The Institution of
StructuralEngineers

# Structural analysis and design with decommissioned wind turbine blades

12 October 2021

Larry Bank & Kieran Ruane
Re-Wind Network

Georgia Tech
CUNY THE CITY UNIVERSITY OF NEW YORK
UCC University College Cork, Ireland
Coláiste na hOllscoile Corcaigh
QUEEN'S UNIVERSITY BELFAST
MTU Ollscoil Teicneolaíochta na Mumhan
Munster Technological University
RE-WIND NETWORK
BLADE REPURPOSING SOLUTIONS

# Outline

- Overview of the Re-Wind project www.re-wind.info
- Blade Repurposing
  - Codes and standards
  - Structural Engineering Analysis and Design
  - Example Projects
    - BladeRoof
    - BladePole
    - BladeBridge
      - Cork Project – Testing, Design & Construction

# Re-Wind Partners, Projects, Funding

**Network University Members:**

- Georgia Tech
- City University of New York
- University College Cork
- Queens University Belfast
- Munster Technological University

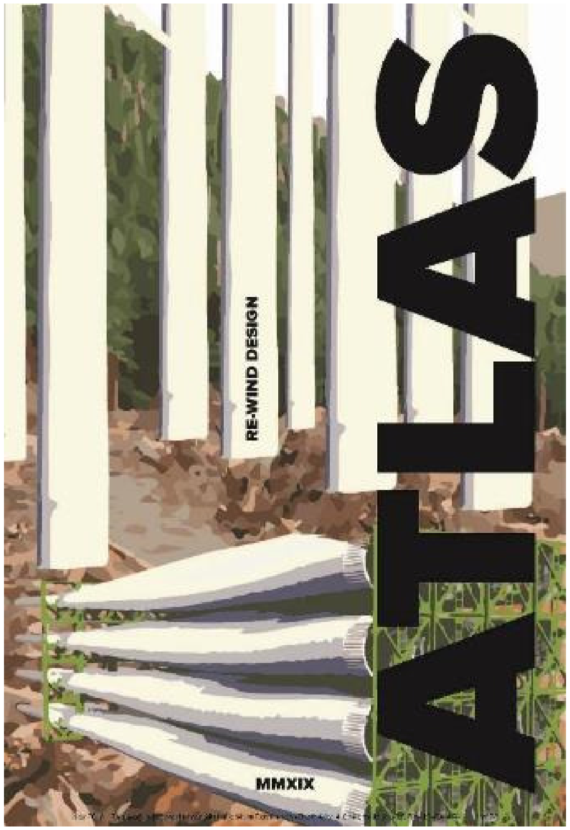
**Funding (~$2m 2014-current)**

- NSF (CBET, PFI, I-CORPS)
- NYSERDA
- SFI
- DfE
- ENEL Green Power

**Current Project Partners:**

- Logisticus Group
- ENEL Green Power
- Siemens-Gamesa RE
- Cork County Council
- NYC Dept of Design and Construction (DDC)
- IEA Task 45

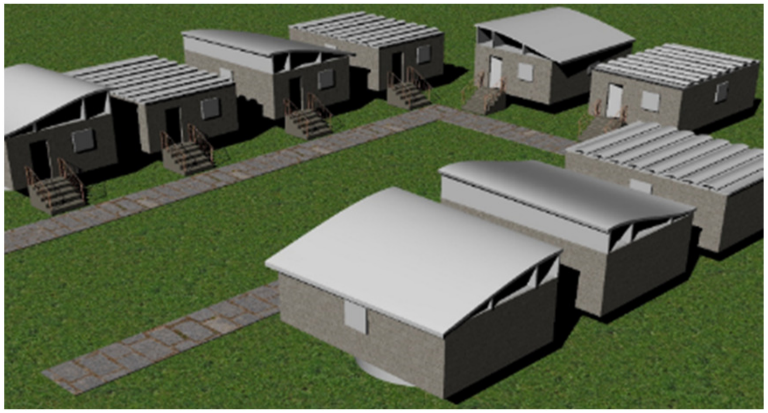
# Blade Repurposing Concepts



2018

2021

# Some Re-Wind Blade Repurposing Concepts



**BladeHousing**

**BladeBridge**

**BladePole**

**BladeBarrier**

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# What's a wind blade?

## Exterior

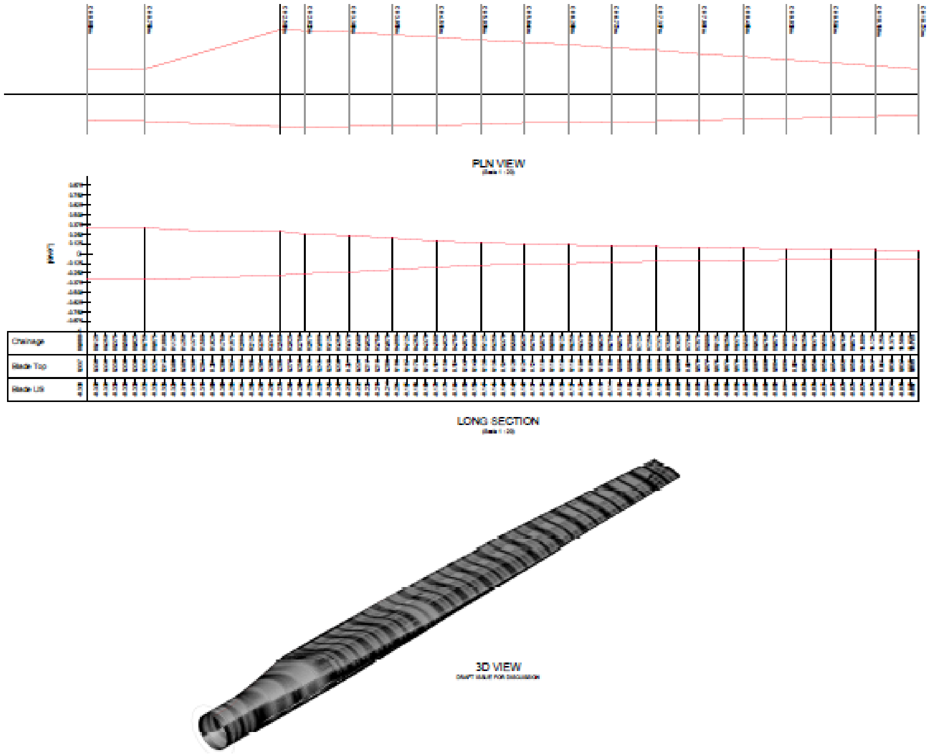
Vestas V82 from a 2004 1.65 MW turbine
40m long blade ~ 2.5m at max chord

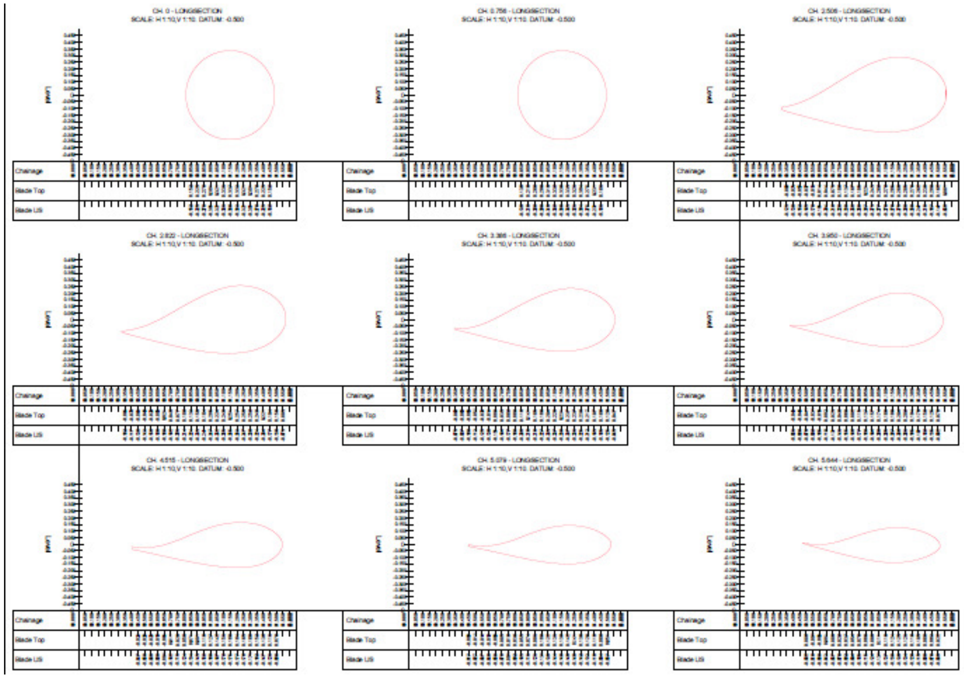
# Interior

46.7m long Clipper C96
Spar Box (2 shear webs)

37m long GE 37
I –Beam Spar (1 shear web)

# Along the length





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# Codes and Standards

**Structural Design of Polymer Composites**

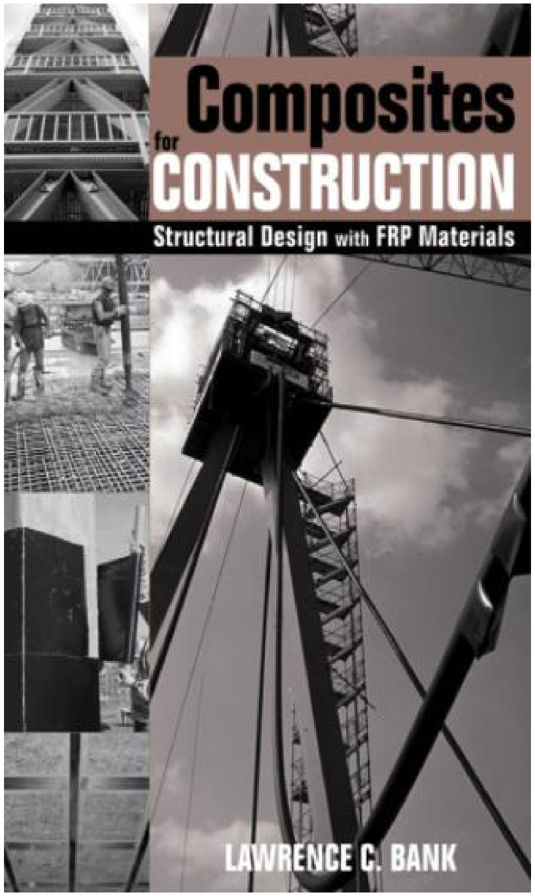
EUROCOMP Design Code and Handbook

THE EUROPEAN STRUCTURAL POLYMERIC COMPOSITES GROUP

Edited by
JOHN L. CLARKE

CRC Press
Taylor & Francis Group
A TAYLOR & FRANCIS BOOK

1996



**Composites for CONSTRUCTION**

Structural Design with FRP Materials

LAWRENCE C. BANK

2006

JRC SCIENCE FOR POLICY REPORT

PROSPECT FOR NEW GUIDANCE IN THE DESIGN OF FRP

*Support to the implementation, harmonization and further development of the Eurocodes*

Authors

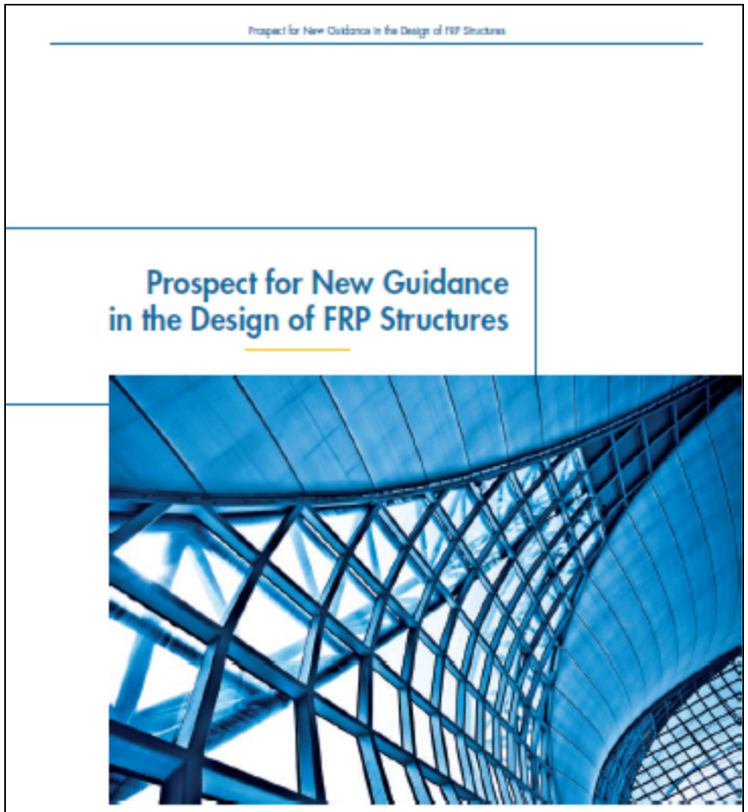
Luigi Ascione, Jean-François Caron, Patrice Godonou, Kees van IJselmuijden, Jan Knippers, Toby Mottram, Matthias Oppe, Morten Gantriis Sorensen, Jon Taby, Liesbeth Tromp

Editors

Luigi Ascione, Eugenio Gutierrez, Silvia Dimova, Artur Pinto, Steve Denton

2016

2016

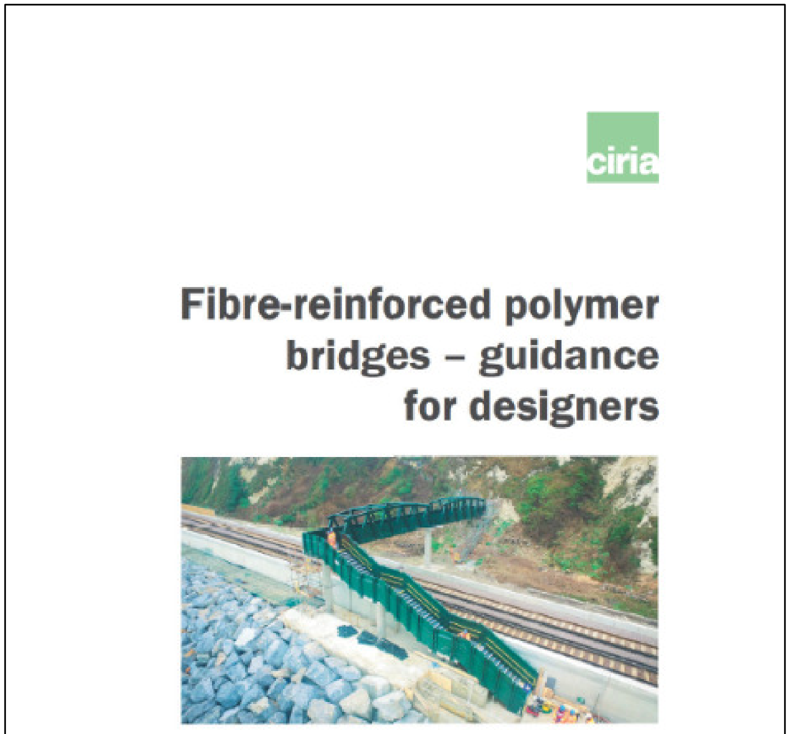


Prospect for New Guidance in the Design of FRP Structures

Prospect for New Guidance in the Design of FRP Structures

https://eucia.eu/userfiles/files/Eucia_Prospect%20for%20New%20Guidance%20in%20the%20Design%20of%20FRP%20Structures_web2.pdf

2017



Fibre-reinforced polymer bridges – guidance for designers

https://www.ciria.org/ItemDetail?iProductCode=C779F&Category=FREEPUBS

2017

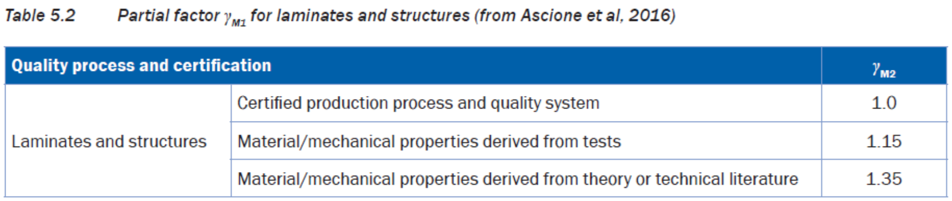


*Table 5.2* *Partial factor $\gamma_{M1}$ for laminates and structures (from Ascione et al, 2016)*

| **Quality process and certification** | | $\gamma_{M2}$ |
|---|---|---|
| Laminates and structures | Certified production process and quality system | 1.0 |
| | Material/mechanical properties derived from tests | 1.15 |
| | Material/mechanical properties derived from theory or technical literature | 1.35 |

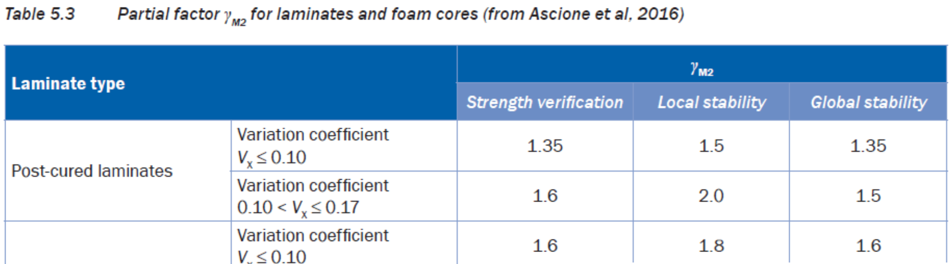


*Table 5.3* *Partial factor $\gamma_{M2}$ for laminates and foam cores (from Ascione et al, 2016)*

| **Laminate type** | | $\gamma_{M2}$ | | |
|---|---|---|---|---|
| | | *Strength verification* | *Local stability* | *Global stability* |
| Post-cured laminates | Variation coefficient $V_x \leq 0.10$ | 1.35 | 1.5 | 1.35 |
| | Variation coefficient $0.10 < V_x \leq 0.17$ | 1.6 | 2.0 | 1.5 |
| Non-post-cured laminates | Variation coefficient $V_x \leq 0.10$ | 1.6 | 1.8 | 1.6 |
| | Variation coefficient $0.10 < V_x \leq 0.17$ | 1 | | |
| Foam core | Foam under shear | 1 | | |
| | Foam under compression | 1 | | |

The draft of the <u>CEN Technical Specification (TS)</u> '<u>Design of Fibre-Polymer Composite Structures</u>' was submitted to CEN at the end of January 2020 for a review process by the National Standards Bodies. <u>The TS, expected to be published by 2023, represents the second step of the general procedure established by CEN/TC250 in order to create a new generation of Structural Eurocodes</u>.

