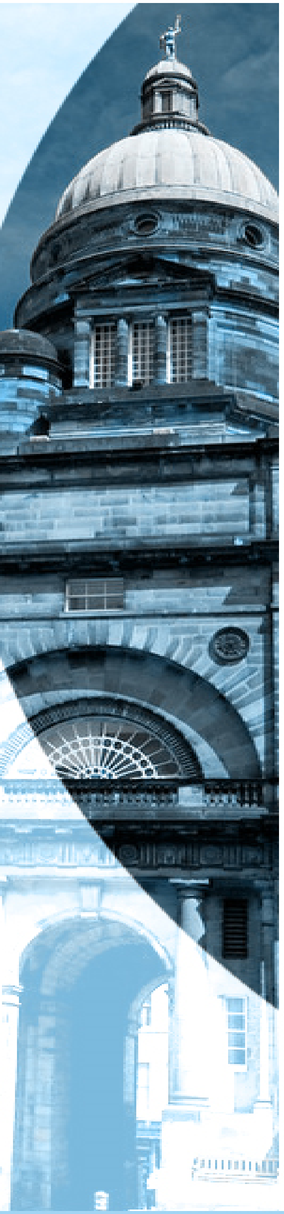
$$\frac{d\alpha}{dt} = \frac{(k_{\alpha 1} + k_{\alpha 2} + k_{\alpha 3}\alpha^m)(1-\alpha)^n}{1 + \exp[C(\alpha - \alpha_c)]}$$

$$\frac{T_g - T_{g0}}{T_{g\infty} - T_{g0}} = \frac{\lambda\alpha}{1 - (1-\lambda)\alpha}$$

Maguire et al., <u>Materials and Design</u>, 2018.
https://doi.org/10.1016/j.matdes.2017.10.068

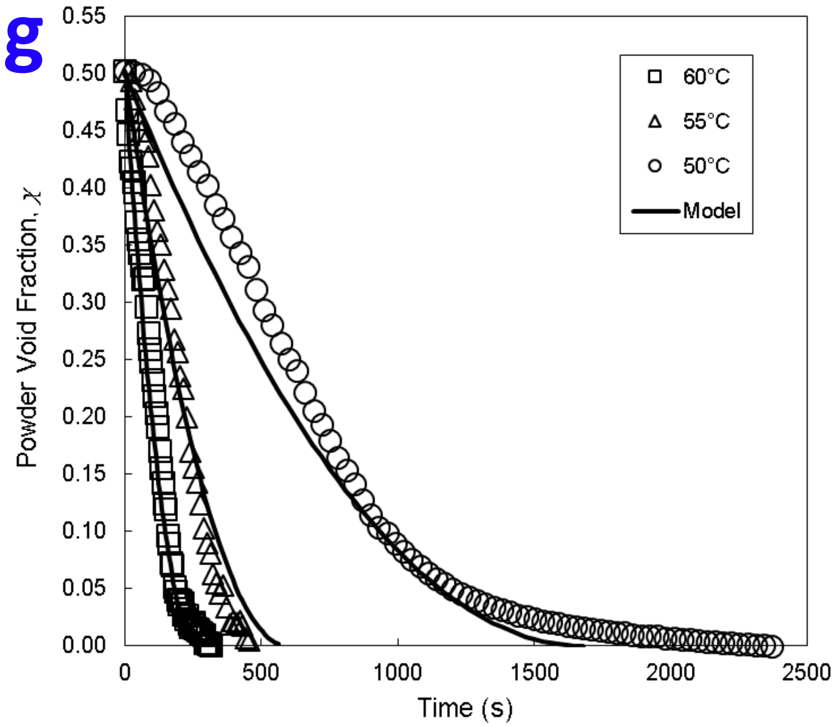
MARINCOMP

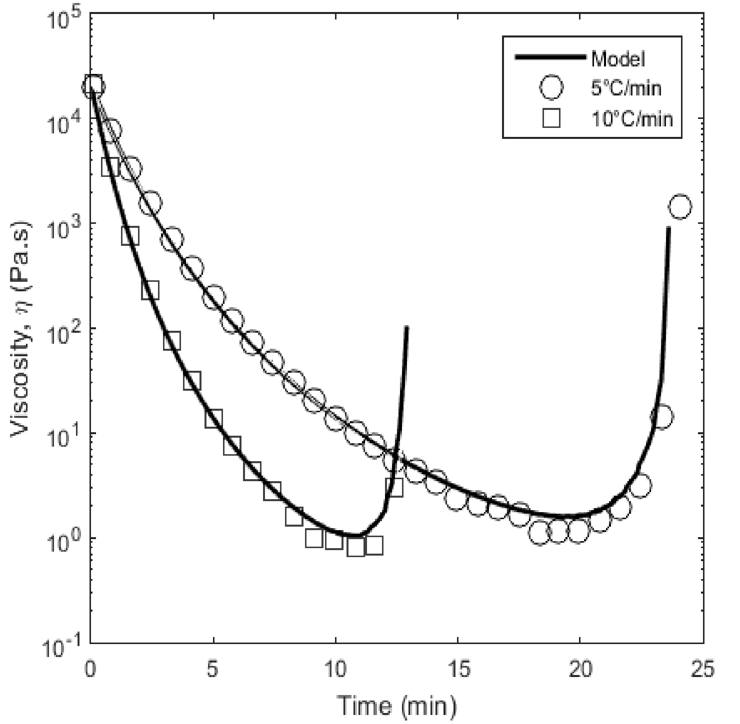
SUZLON



Material Modelling

- **Cure Kinetics**
- **Relationship of T_g and degree of cure**
- **Powder Sintering**
- **Chemorheology**





$$\frac{d\chi}{dt} = -\chi_0 \exp\left(\frac{C_{\chi1}[T-T_\theta]}{C_{\chi2}+T-T_\theta}\right)(\chi-\chi_\infty)^B$$

$$\eta = \eta_{g0}\ \exp\left(\frac{-C_{\eta1}[T-T_g(\alpha)]}{C_{\eta2}+T-T_g(\alpha)}\right)\left(\frac{\alpha_g}{\alpha_g-\alpha}\right)^A$$