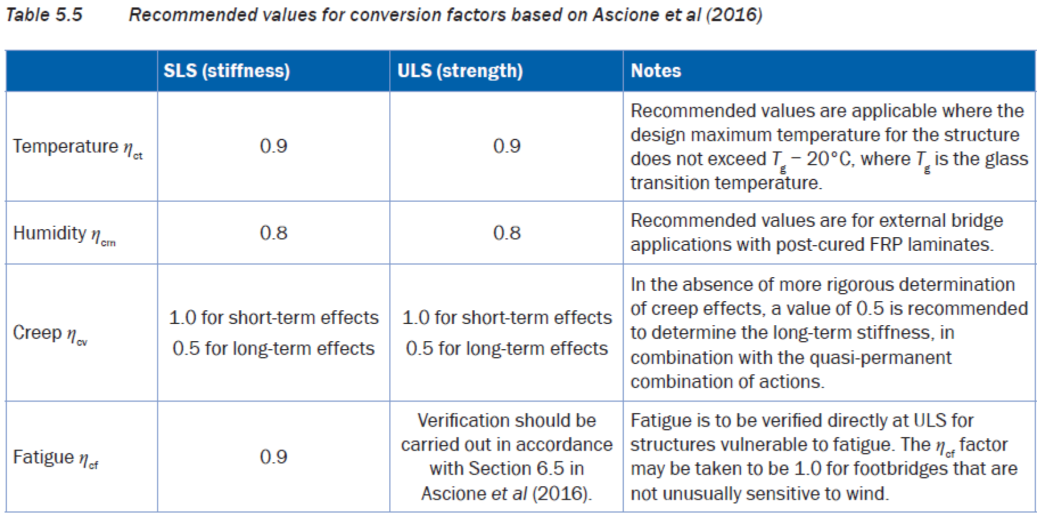


*Table 5.5* *Recommended values for conversion factors based on Ascione et al (2016)*

| | **SLS (stiffness)** | **ULS (strength)** | **Notes** |
|---|---|---|---|
| Temperature $\eta_{ct}$ | 0.9 | 0.9 | Recommended values are applicable where the design maximum temperature for the structure does not exceed $T_g$ − 20°C, where $T_g$ is the glass transition temperature. |
| Humidity $\eta_{cm}$ | 0.8 | 0.8 | Recommended values are for external bridge applications with post-cured FRP laminates. |
| Creep $\eta_{cv}$ | 1.0 for short-term effects<br>0.5 for long-term effects | 1.0 for short-term effects<br>0.5 for long-term effects | In the absence of more rigorous determination of creep effects, a value of 0.5 is recommended to determine the long-term stiffness, in combination with the quasi-permanent combination of actions. |
| Fatigue $\eta_{cf}$ | 0.9 | Verification should be carried out in accordance with Section 6.5 in Ascione *et al* (2016). | Fatigue is to be verified directly at ULS for structures vulnerable to fatigue. The $\eta_{cf}$ factor may be taken to be 1.0 for footbridges that are not unusually sensitive to wind. |

## 2.3.4 Material partial factors

$$y_{M} = y_{M1} \cdot y_{M2}$$

$y_{M1}$ is the material partial factor linked to uncertainties in obtaining the correct material properties. (1.0, 1.15, or 1.35)

$y_{M2}$ is the material partial factor owing to uncertainties in material properties due to the nature of the constituent parts and depends on the production method. (1.35, 1.5, 1.6, or 2.0)

Characteristic value must be defined as:
5 % fractile if a low value for a material property

Worst Case = 1.35 x 2.0 = 2.7   1 / 2.7 = 0.37

Best Case = 1.0 x 1.35 = 1.35   1 / 2.7 = 0.74

## 2.3.6 Relevant conversion factors

The total conversion factor, $\eta_{c}$, for the limit states analysis should be determined from:

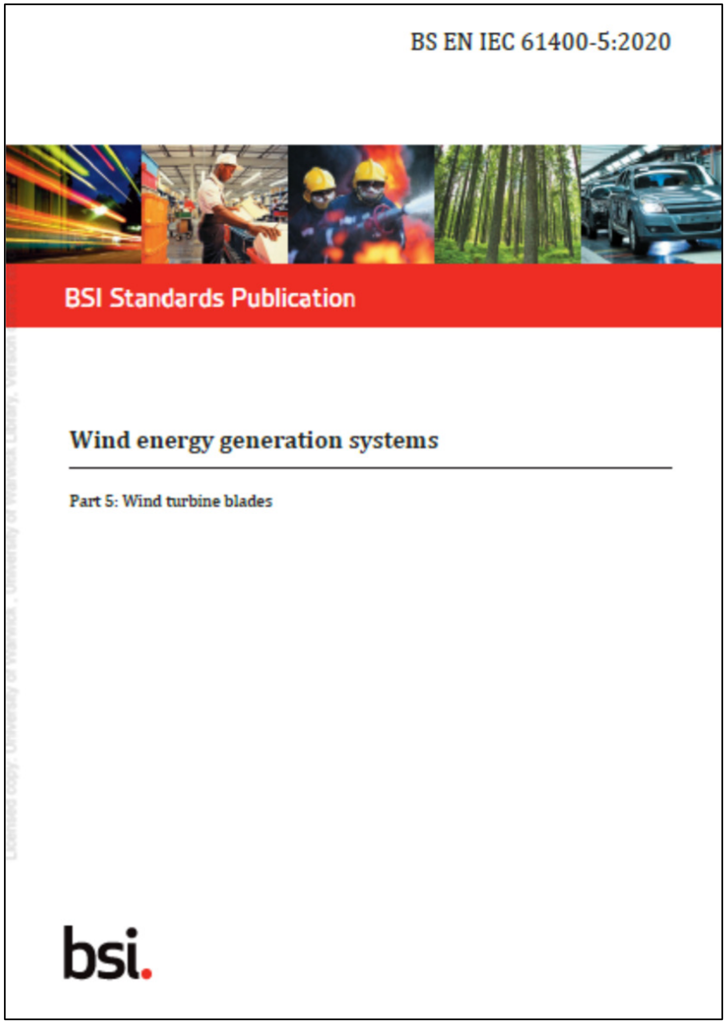
$$\eta_{c} = \eta_{ct} \cdot \eta_{cm} \cdot \eta_{cv} \cdot \eta_{cf}$$

$\eta_{ct}$ is the conversion factor for temperature effects; (0.9 or 1.0)

$\eta_{cm}$ is the conversion factor for humidity effects; (0.7, 0.9 or 1.0)

$\eta_{cv}$ is the conversion factor for creep effects; (0.25 to 1.0 depending on load duration)

$\eta_{cf}$ is the conversion factor for fatigue effects (required when fatigue load cycles is expected to exceed 5000)



BS EN IEC 61400-5:2020

BSI Standards Publication

Wind energy generation systems

Part 5: Wind turbine blades

bsi.

2020

## 6.6.4 Partial safety factors for materials

### 6.6.4.1 Definitions

The value of the partial safety factor for materials accounts for the inherent variability and uncertainties in FRP materials, laminated sandwich structures, bonded joints, methods and load resolution. To account for this, the material factors shall be specifically developed for each material type and combination of materials. This can be done either through a reliability-based dedicated test program or through an empirical approach. When using an empirical approach, appropriate partial safety factors shall be applied as follows:

$$\gamma_m = \gamma_{m0}\ \gamma_{m1}\ \gamma_{m2}\ \gamma_{m3}\ \gamma_{m4}\ \ \gamma_{m5}$$

where

$\gamma_{m0}$ is the “base” material factor (to be included in all analyses);

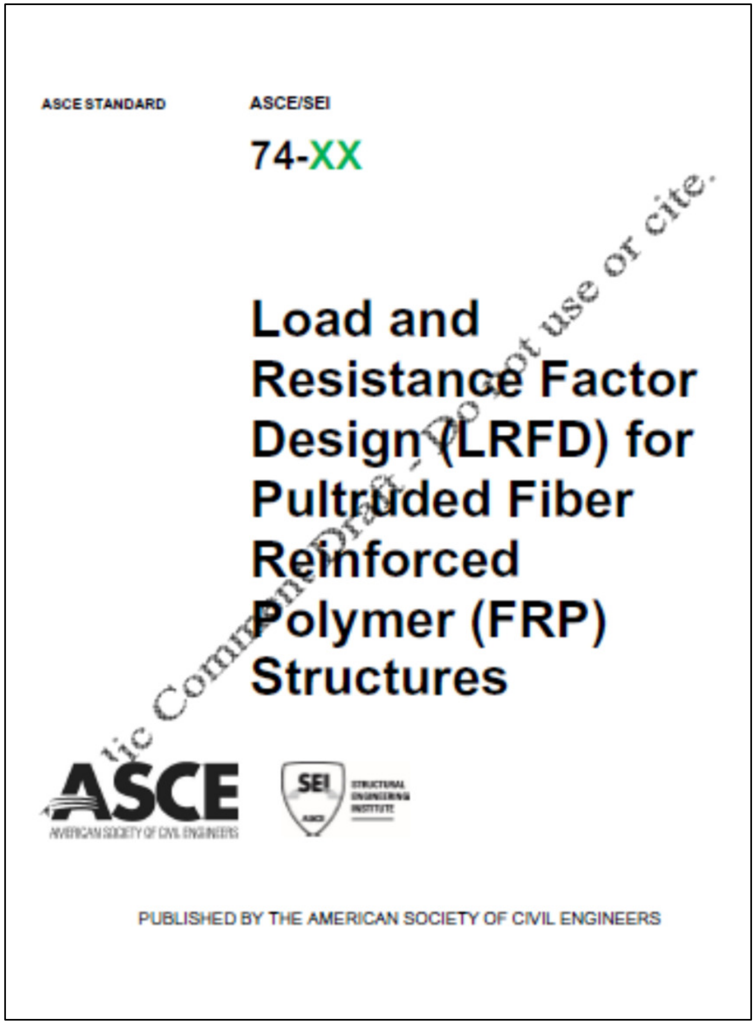
$\gamma_{m1}$ is the factor for environmental degradation (non-reversible effects);

$\gamma_{m2}$ is the factor for temperature effects (reversible effects);

$\gamma_{m3}$ is the factor for manufacturing effects;

$\gamma_{m4}$ is the factor for calculation accuracy and validation of method;

$\gamma_{m5}$ is the factor for load characterization.



ASCE STANDARD

ASCE/SEI

74-XX

# Load and Resistance Factor Design (LRFD) for Pultruded Fiber Reinforced Polymer (FRP) Structures

ASCE
AMERICAN SOCIETY OF CIVIL ENGINEERS

SEI
STRUCTURAL ENGINEERING INSTITUTE

PUBLISHED BY THE AMERICAN SOCIETY OF CIVIL ENGINEERS

Forthcoming 2022

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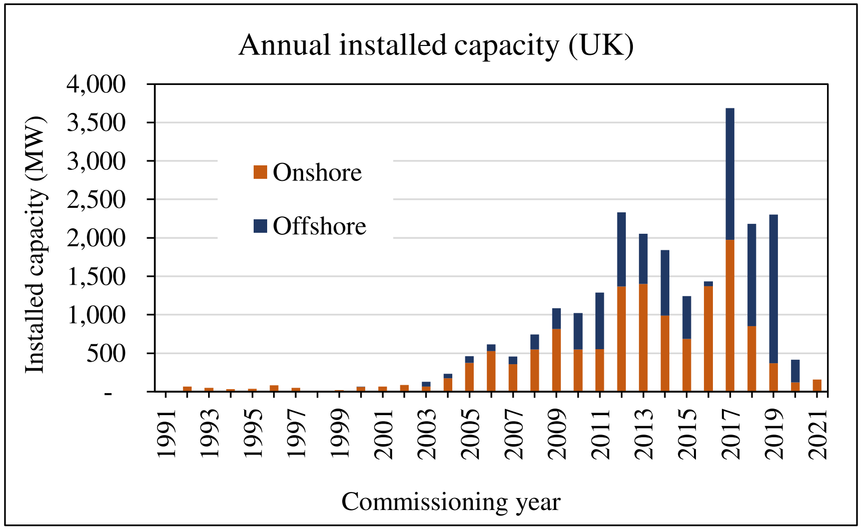
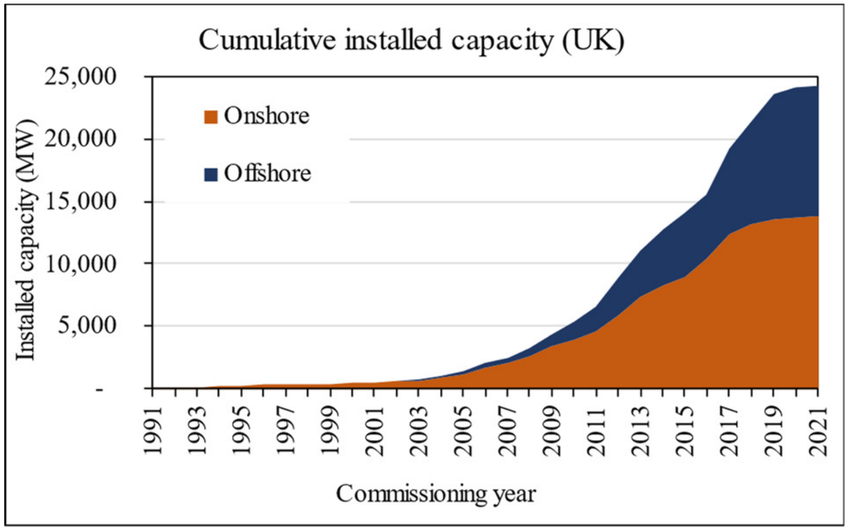
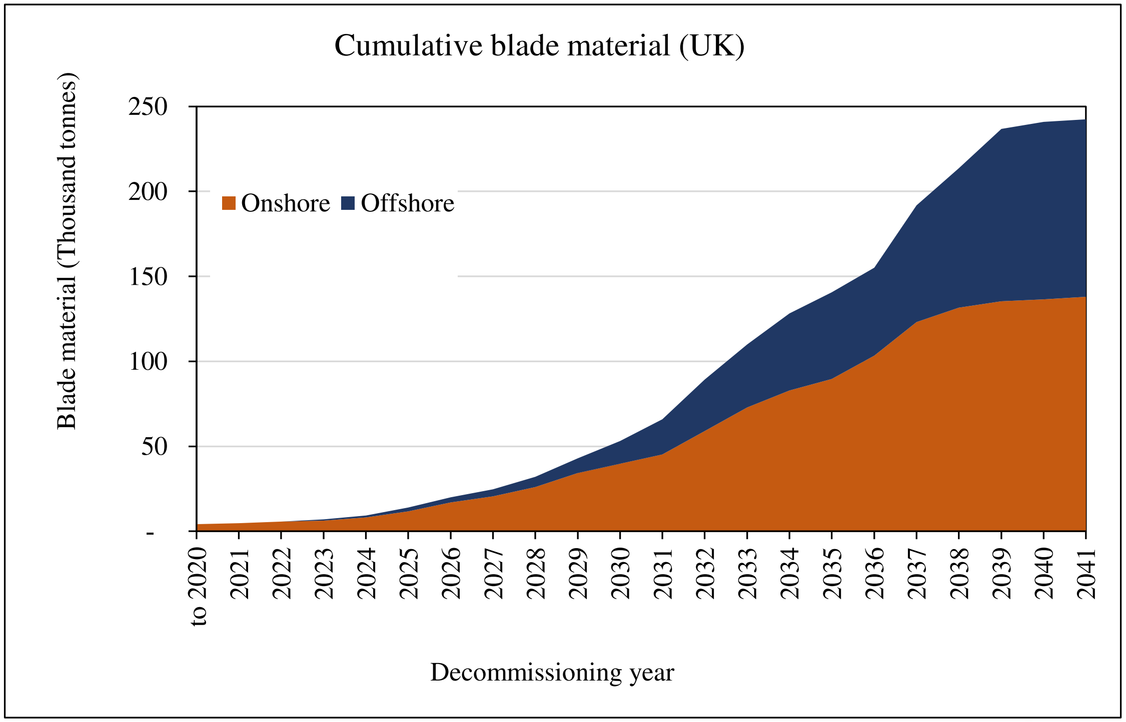
# Wind blade material quantity in the UK


Annual installed capacity (UK)


Cumulative installed capacity (UK)


Cumulative blade material (UK)

**Assumes 20-year life and 10 t/MW**

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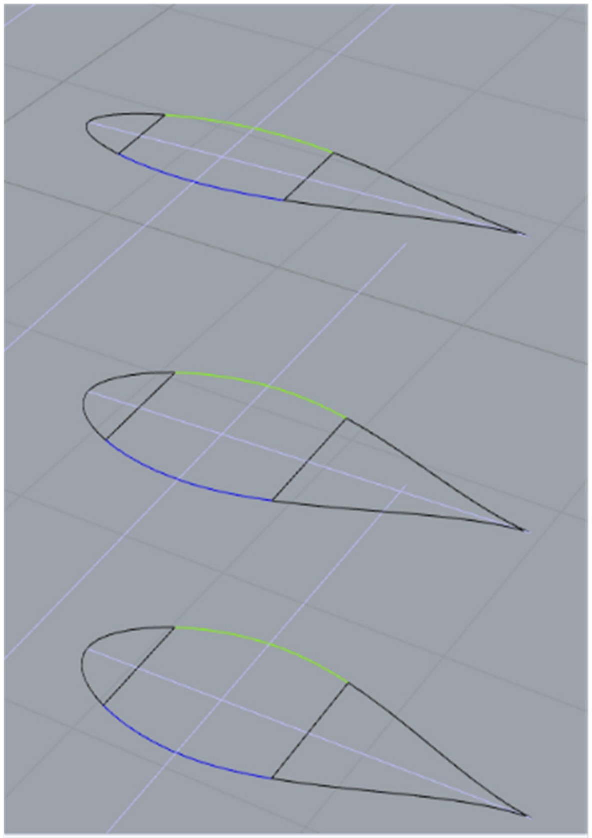
# What is needed for Engineering Analyses

1. **External geometry** – Airfoil shapes along the length, prebend and twist along the length.
2. **Internal geometry** – location and thickness of spar caps, webs, and shell sandwich panels along the length.
3. **Material types** (e.g., glass, polyester, epoxy) and laminates (or sandwich laminates) for spar cap, shell and webs, Mass (or volume fractions) of fiber and resin in the laminates in the spar cap, shell and webs, Fabric types used (e.g., +-45, mats, UD)
4. **Strength and stiffness** in the longitudinal and transverse directions and shear strength and stiffness of the spar cap, shell and web laminates; of the spar cap, shell and web laminates. Bearing strength for connections. As-received properties and estimate of residual related to virgin.
5. **Global blade structural properties** along the length $EI_x$, $EI_y$, GJ, kAG (where x and y and the chord axis and its perpendicular through the centroid of the cross-section. Principal axes and shear center.)

# Re-Wind BladeMachine

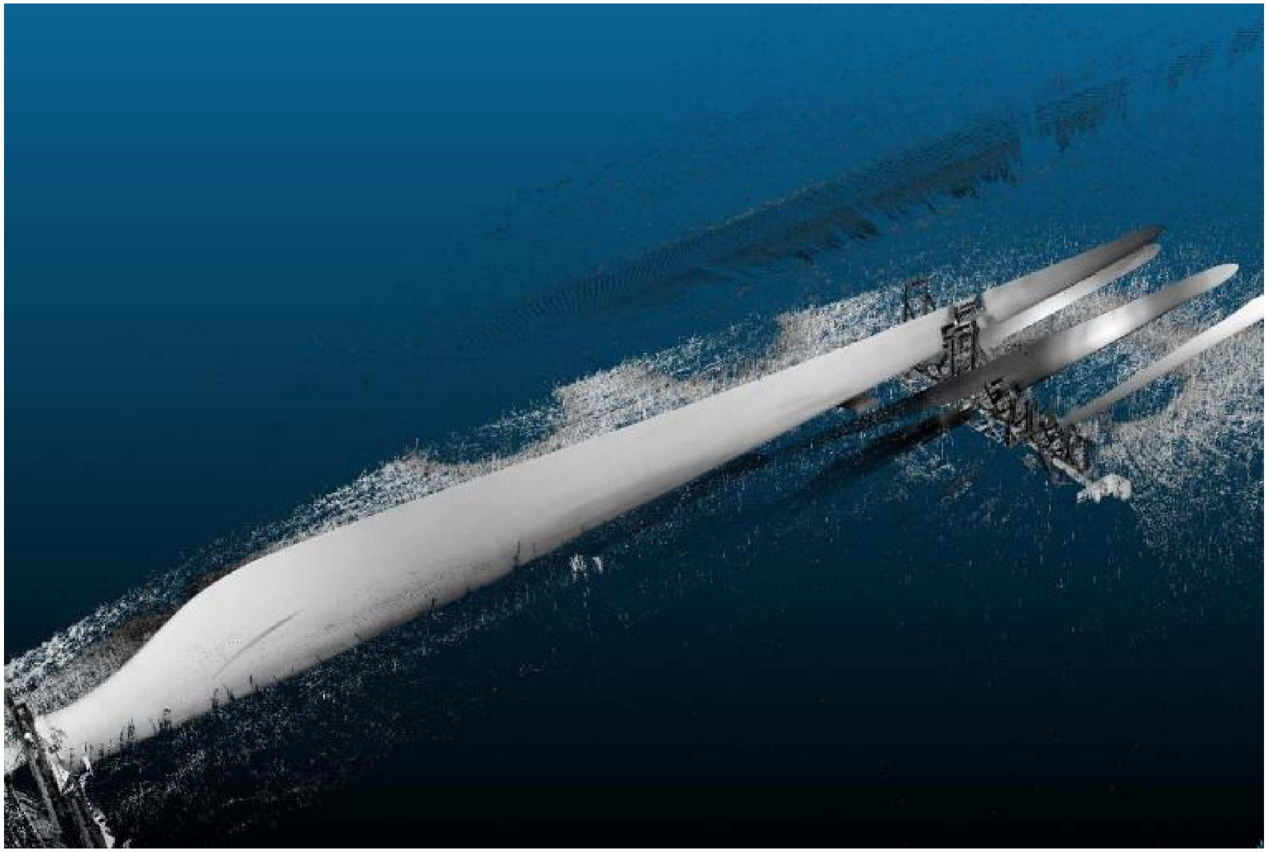
BladeMachine is software that automates the generation of architectural, engineering and fabrication models of the wind blades

The BladeMachine is written largely in Rhino/Grasshopper and python.



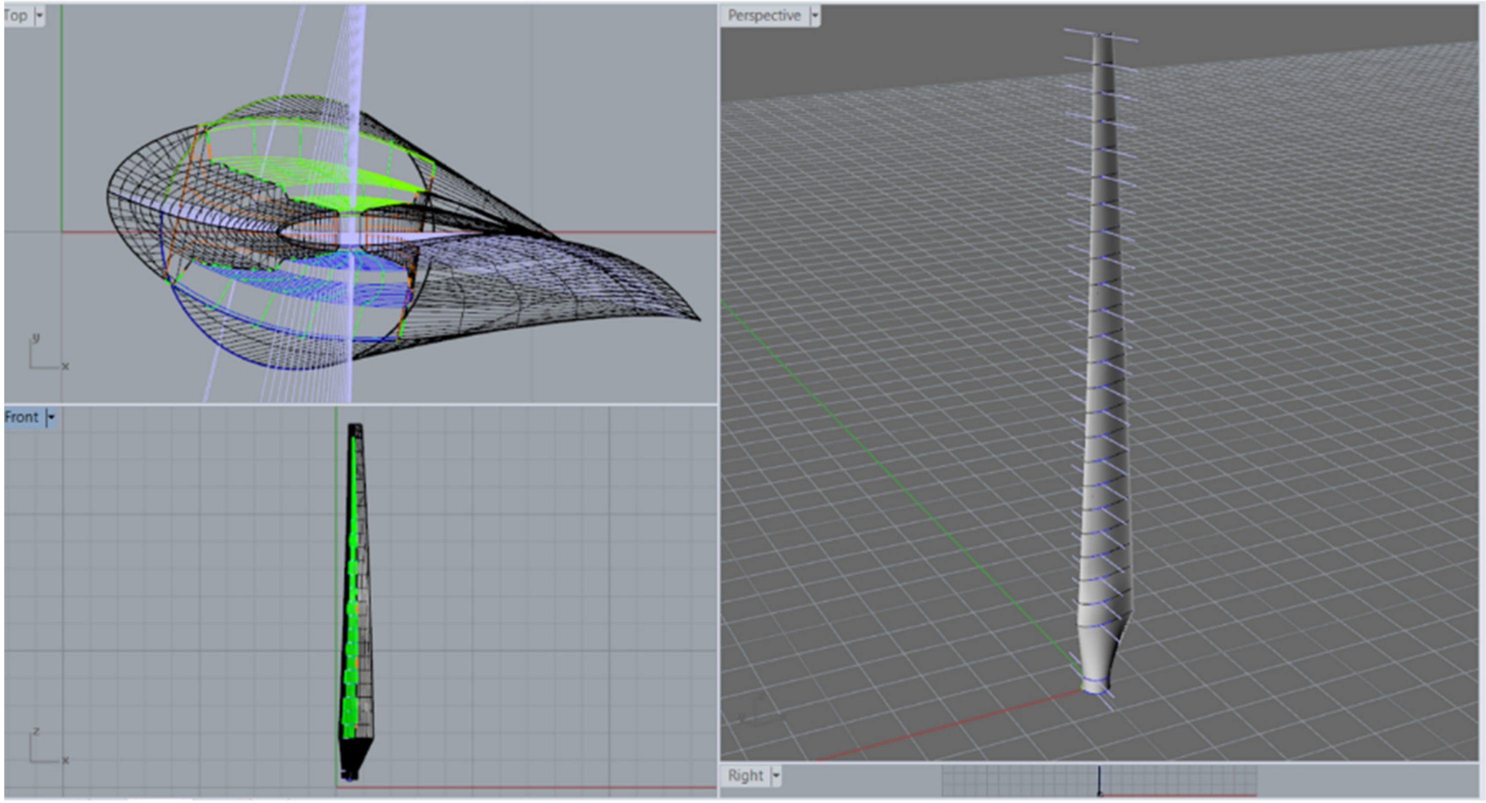
Patent Pending: Georgia Tech

# BladeMachine – 1. LiDAR scanning



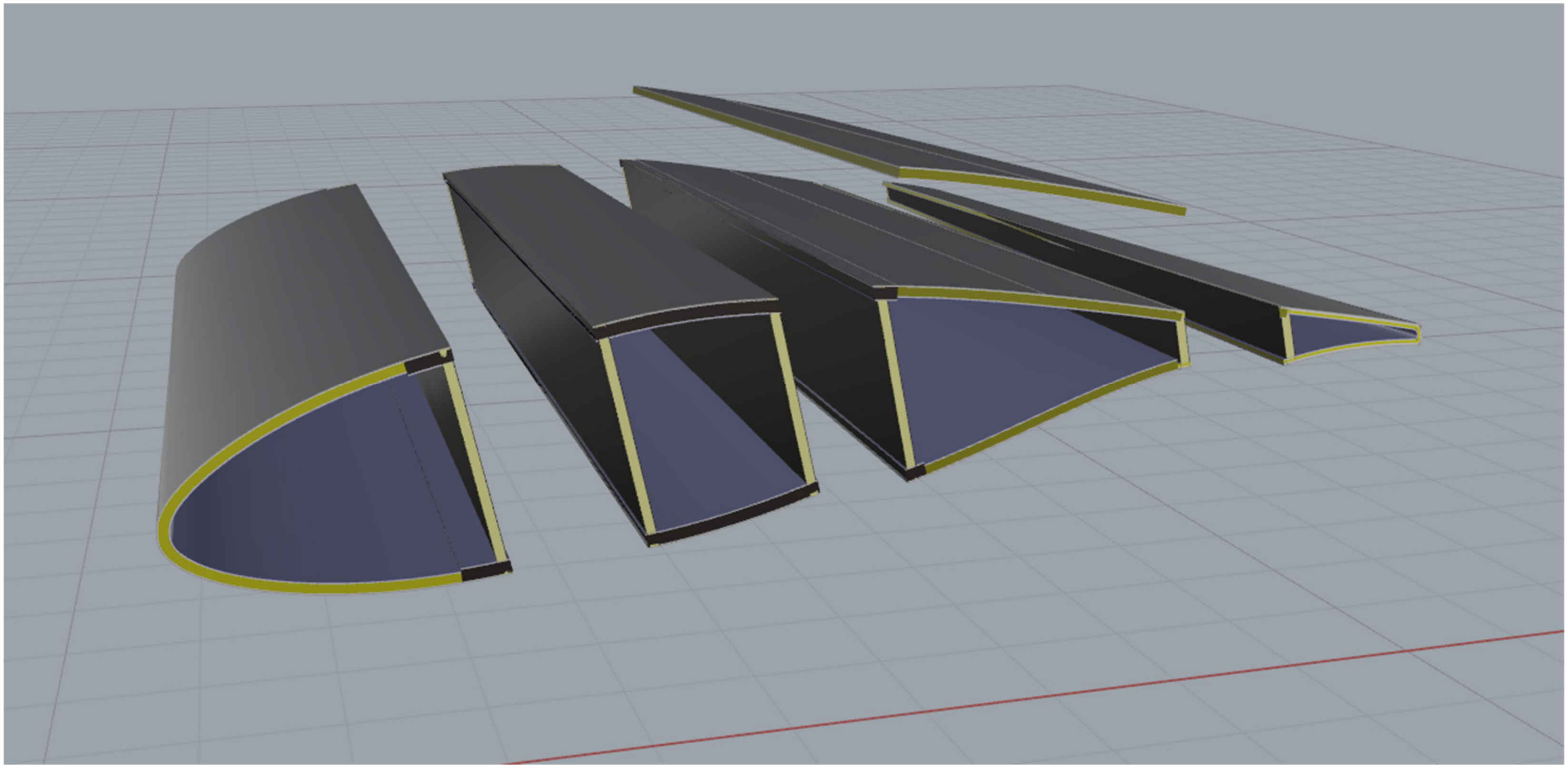
Patent Pending: Georgia Tech

# BladeMachine – 2. Geometry Construction

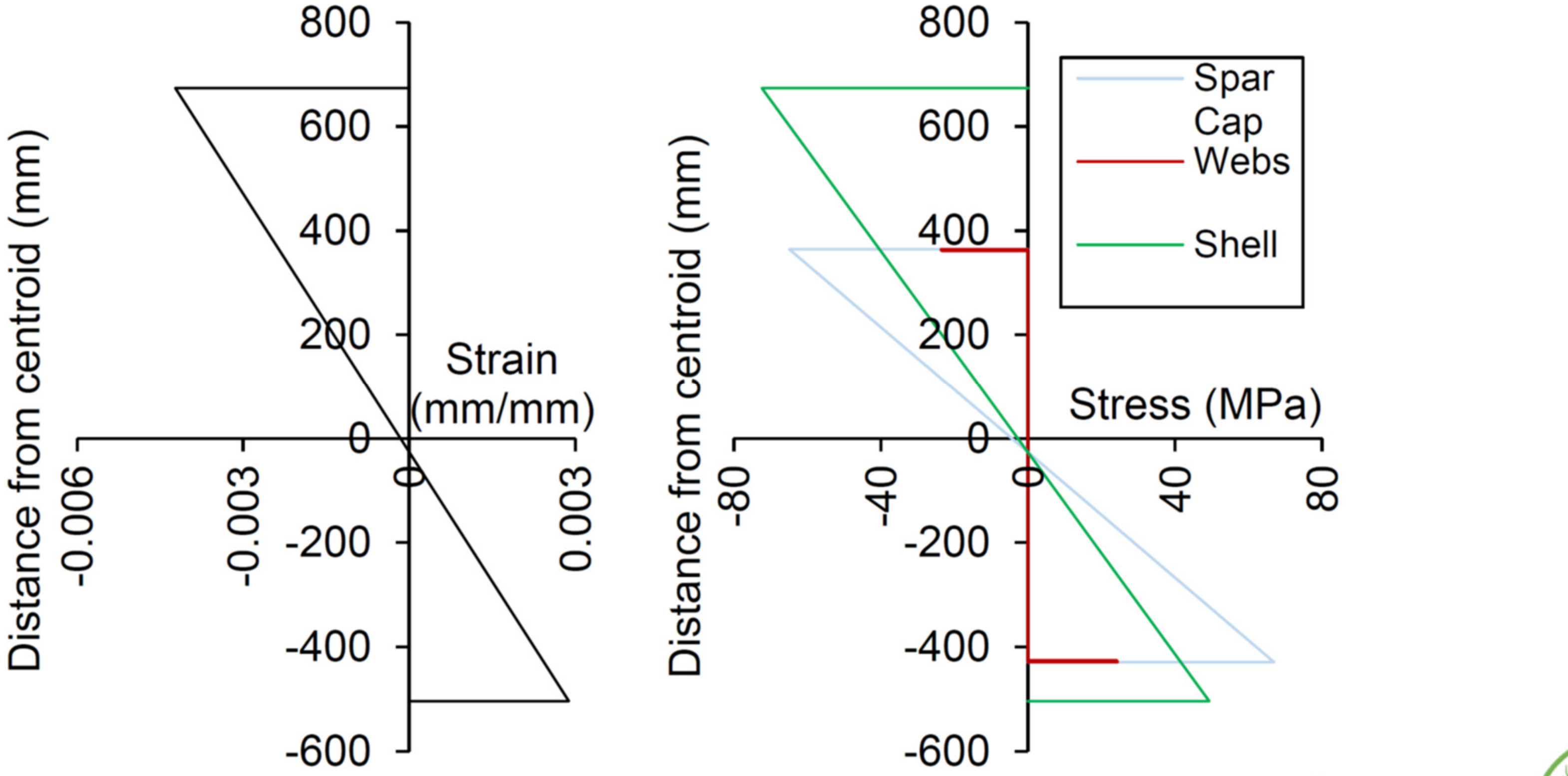


Patent Pending: Georgia Tech

# BladeMachine 3. “Thick” Model



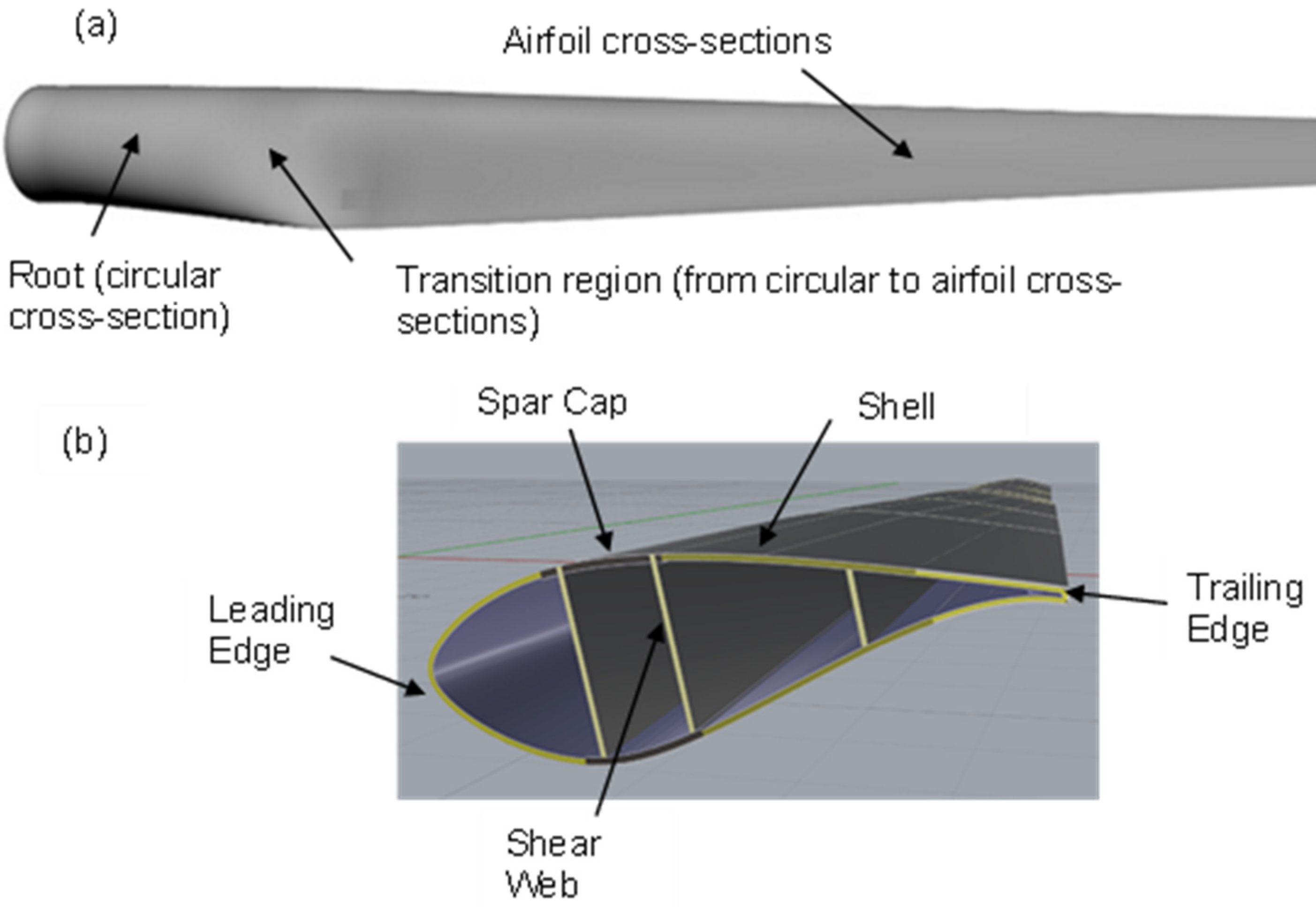
# BladeMachine – 4. Section Properties and Stress Analysis

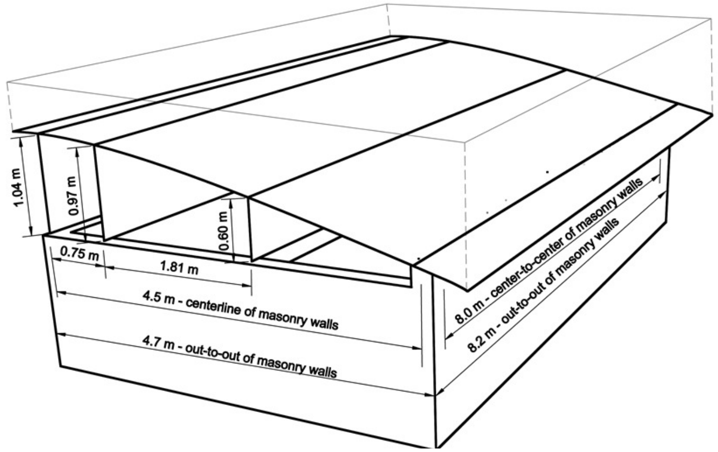


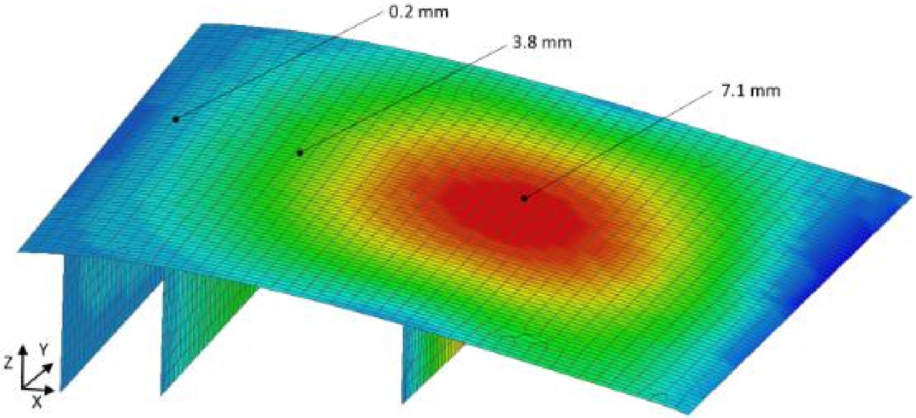
predicted flexural stresses from edgewise loading

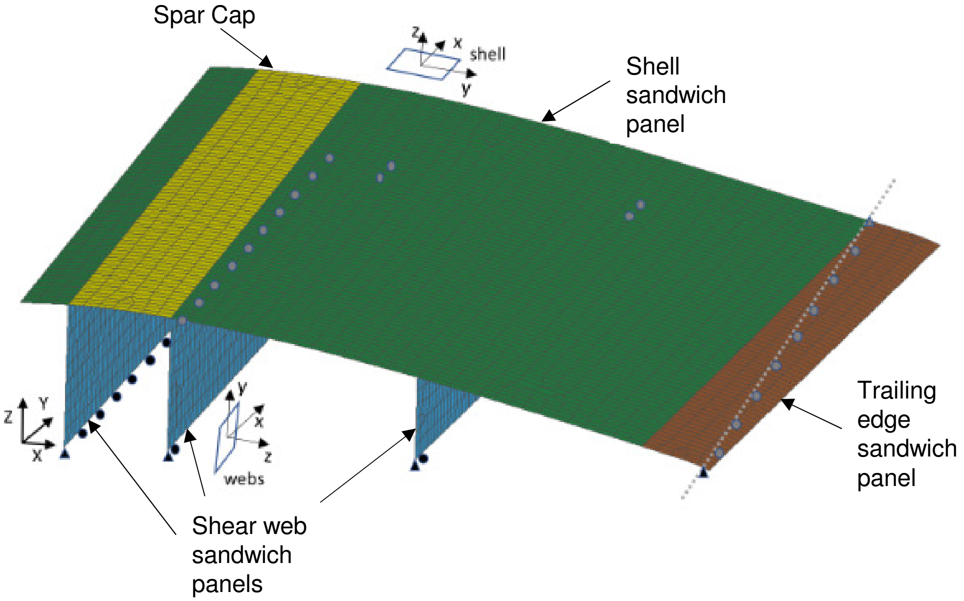
# Examples of Engineering Analyses

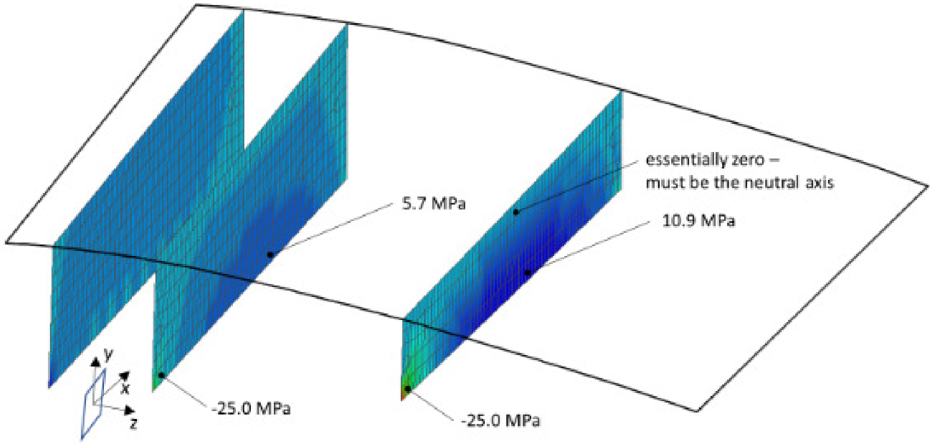
1. FEM of a blade section used as a roof for a $40m^2$ affordable house
2. Structural analysis of an entire blade used as a 230 kV transmission pole
3. Design and analysis of a pedestrian and cyclist bridge for a greenway