Maguire et al., Materials and Design, 2018.
https://doi.org/10.1016/j.matdes.2017.10.068

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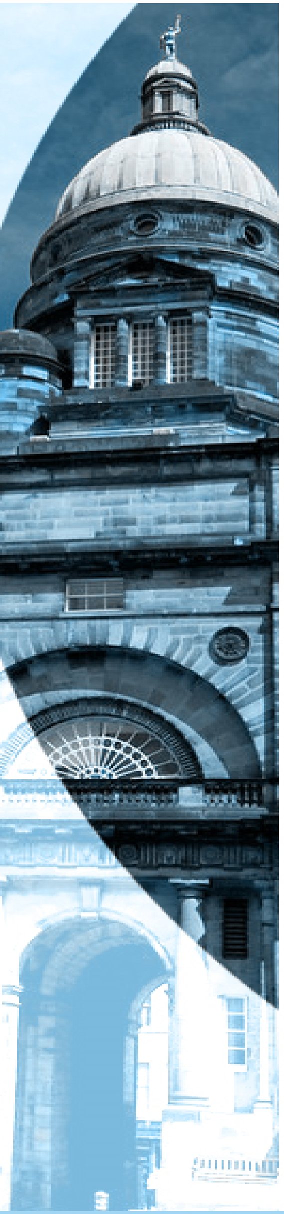
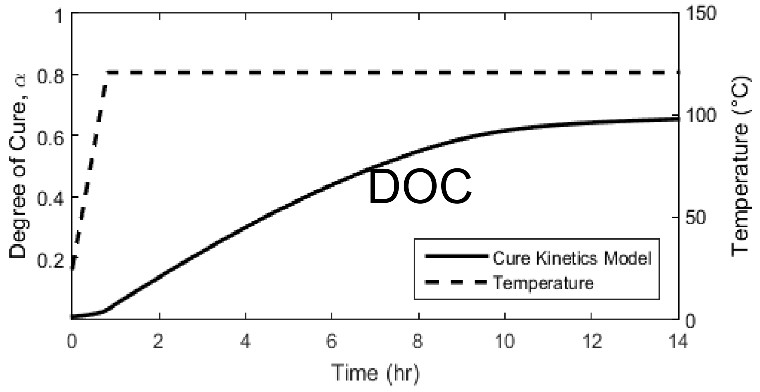


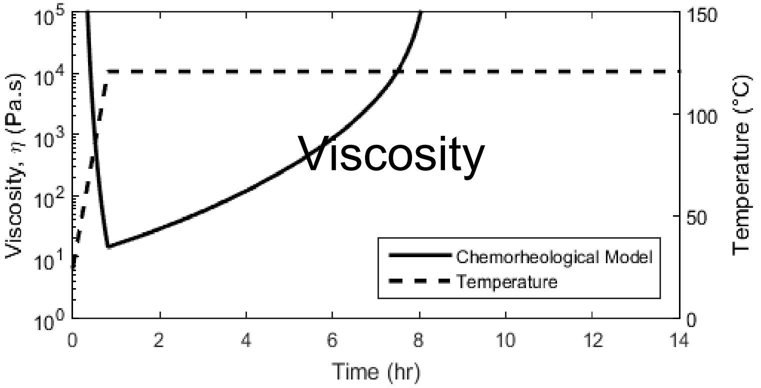
Process Modelling

Investigating the process cycle

Single Ramp



Single Ramp



Maguire et al., Materials and Design, 2018.
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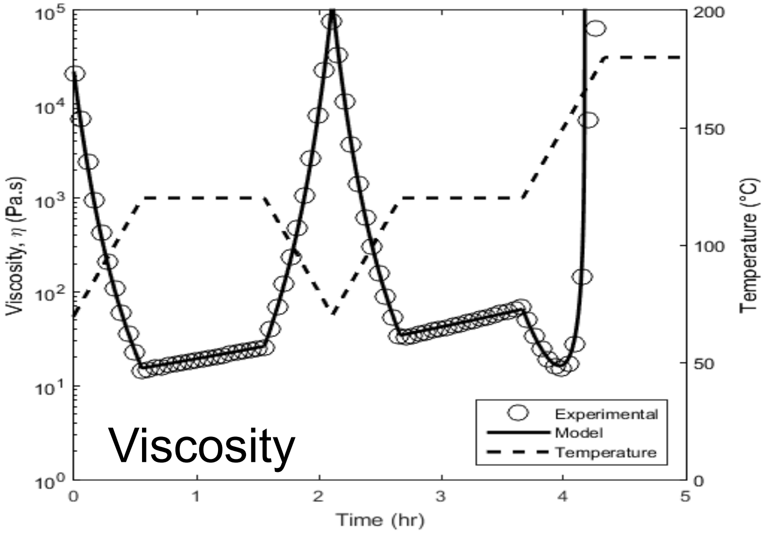
Typical WT blade process cycle involves separate consolidation and cure cycles



Ramp to 120°C
Cool to RT
Ramp to 120°C
Ramp to 180°C

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