(a)
Airfoil cross-sections
Root (circular cross-section)
Transition region (from circular to airfoil cross-sections)
Tip
(b)
Spar Cap
Shell
Leading Edge
Trailing Edge
Shear Web









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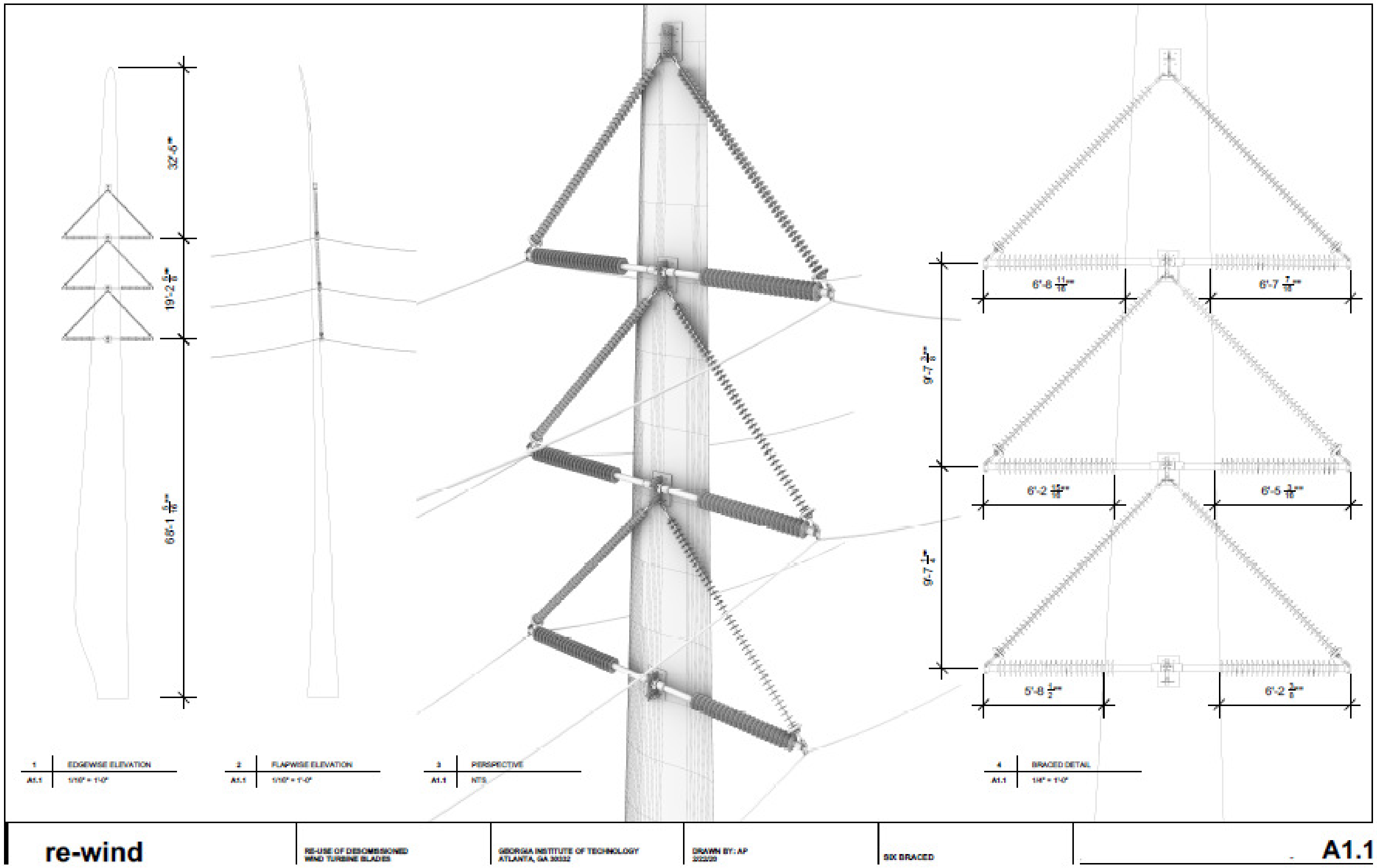
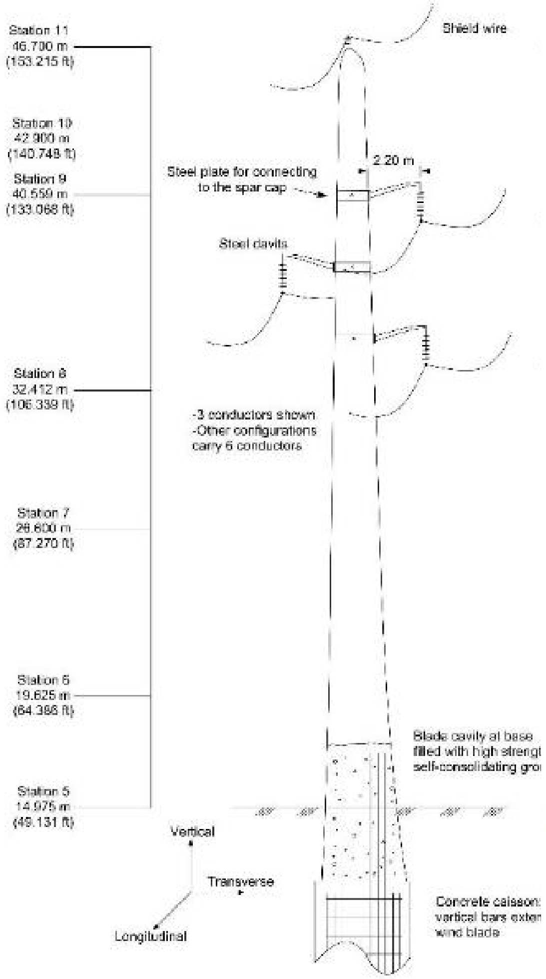
# BladePole Example

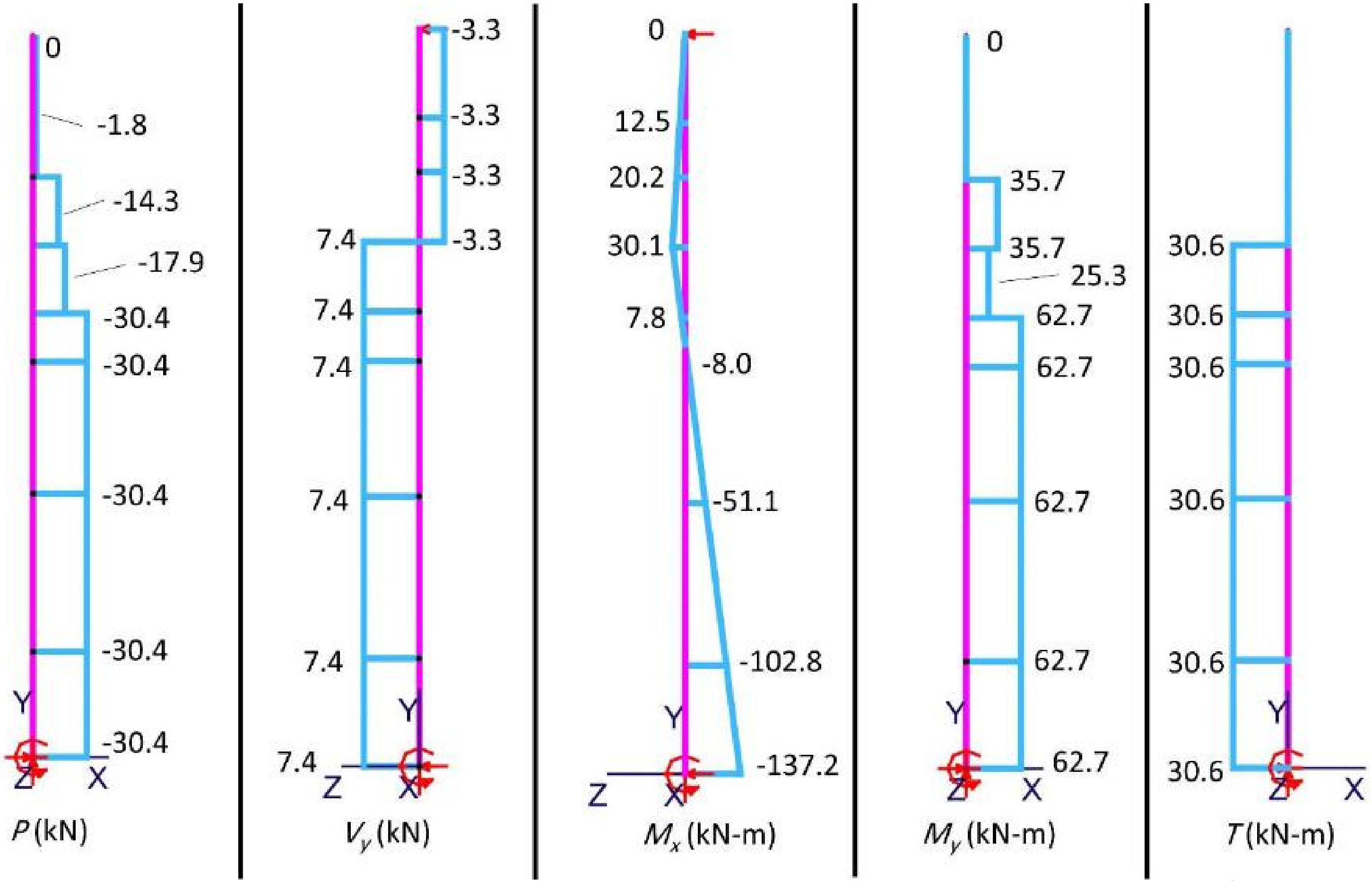
Patent Pending: Georgia Tech

# BladePole - Detailed Design



Patent Pending: Georgia Tech


Station 11
46.700 m
(153.215 ft)
Shield wire
Station 10
42.900 m
(140.748 ft)
2.20 m
Station 9
40.559 m
(133.068 ft)
Steel plate for connecting
to the spar cap
Steel davits
Station 8
32.412 m
(106.339 ft)
-3 conductors shown
-Other configurations
carry 6 conductors
Station 7
26.600 m
(87.270 ft)
Station 6
19.625 m
(64.388 ft)
Blade cavity at base
filled with high strengt
self-consolidating gro
Station 5
14.975 m
(49.131 ft)
Vertical
Transverse
Longitudinal
Concrete caisson:
vertical bars exter
wind blade


0
-1.8
-14.3
-17.9
-30.4
-30.4
-30.4
-30.4
-30.4
Y
Z
X
P (kN)
-3.3
-3.3
-3.3
-3.3
7.4
7.4
7.4
7.4
7.4
7.4
Y
Z
X
V_y (kN)
0
12.5
20.2
30.1
7.8
-8.0
-51.1
-102.8
-137.2
Y
Z
X
M_x (kN-m)
0
35.7
35.7
25.3
62.7
62.7
62.7
62.7
62.7
Y
Z
X
M_y (kN-m)
30.6
30.6
30.6
30.6
30.6
30.6
Y
Z
X
T (kN-m)

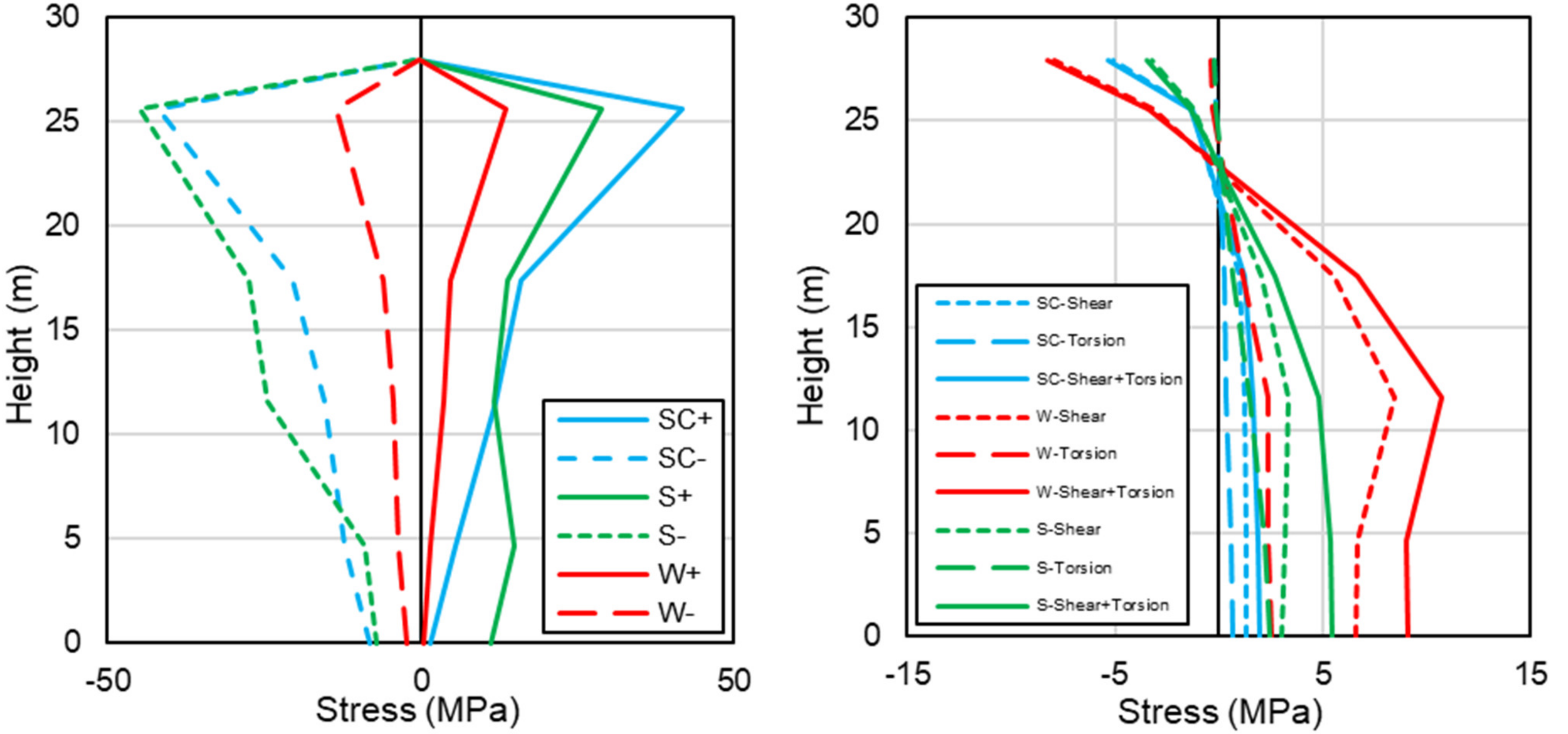


**Figure 4.** Diagrams for: (**a**) controlling axial stresses from load case 1; (**c**) controlling shear stresses from load case 2

# The BladeBridge (2016 – to-date)

- 2016- 2017 – Initial Concepts and Alternative Designs; Specific blade identification for demonstration project (LM13.4 or V44), LiDAR scanning of V44 blade
- 2018 – Blade mechanical and structural properties determined; Preliminary bridge structural analysis and design completed
- 2019 - First (ever) paper published on the BladeBridge analysis and design
  - R. Suhail et al., (2019), "Analysis and Design of a Pedestrian Bridge with Decommissioned FRP Windblades and Concrete," Proceedings of FRPRCS14, Paper 176, Belfast, UNITED KINGDOM.
- 2020 - N29 (LM 13.4) Blades obtained from Everun in Northern Ireland and delivered to Munster Technological University in Cork; Bridge design engineer Kieran Ruane joins team; BladeBridge approved in County Cork, Ireland.
- 2020 – N29 blades delivered to Queen's University Belfast for 8 m test bridge.
- 2021 – Blade characterization and testing. Bridge detailed design.
- 2021 – BladeBridge currently being constructed and installed (Oct-Dec 2021).
- 2022 – Paper at Transportation Research Board, Washington, DC (Jan, 2022)
  - K. Ruane et al., (2022) "Experimental Investigation of an FRP Wind Turbine Blade for use as a Bridge Girder"

# BladeBridges

Nordex N29 (~13 m)
Vestas V29/A29
5-8 m BladeBridge

Vestas V44 (~21 m)
12-15 m BladeBridge

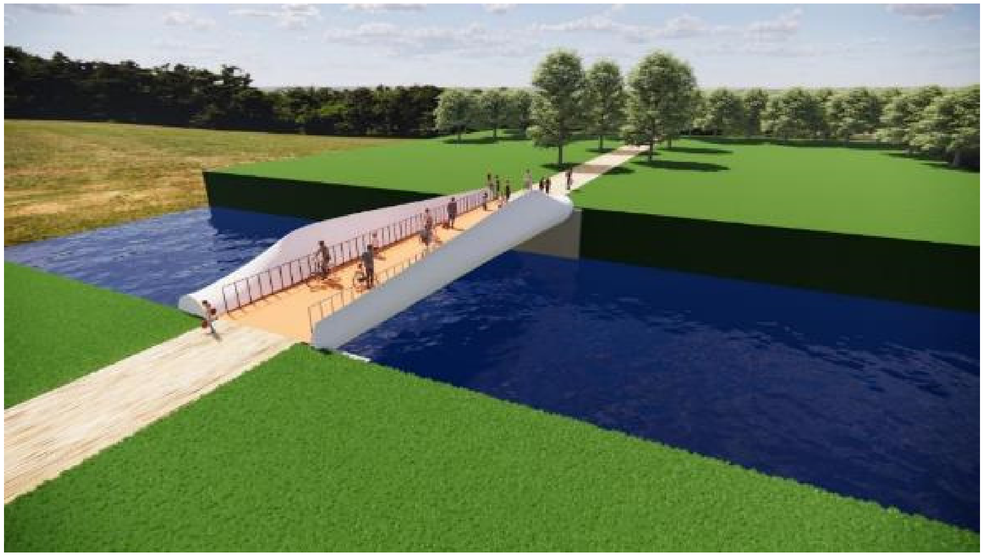
# BladeBridges

**GE 37 (~37m)**
**15-25m BladeBridge**

**Clipper C96 (~46m)**
**25-35m BladeBridge**

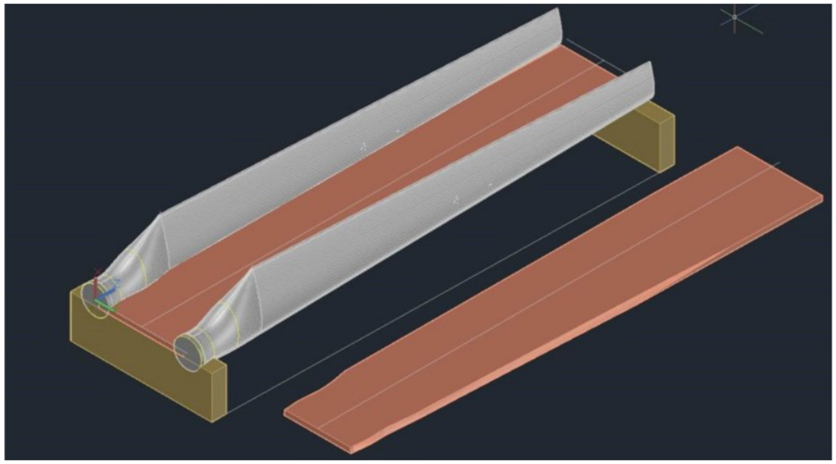
# BladeBridges

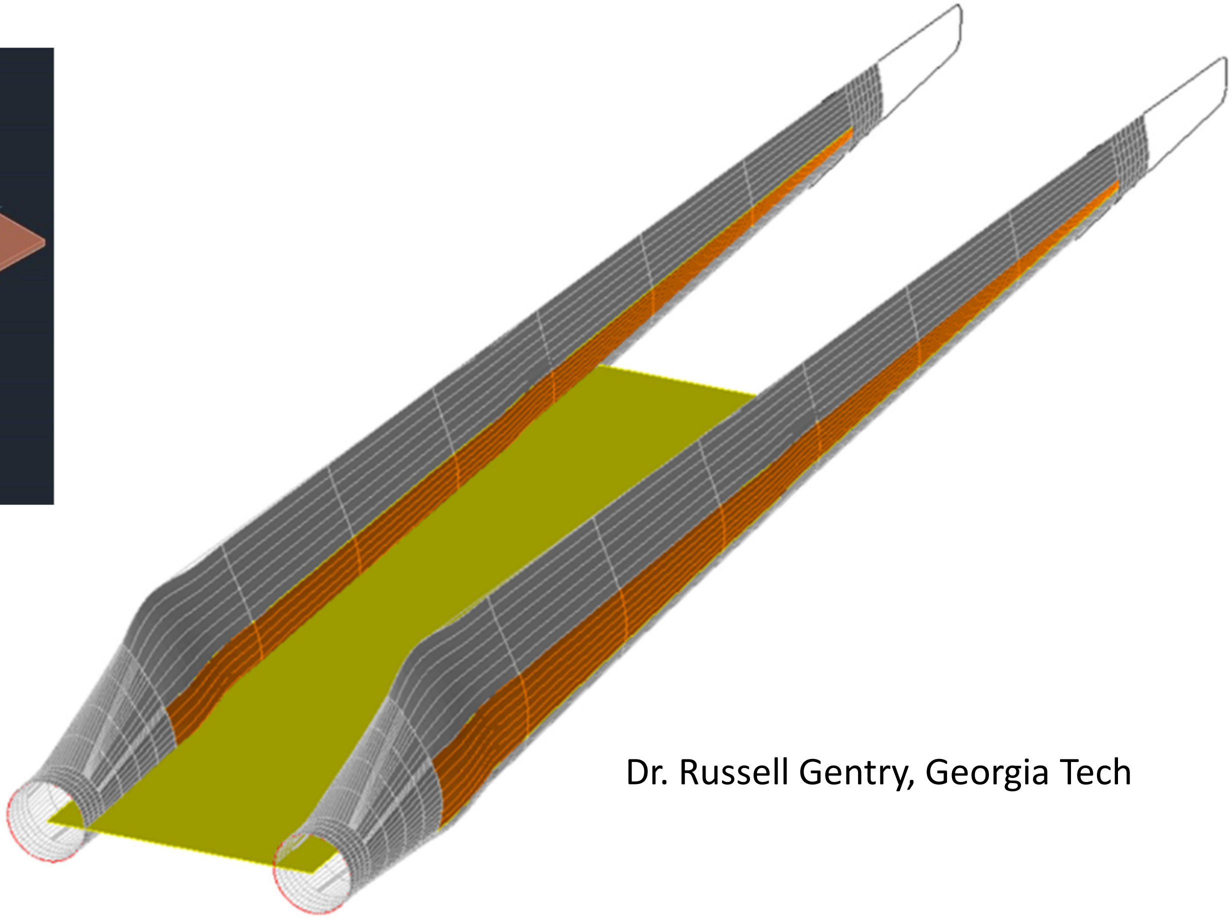
**Extensions**



**Asymmetrical**

# 2017-2018 – Preliminary Concept and CAD model



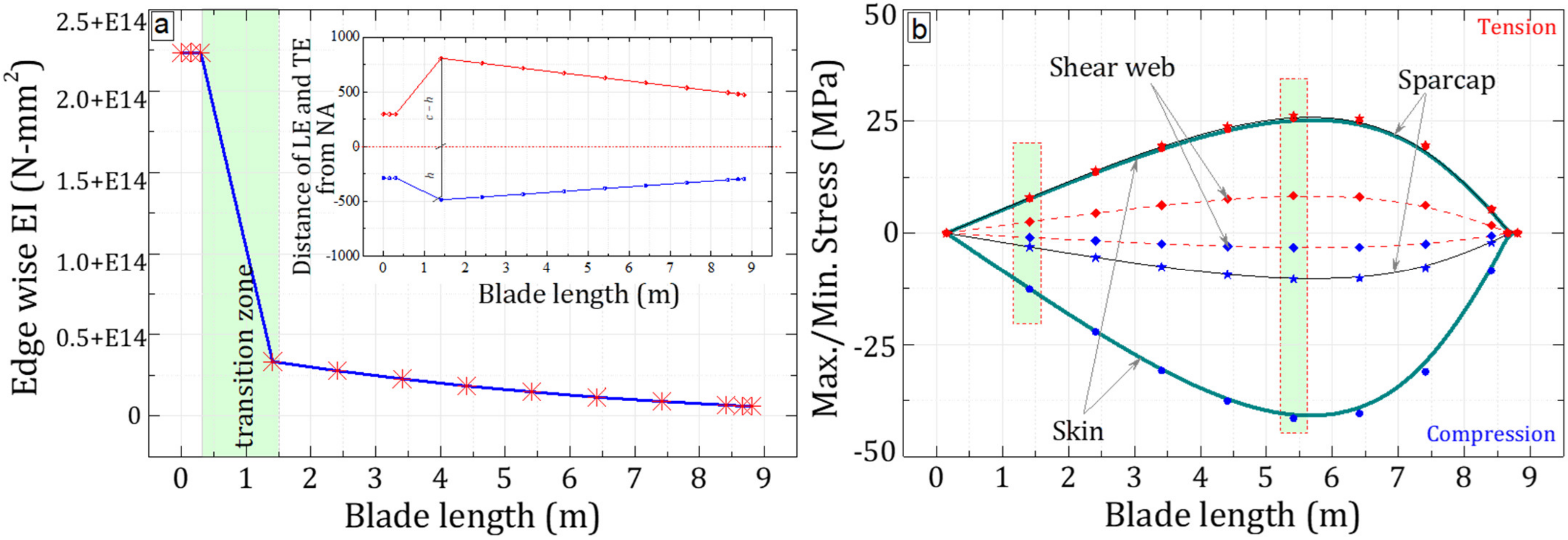


Dr. Russell Gentry, Georgia Tech

Why this "simple" design?

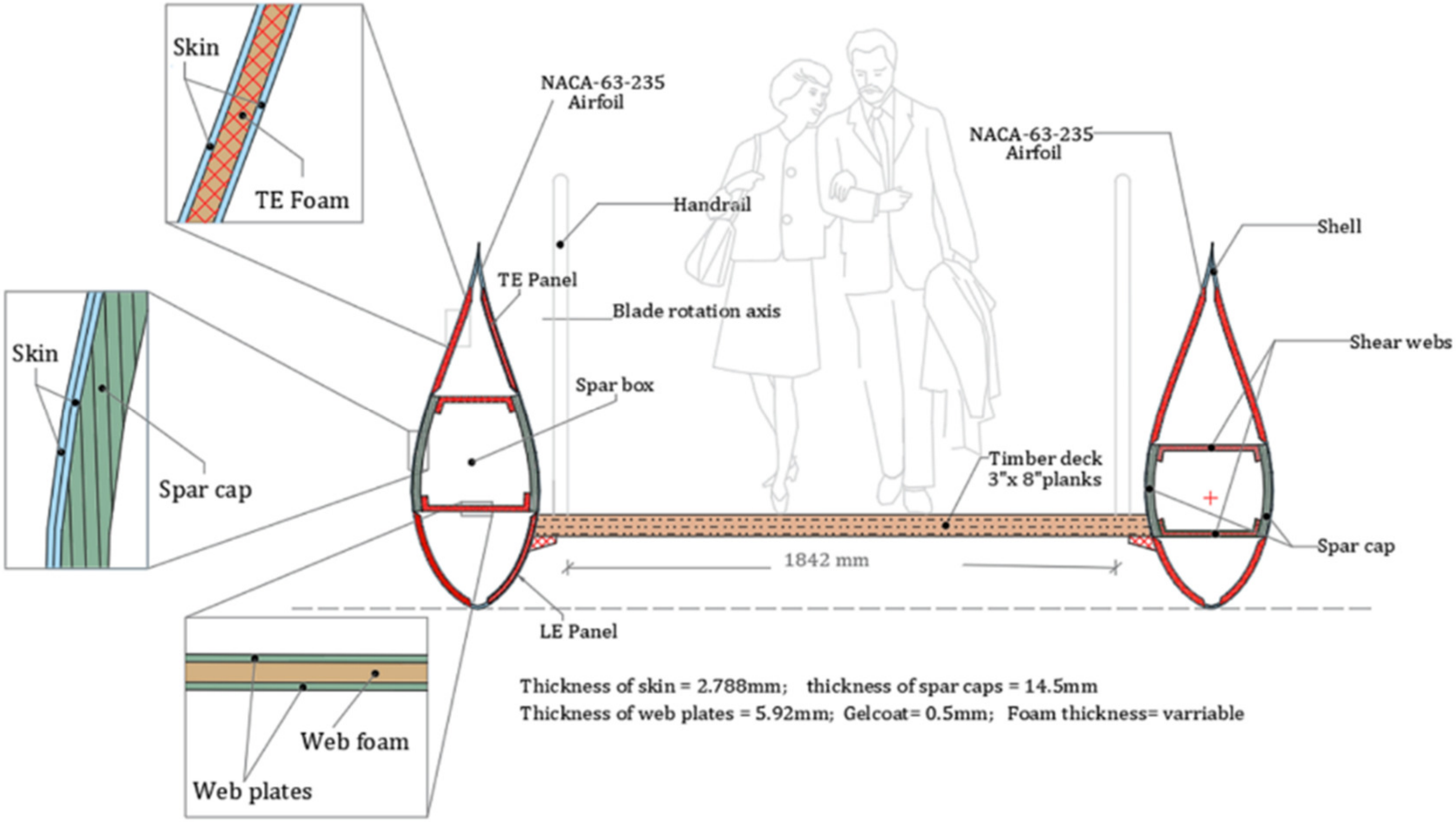
- Mass market not bespoke
- It is "simple" for structural analysis, design and construction
- Fits all size blades

# 2018-2019 – Preliminary Structural Analysis



Dr. Raj Suhail and Dr. Jian Fei Chen, Queen’s University Belfast

# 2018-2019 – Preliminary BladeBridge design



Thickness of skin = 2.788mm; thickness of spar caps = 14.5mm

Thickness of web plates = 5.92mm; Gelcoat= 0.5mm; Foam thickness= varriable

Dr. Raj Suhail and Dr. Jian Fei Chen, Queen's University Belfast

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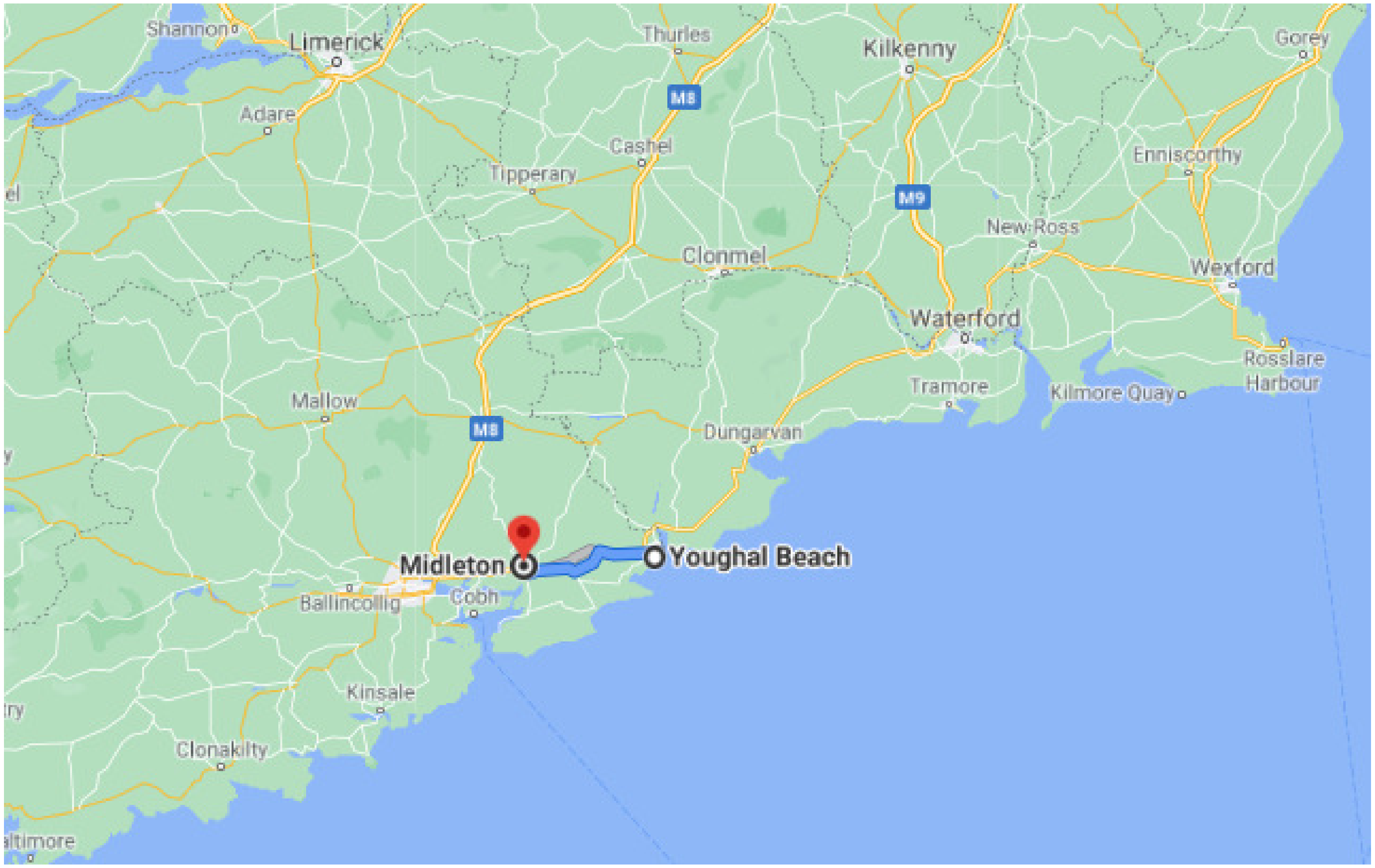
# The Cork BladeBridge - 2021

# Context


Shannon
Limerick
Thurles
Kilkenny
Gorey
M8
Adare
Cashel
Tipperary
Enniscorthy
M9
New Ross
Clonmel
Wexford
Waterford
Rosslare Harbour
Tramore
Kilmore Quay
Mallow
M8
Dungarvan
Midleton
Youghal Beach
Ballincollig
Cobh
Kinsale
Clonakilty

# Context

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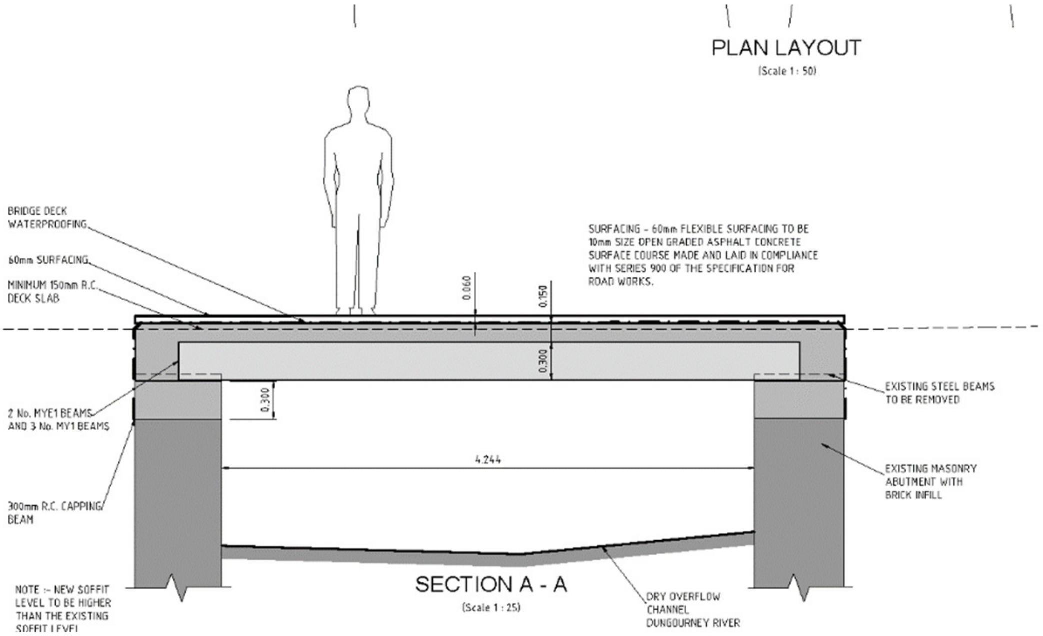
# Context

**Span ~ 5.0**

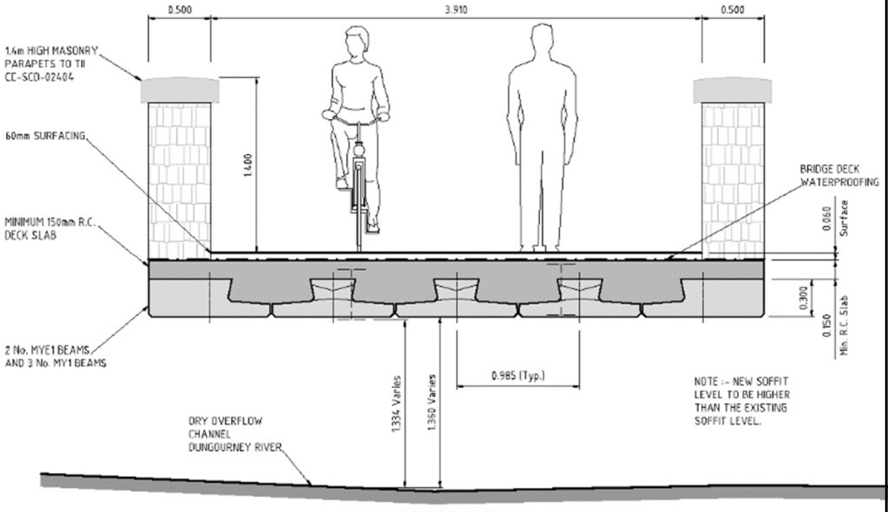
**Width ~ 3-4m**

**Skew ~ 18°**

# Context – Original Plan



SECTION A - A
(Scale 1 : 25)



SECTION B - B
(Scale 1 : 25)

# Conceptual Design

Ms. Zoe Zhang, GT

# Conceptual Design

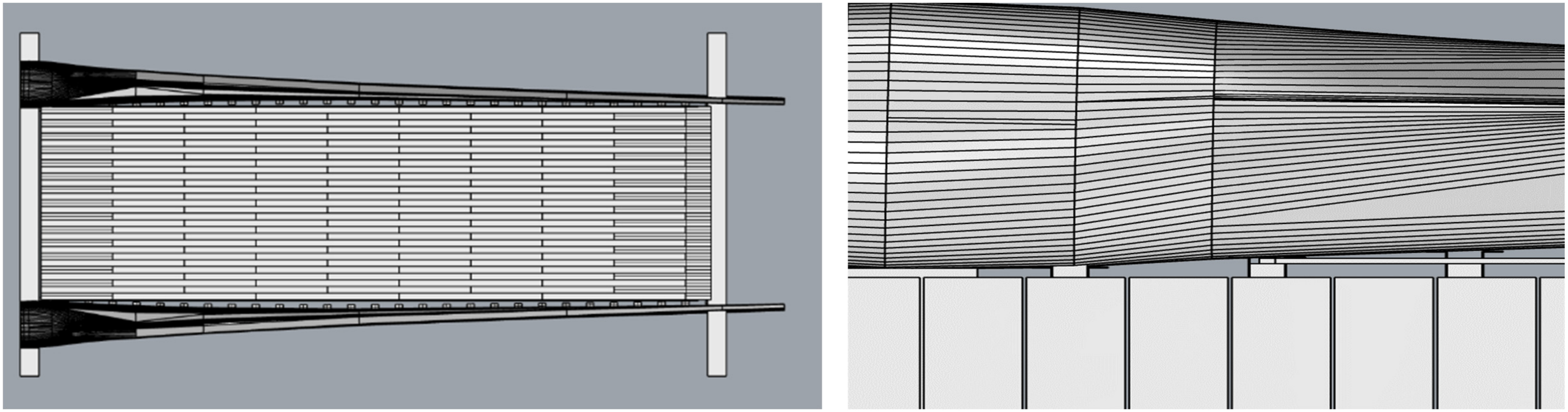
RE-WIND
NETWORK
BLADE REPURPOSING
SOLUTIONS

# Conceptual Design

Ms. Zoe Zhang, GT

# Conceptual Design

## Windblade Alignment



Ms. Zoe Zhang, GT

Complexity of Geometry must be accounted for in actual designs:
Pitch of blades, straightness of blades, spacing between blades

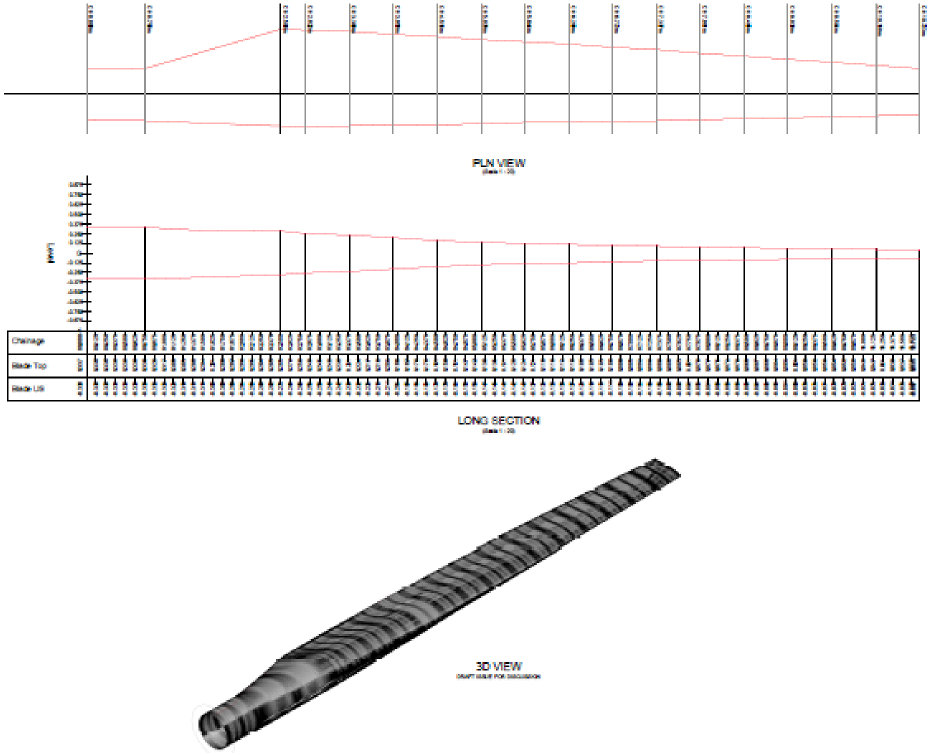
# Sourcing Blades – Laser Scanning

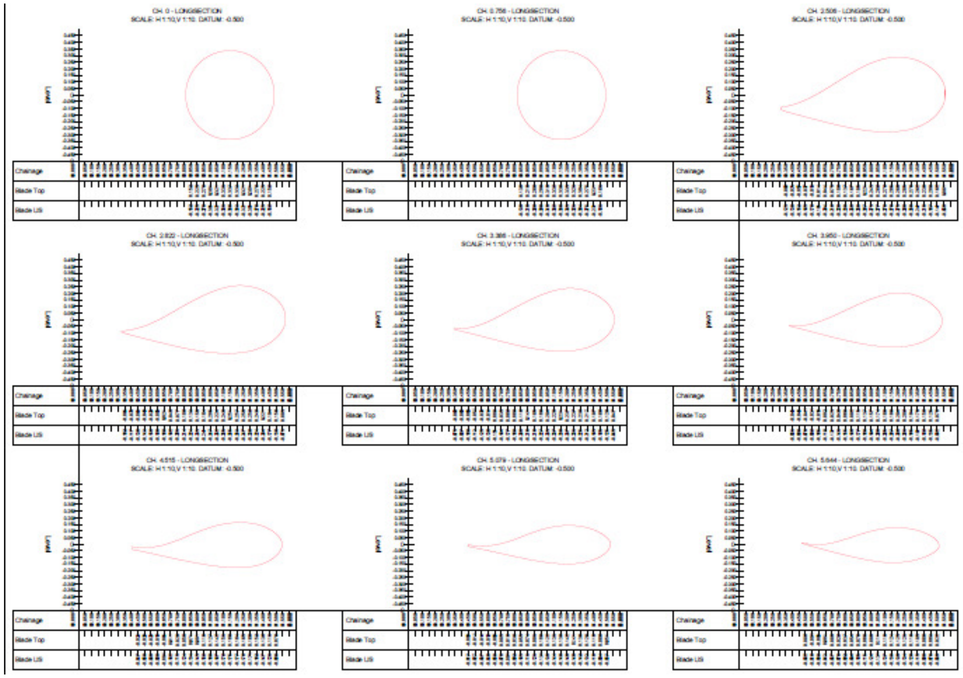
# Working with the N29 Blades – MTU Structures Laboratory

# Working with the N29 Blades – MTU Structures Laboratory

# Working with the N29 Blades – Scanning & Measuring

# Working with the N29 Blades – Scanning and Measuring



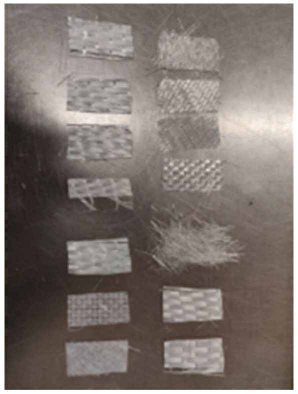


# N29 Testing and Investigating

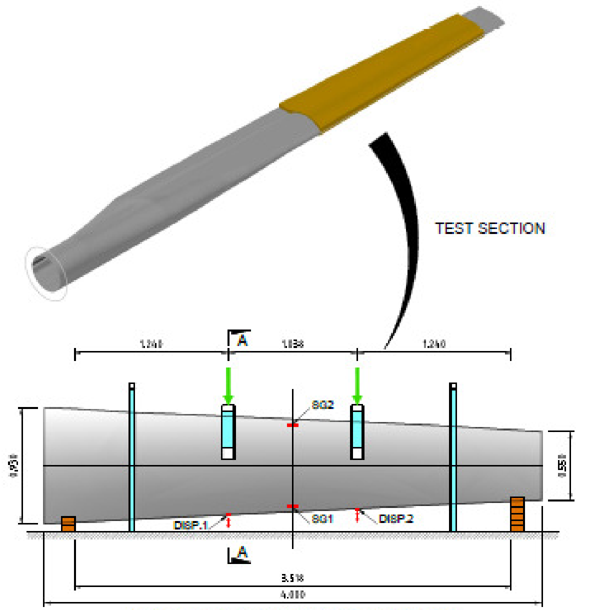
Static loads

Connections

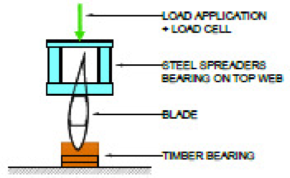
GFRP burn-out



# N29 Testing and Investigating – Static Load Tests



ELEVATION OF TEST SECTION
(Scale 1 : 25)



SECTION A - A
(Scale 1 : 25)

# N29 Testing and Investigating – Static Load Tests

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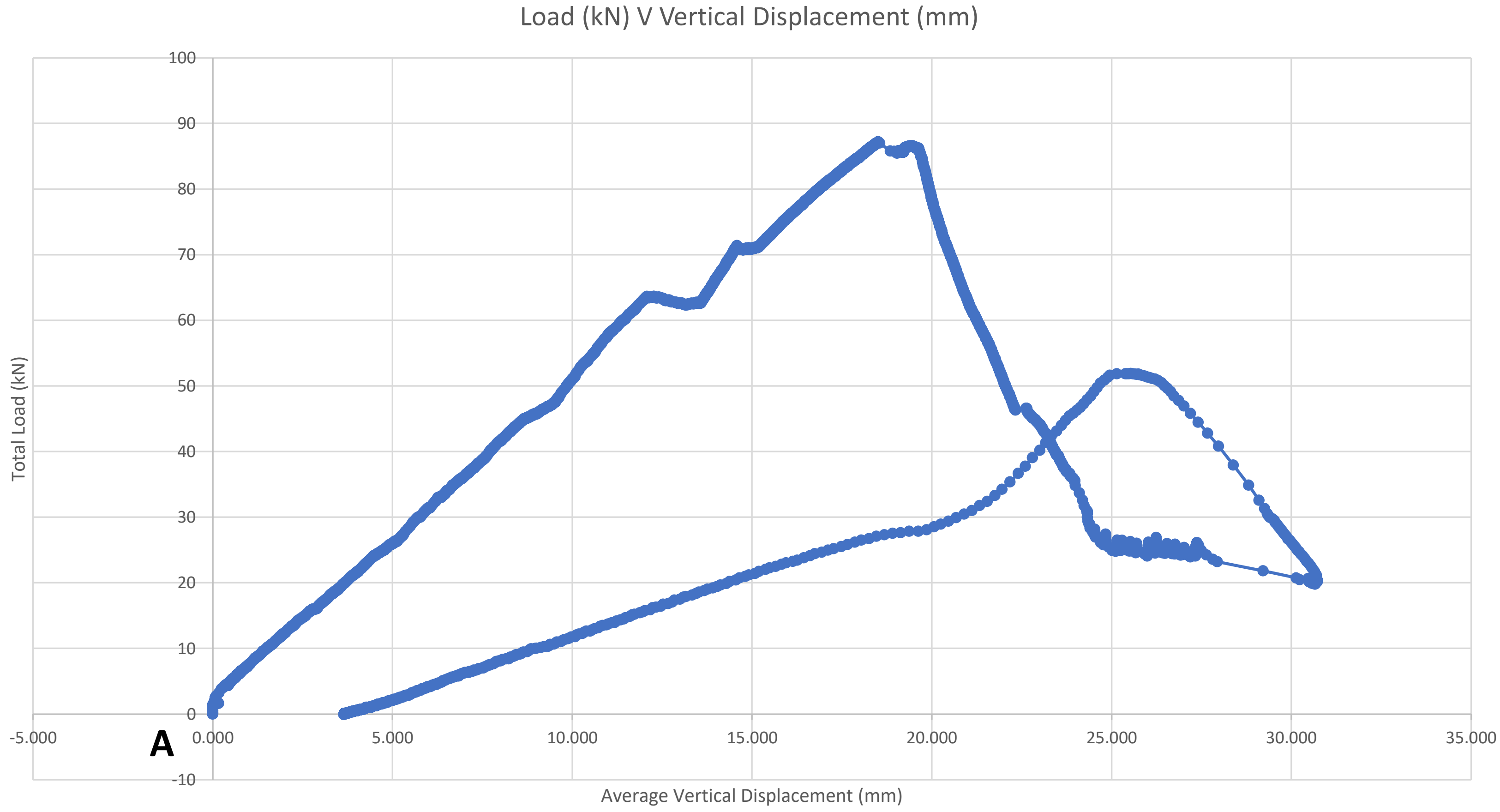
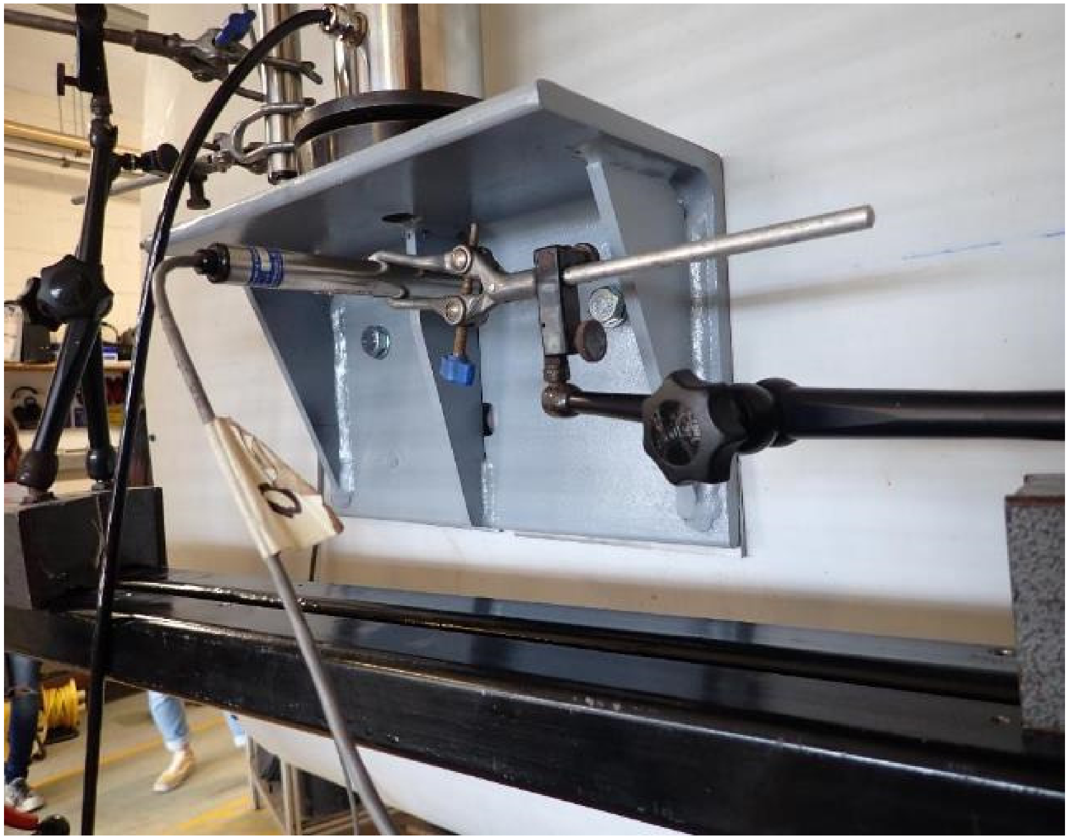
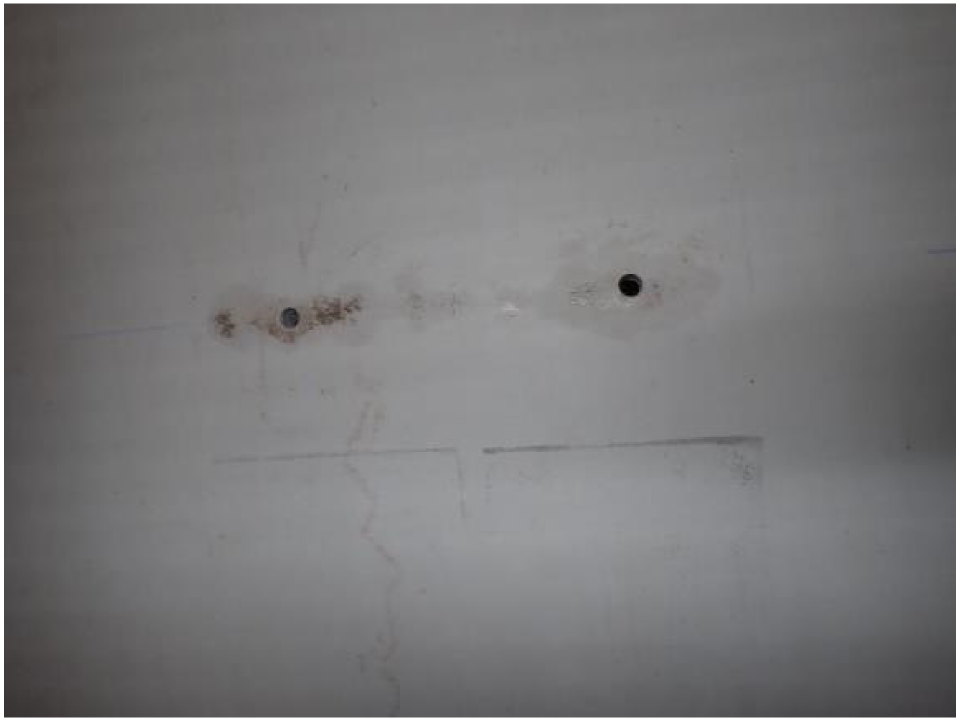


# N29 Testing and Investigating – Connection Tests (3 No.)



- M12 Grade 8.8 Bolts
- M12 Grade 8.8 BlindBolts
- 12 dia Threaded Bar

# N29 Testing and Investigating – Connection Tests (3 No.)



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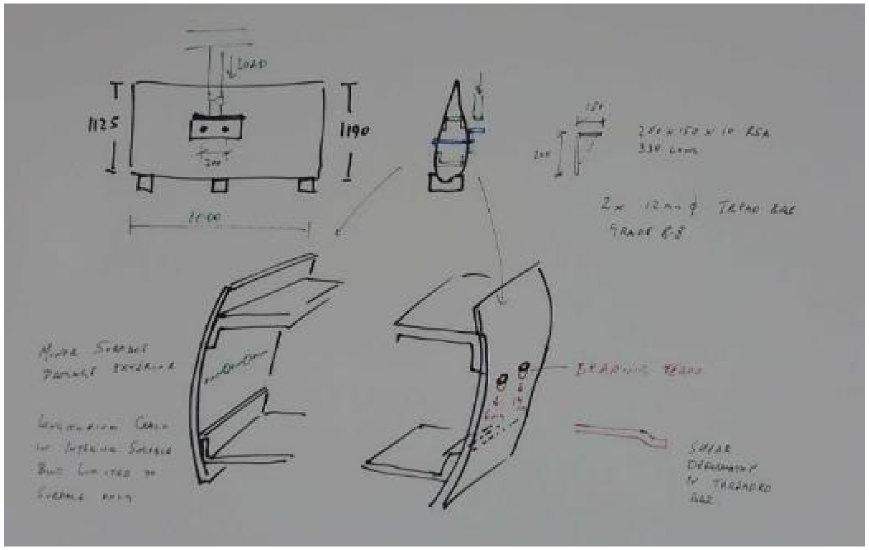

# N29 Testing and Investigating – Connection Tests (3 No.)

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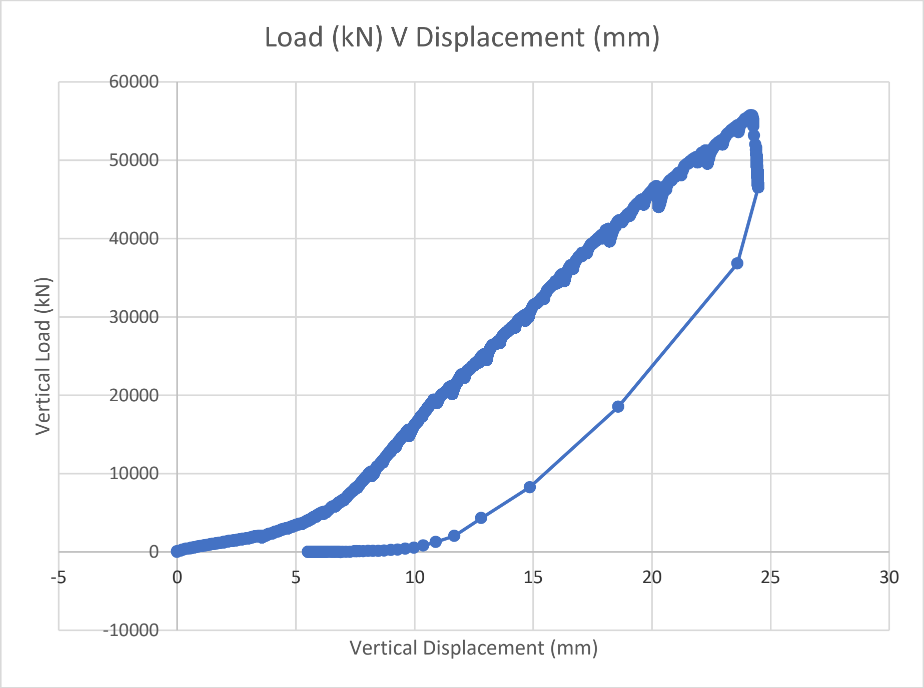
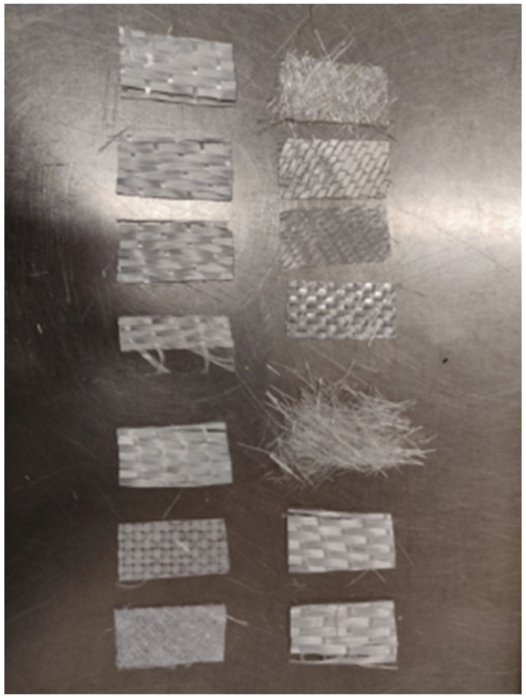
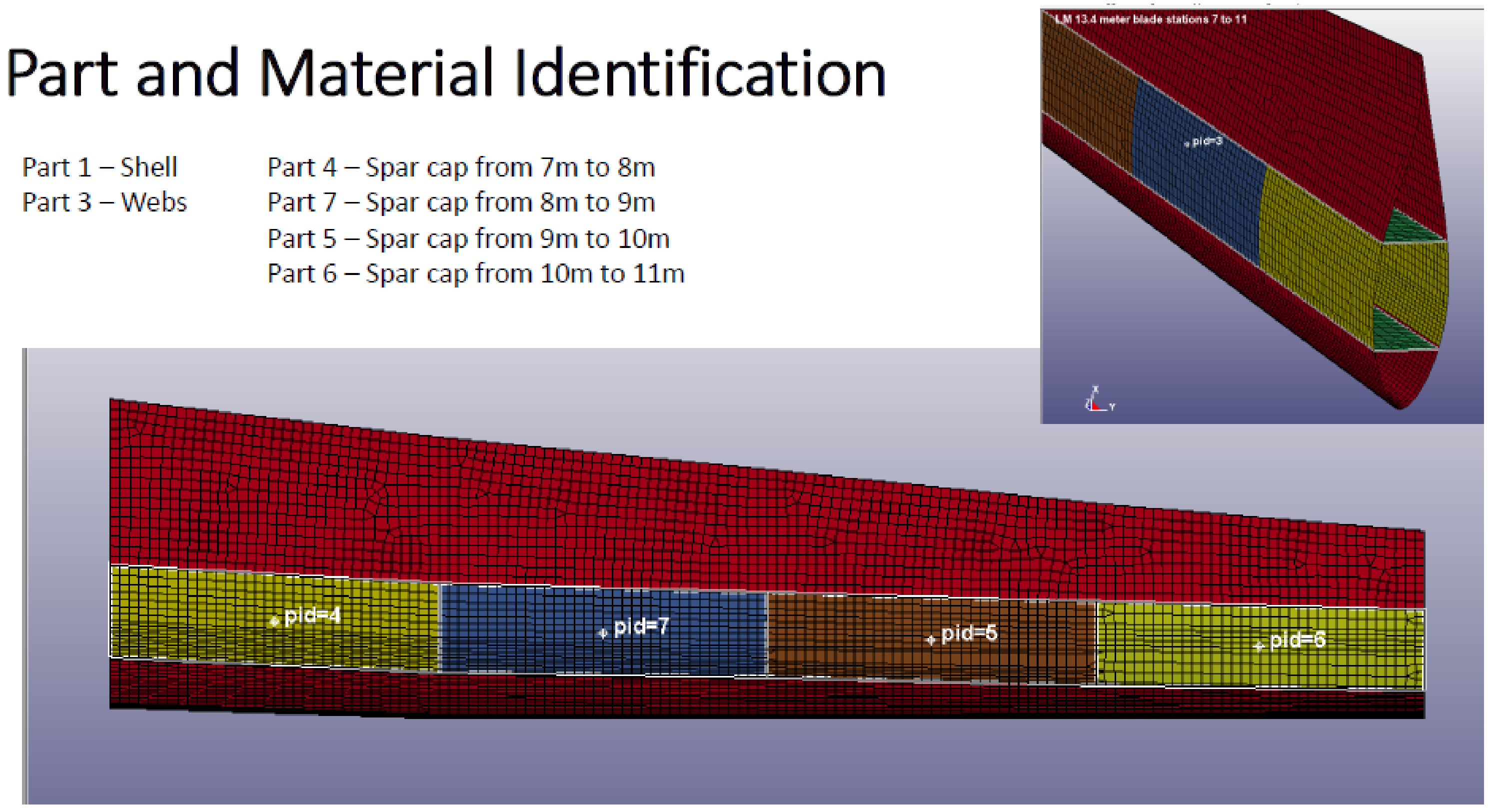


# N29 Testing and Investigating – GFRP Burnout & LS-DYNA FEA (GT)



# N29 Testing and Investigating – GFRP Burnout & LS-DYNA FEA (GT)



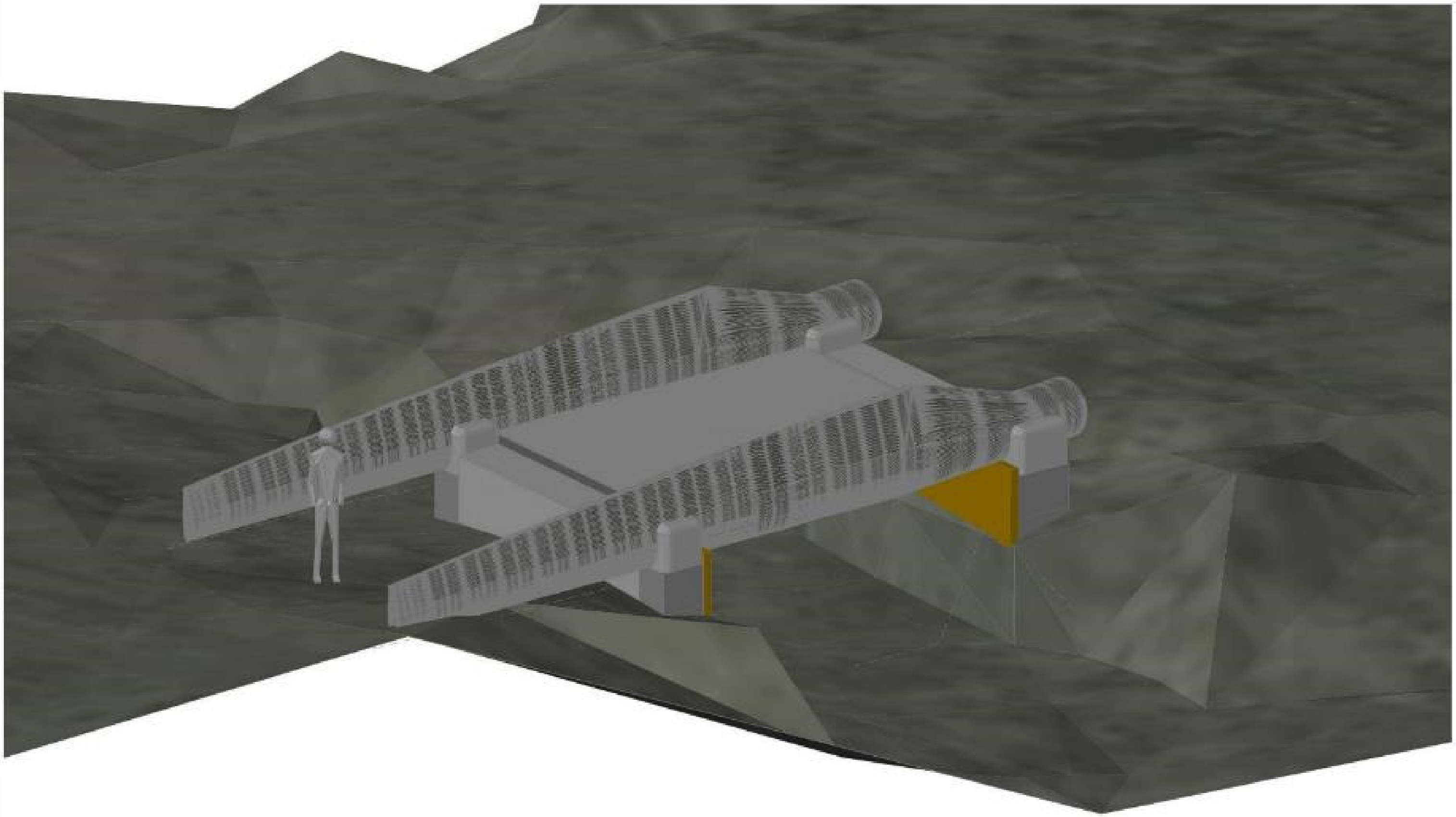
## Part and Material Identification

Part 1 – Shell
Part 3 – Webs

Part 4 – Spar cap from 7m to 8m
Part 7 – Spar cap from 8m to 9m
Part 5 – Spar cap from 9m to 10m
Part 6 – Spar cap from 10m to 11m

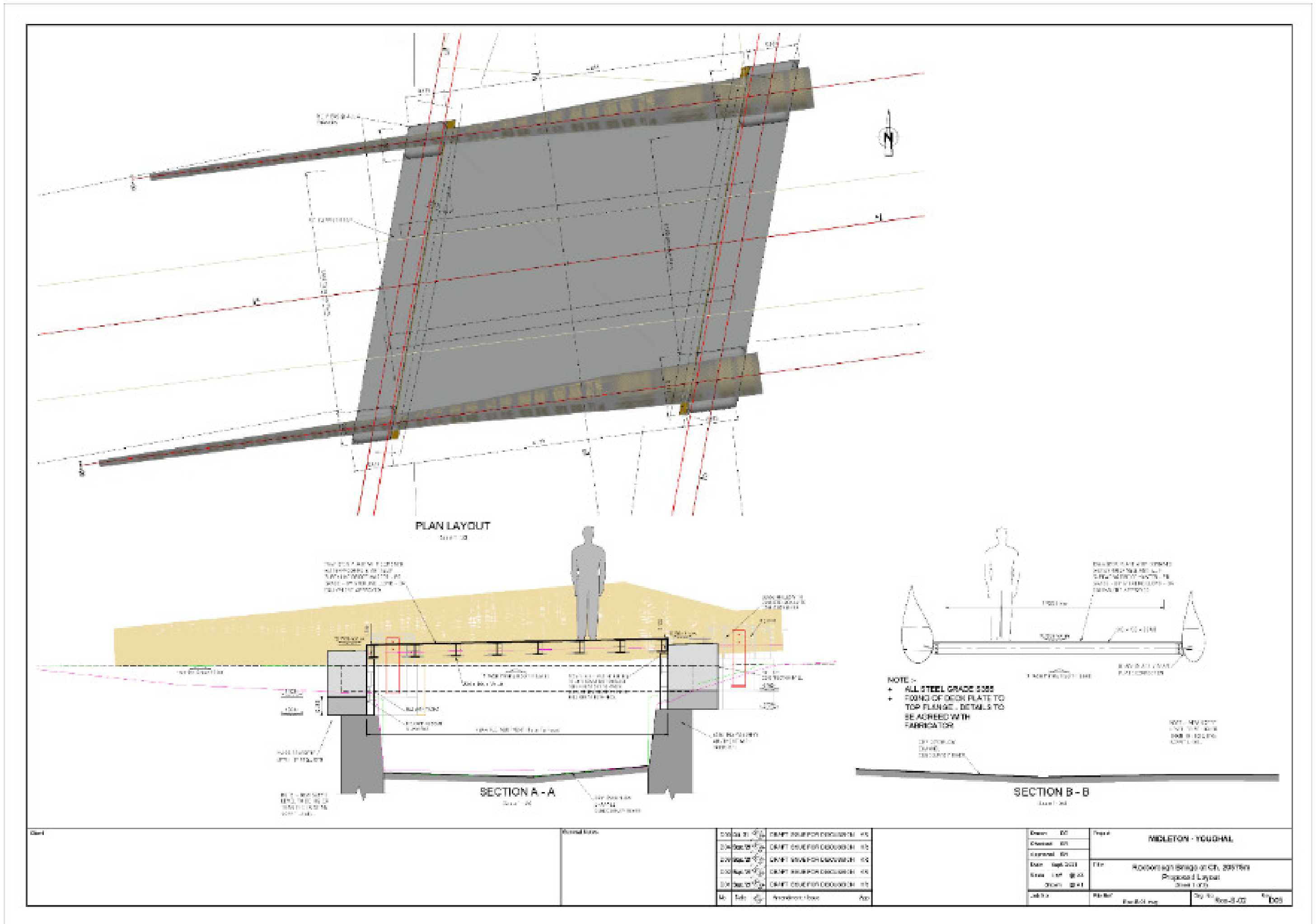
Dr. Russell Gentry, GT

# Blade Bridge – Design Development



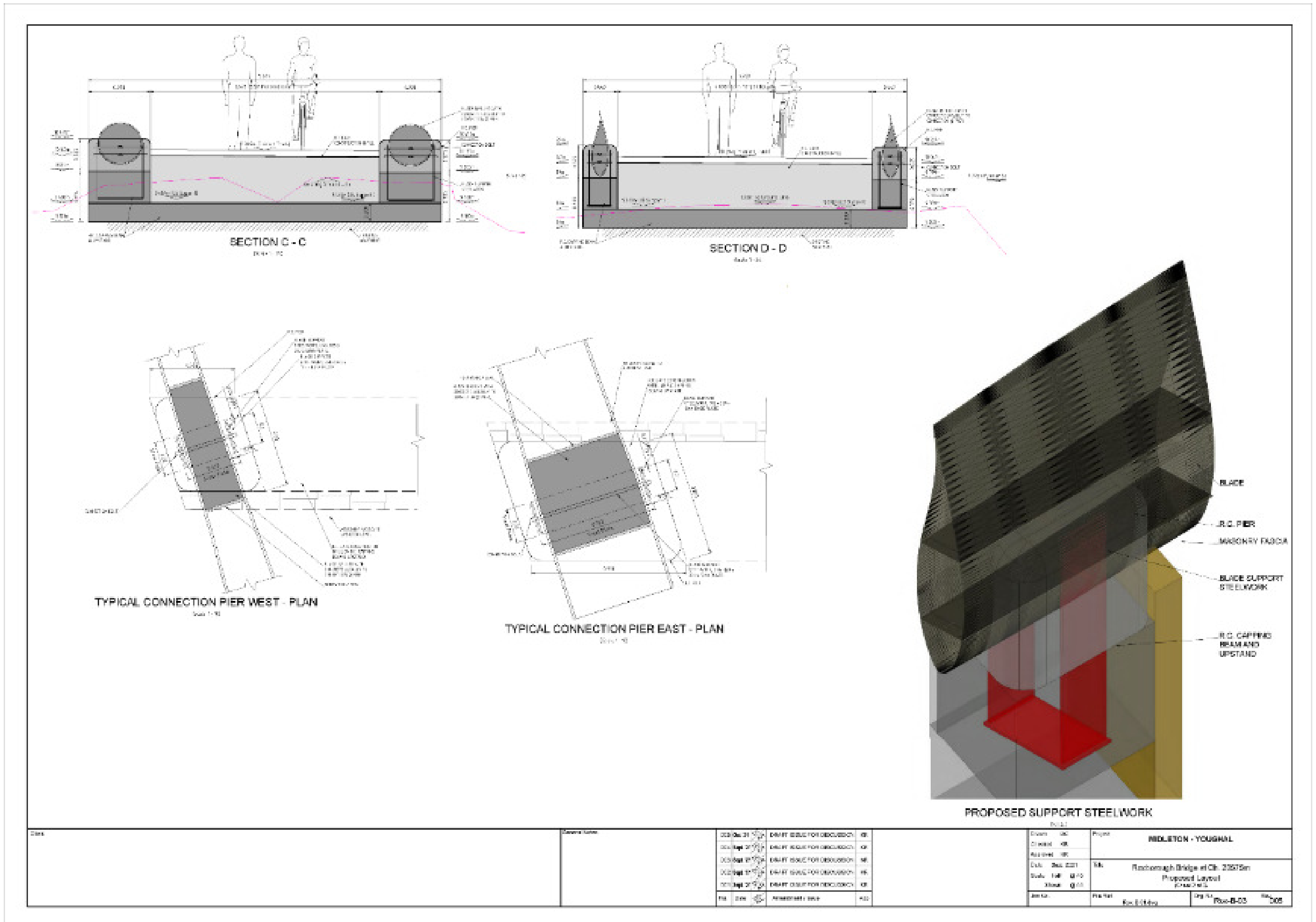
PROPOSED BRIDGE

# Blade Bridge – Design Development

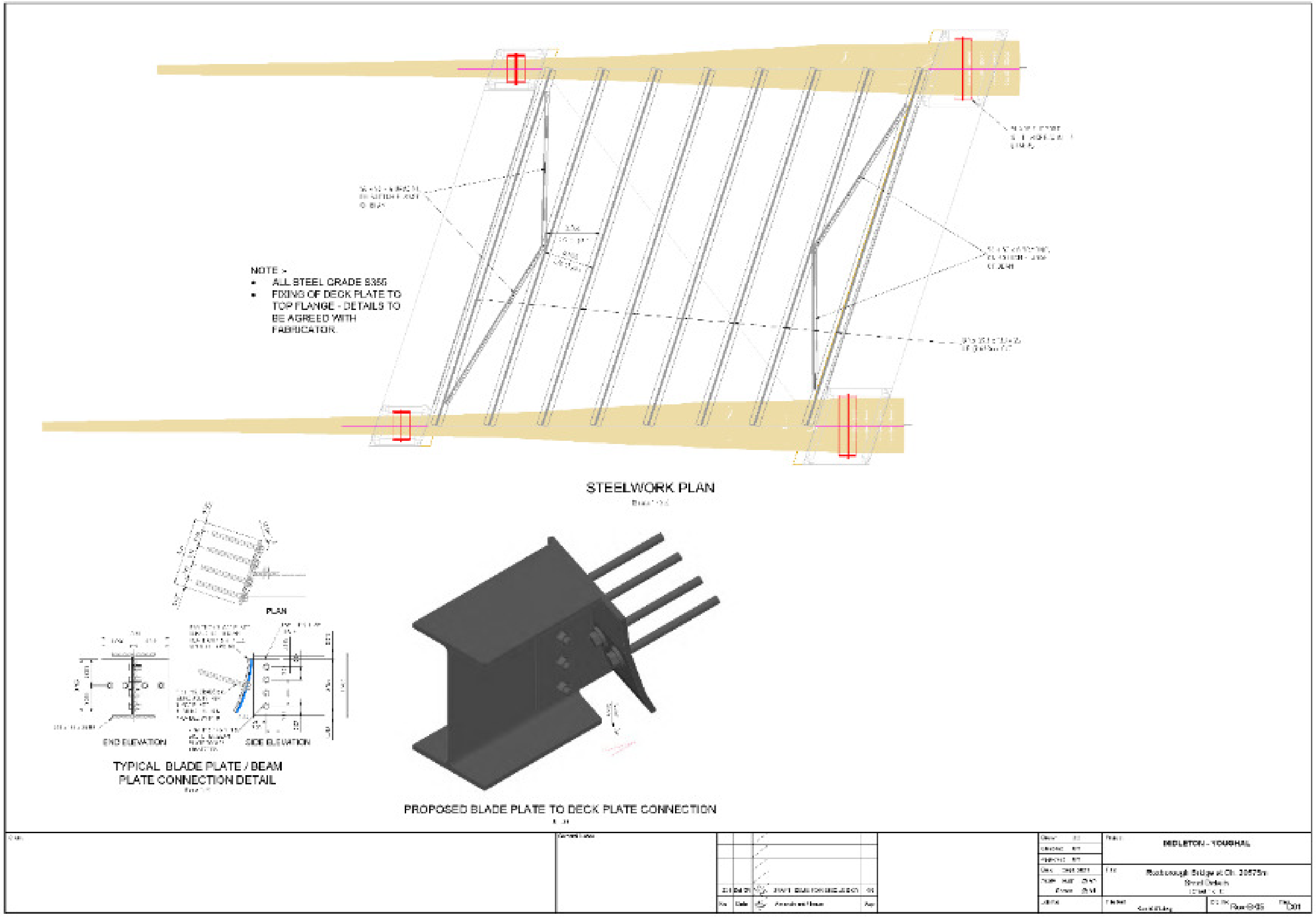


RE-WIND
NETWORK
BLADE REPURPOSING SOLUTIONS

# Blade Bridge – Design Development



# Blade Bridge – Design Development

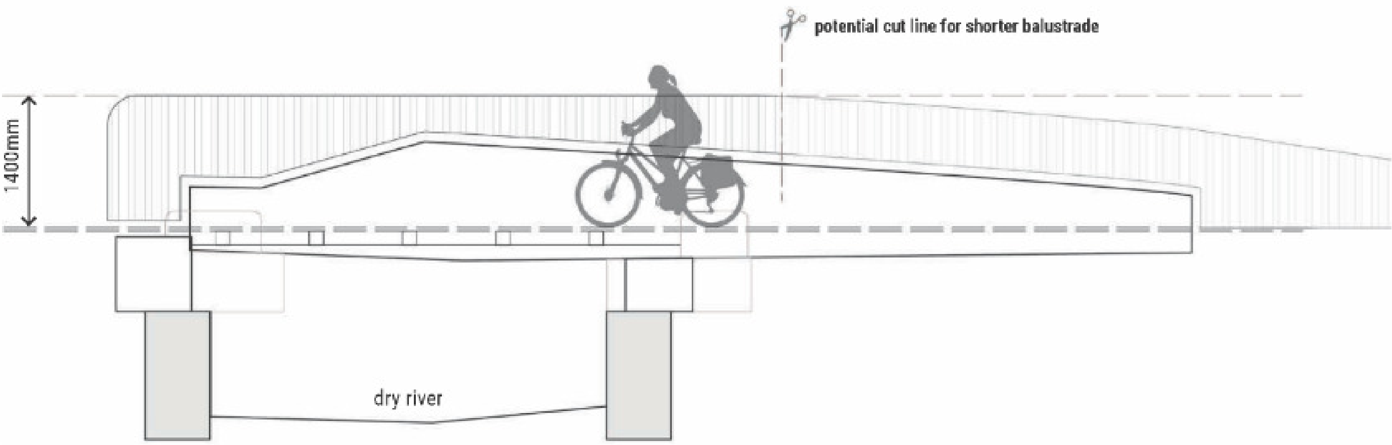


# Blade Bridge – Design Development

## Turbine blade bridge balustrade - Idea 1

thepaulhogarthcompany

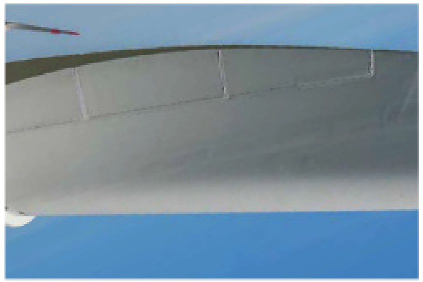
Comhairle Contae Chorcaí
Cork County Council



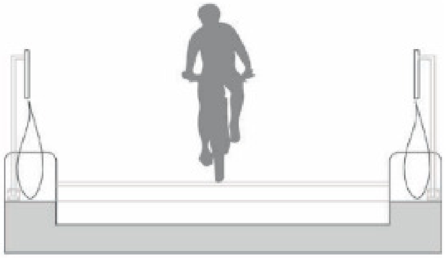
**Idea 1 - railing offset from blade**

- balustrade appears to float above the blade, and tapers smoothly away at the point there is no further risk of falling
- maximises width of path between railings, ensuring required 3m is achieved
- retains access to the surface of the blade, allowing its smooth surface and tacility to be experienced without obstruction

Top and bottom rail, galvanised flat bar. Intermediate posts galvanised square hollow section. Infill of upright galvanised steel solid circular bar or mesh.



**above:** turbine blades are usually seen from a distance. The bridge creates an opportunity to appreciate them closer at hand.



**Section:**

Balustrade is fixed to bridge structure on the off-side from the deck, allowing the balustrade to "float" above the blade.

RE-WIND NETWORK

# Blade Bridge – Design Development

## Turbine blade bridge balustrade - Idea 2

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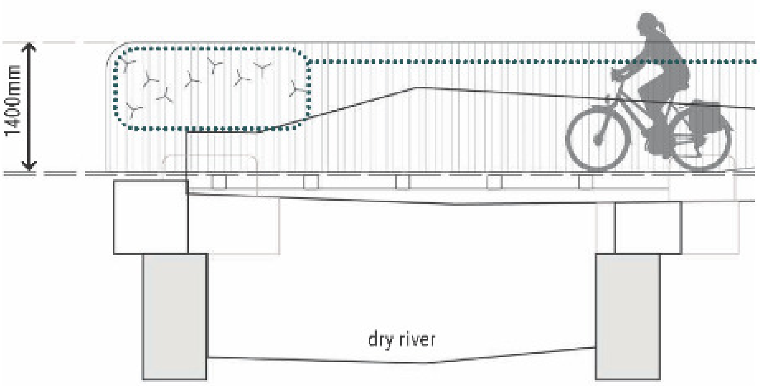
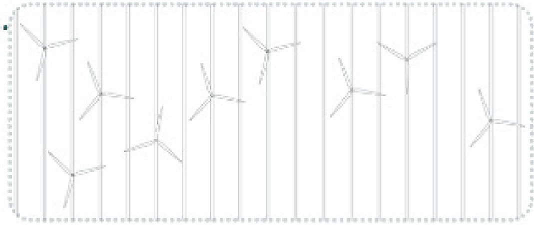
Cork County Council





**above:** aluminium pinwheels fixed to the uprights of the balustrade so that they can spin in the wind

**Idea 2 - turbine pinwheels applied to railings**

- small aluminium pinwheels fixed to the balustrade highlight the use of the turbine blade as part of the bridge structure
- incorporates a playful feature within the balustrade to strengthen the identity of the bridge and add meaning

Top and bottom rail, flat bar painted steel. Intermediate posts painted square hollow section steel. Infill of upright painted steel solid circular bar with painted aluminium rotating pinwheels.

right: inspiration - Najla El Zein Studio, *Wind Portal*, 2013

below: grouped wind turbines

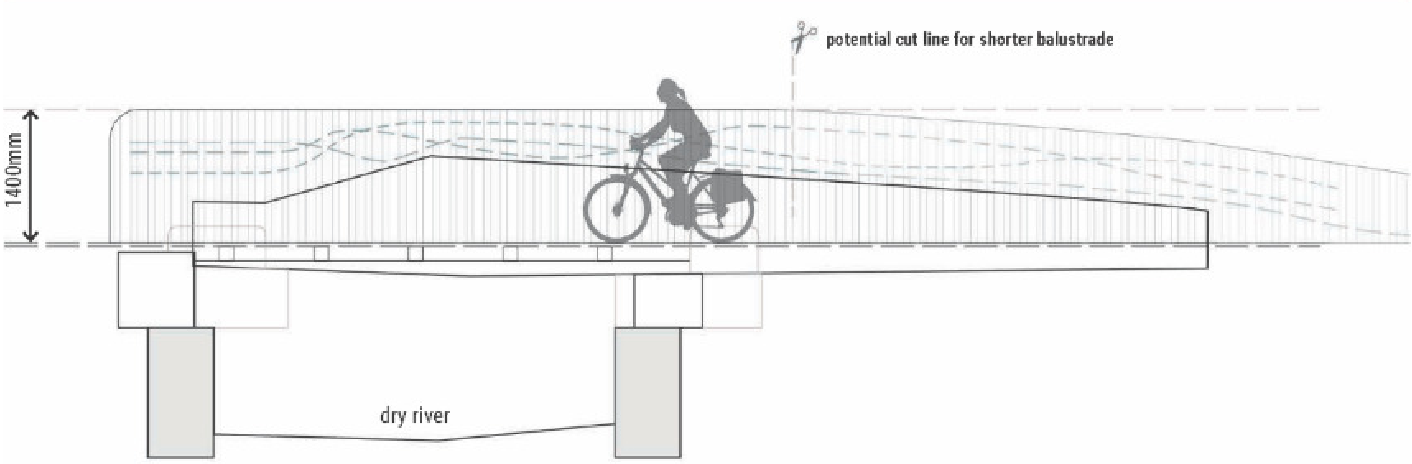
**Section:**

Balustrade is fixed to bridge deck allowing simple construction. Potential requirement to widen deck to achieve required 3m width between railings.

RE-WIND NETWORK
BLADE REPURPOSING SOLUTIONS

# Blade Bridge – Design Development

## Turbine blade bridge balustrade - Idea 3



**Idea 3 - applied ribbons**

- ribbons of metal applied to the ribbons represent the flow of wind along the blade
- ribbons would need to be raised sufficiently off ground to prevent climbing

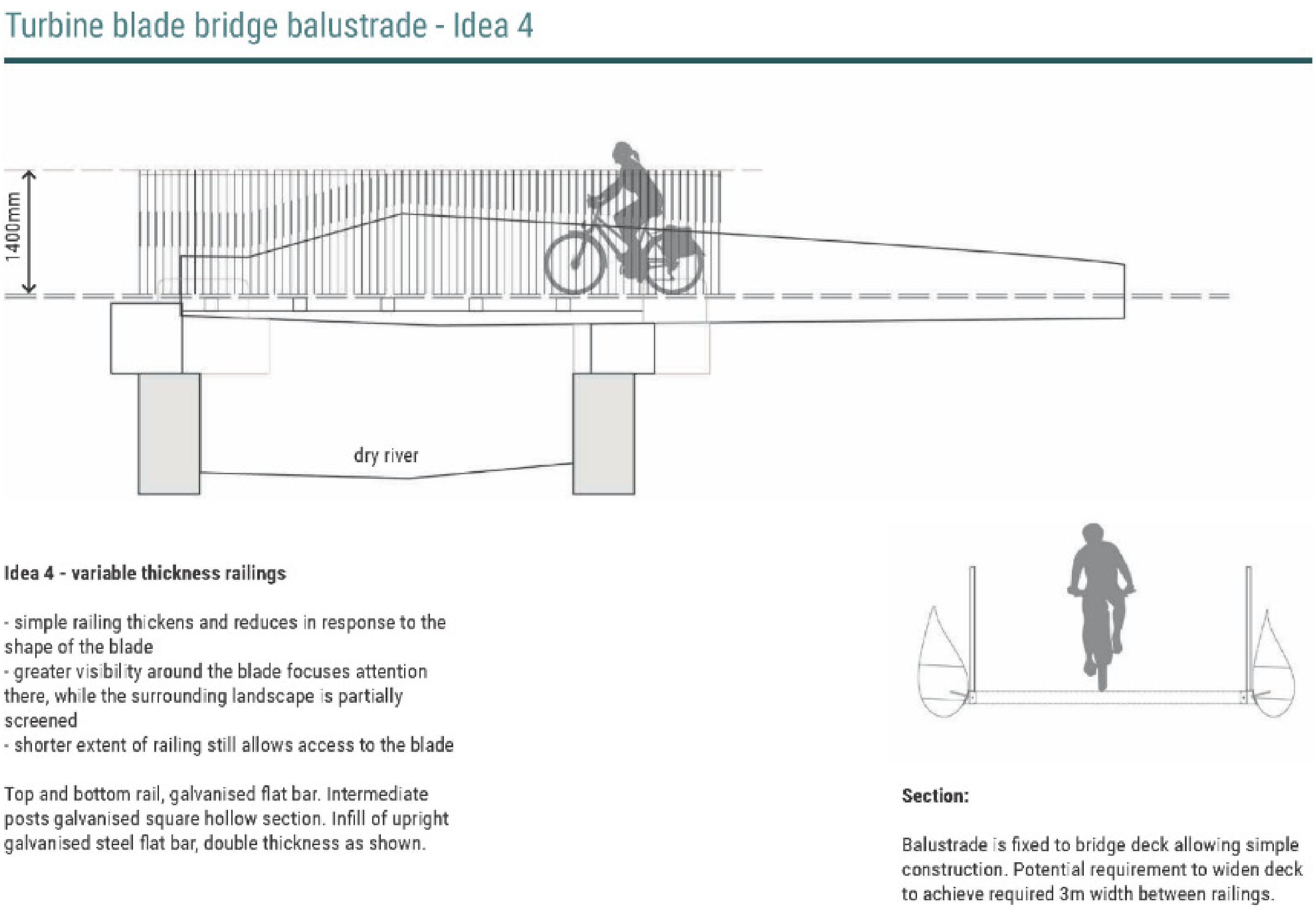
Top and bottom rail, galvanised flat bar. Intermediate posts galvanised square hollow section. Infill of upright galvanised steel flat bar with galvanised or painted steel ribbons fixed from back.

**above:** ribbons applied to the railings communicate the current of air round the blade

**Section:**

Balustrade is fixed to bridge deck allowing simple construction. Potential requirement to widen deck to achieve required 3m width between railings.

# Blade Bridge – Design Development



## Turbine blade bridge balustrade - Idea 4

**Idea 4 - variable thickness railings**

- simple railing thickens and reduces in response to the shape of the blade
- greater visibility around the blade focuses attention there, while the surrounding landscape is partially screened
- shorter extent of railing still allows access to the blade

Top and bottom rail, galvanised flat bar. Intermediate posts galvanised square hollow section. Infill of upright galvanised steel flat bar, double thickness as shown.

**Section:**

Balustrade is fixed to bridge deck allowing simple construction. Potential requirement to widen deck to achieve required 3m width between railings.

the paul hogarth company

Comhairle Contae Chorcaí
Cork County Council

RE-WIND NETWORK
BLADE REPURPOSING SOLUTIONS

# Blade Bridge – Design Development

## Turbine blade bridge balustrade - Idea 4

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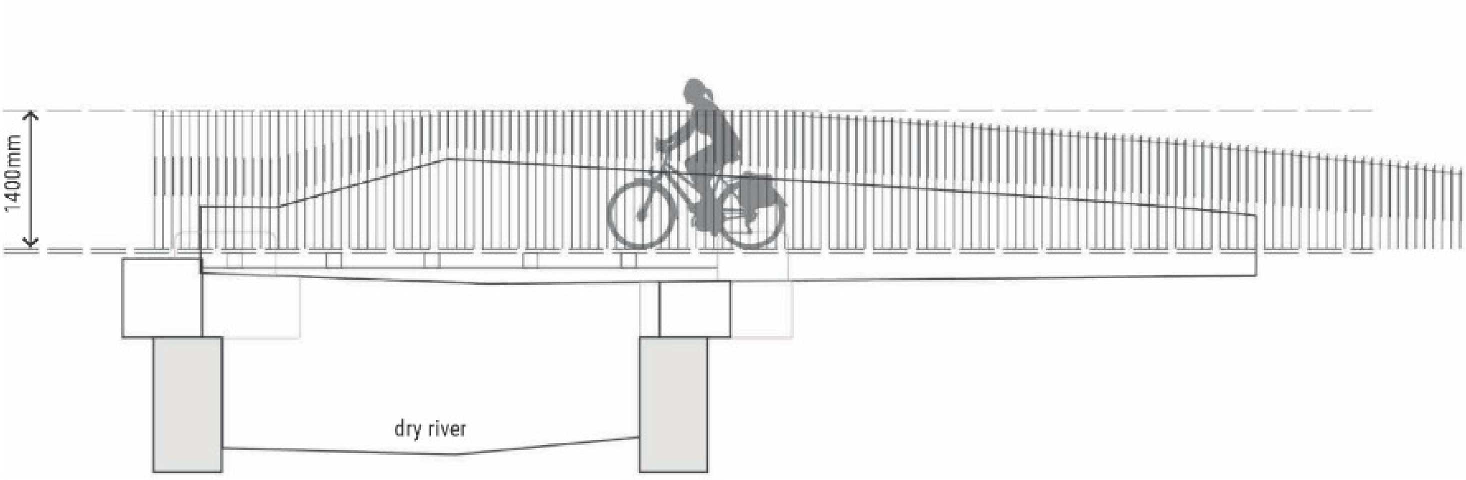


**Idea 4 - extension**

- railing continues to follow the line of the blade, tapering down to the point where it meets the ground
- railing emphasises the form of the blade, and helps to integrate it better into the context

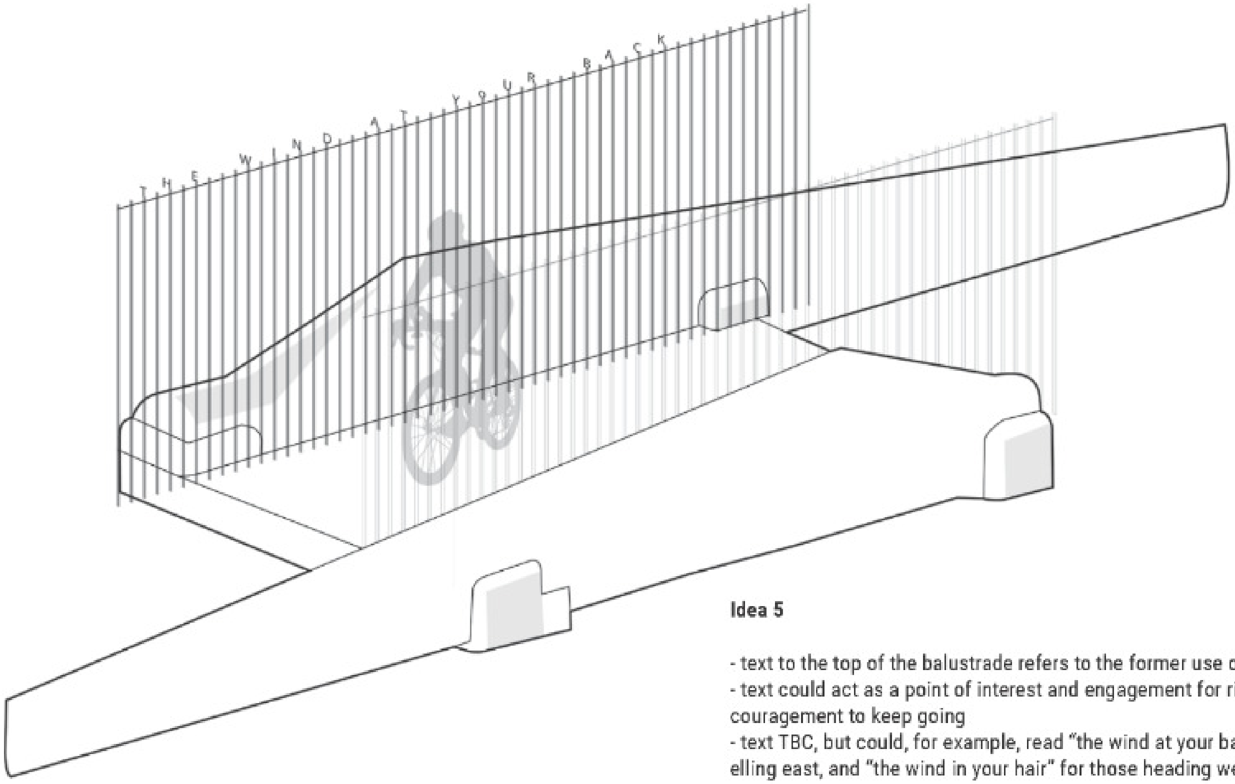
Top and bottom rail, galvanised flat bar. Intermediate posts galvanised square hollow section. Infill of upright galvanised steel flat bar, double thickness as shown.

**above:** articulation of railings creates banding

RE-WIND
NETWORK
BLADE REPURPOSING SOLUTIONS

# Blade Bridge – Design Development

## Turbine blade bridge balustrade - Idea 5



**Idea 5**

- text to the top of the balustrade refers to the former use of the turbine blade
- text could act as a point of interest and engagement for riders, and an encouragement to keep going
- text TBC, but could, for example, read "the wind at your back" for riders travelling east, and "the wind in your hair" for those heading west

Top and bottom rail, galvanised flat bar. Intermediate posts galvanised square hollow section. Infill of upright galvanised steel flat bar, double thickness in places if to be combined with Idea 4.

# Blade Bridge – Design Development

## Turbine blade bridge balustrade - materials

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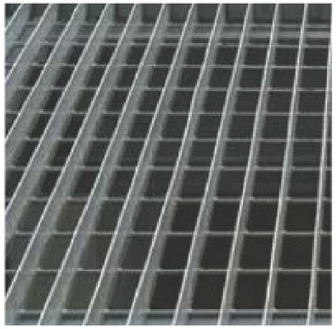
Cork County Council



**Galvanised mild steel**

- hard wearing
- effective contrast with turbine blade

**Painted aluminium**

- reference to modern wind turbine blades
- effective contrast with turbine blade used in bridge
- stand out from surrounding landscape to highlight the bridge

**Weathering steel**

- effective contrast with turbine blade
- integration into the landscape

RE-WIND
NETWORK
BLADE REPURPOSING SOLUTIONS

# Acknowledgements

Re-Wind Cork BladeBridge Team: Paul Leahy, Kieran Ruane, Russell Gentry, Larry Bank, Angie Nagle, Zoe Zhang, An Huynh, Marios Soutsos

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Re-Wind Catalog Team: Larry Bank, Asha McDonald, Chloe Kiernicki, Alex Poff, Zoe Zhang, Sakshi Kakkad, Angie Nagle, Emily Lau

Re-Wind BladeMachine Team: Russell Gentry, Mehmet Bermek, Chloe Kiernicki, Ammar Alshannaq, Sakshi Kakkad

Re-Wind GIS Team: Jenny McKinley, Emma Delaney, Conor Graham

Re-Wind Principal Investigators: Larry Bank (CUNY/GT), Russell Gentry (GT), Paul Leahy (UCC), Jenny McKinley (QUB), Jian-Fei Chen (QUB)

Re-Wind Sponsors: NSF, SFI, DfE, MTU, ENEL Green Power, Logisticus, Cork County Council

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**All publications also available at www.re-wind.info**