Basalt Composite Rebar for Floating Offshore Wind Substructures

Kaloyana Kostova PhD CEng FICE, Engineering Capability Lead at National Composites Centre

8 October 2024

My Research and Standards Development Experience

- PhD thesis: “Design and constructability of fabric-formed concrete elements reinforced with FRP materials”
- 2nd Generation of Eurocode 2 development work (2017-2020)
- Member of BSI committee B/525/2 "Structural use of concrete”
- Member of fib Task Group 5.1 “FRP reinforcement for concrete structures”
- UK nominated expert on ISO/TC 071/SC 06 committee "Non-traditional reinforcing materials for concrete”
- National Composites Centre (NCC) work

NATIONAL COMPOSITES CENTRE

THE UK'S COMPOSITES INNOVATION CENTRE

BRINGING TOGETHER THE BEST MINDS AND BEST TECHNOLOGIES TO SOLVE THE WORLD'S MOST COMPLEX ENGINEERING CHALLENGES.

PhD thesis link:
https://researchportal.bath.ac.uk/en/studentTheses/design-and-constructability-of-fabric-formed-concrete-elements-re

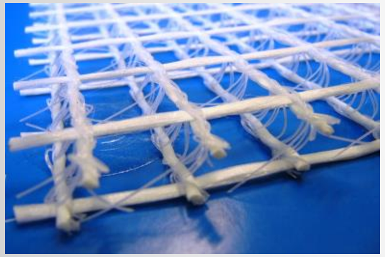
Alternative Reinforcements and Basalt FRP (Fibre-Reinforced Polymer) Rebar

FRP rebar (basalt)

FRP mini bars (basalt)

Basalt fibres

Textile reinforcement



Fibres:

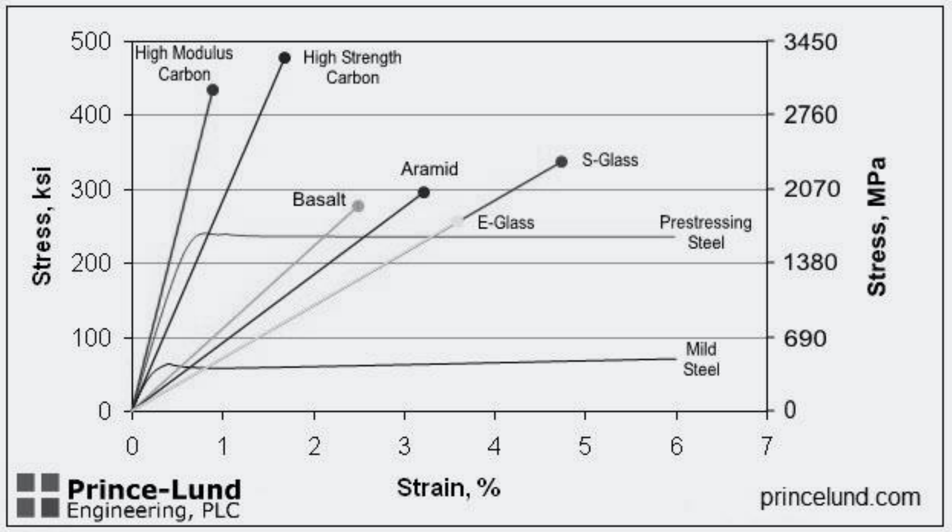
glass, carbon, aramid, BASALT

Unidirectional

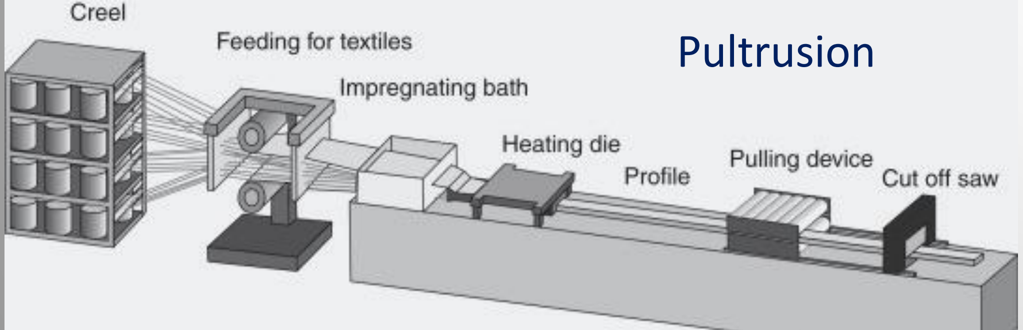
Resins:

polyester, vinyl-ester, epoxy (thermosets), Elium® (thermoplastic)

FRP composites mechanical properties



Pultrusion



Source: https://doi.org/10.1016/B978-0-444-53349-4.00268-5

helically wrapped

sand-coated

indented

Why Use FRP Rebar for Concrete Floating Substructures?

- **Light weight**

20% increase in productivity

BFRP	*GFRP*	*CFRP*	*AFRP*	*steel*
2.8g/cm^3	*2.5g/cm^3*	*1.7g/cm^3*	*1.4g/cm^3*	*7.85g/cm^3*

- **Durability**

Increased service life and resilience

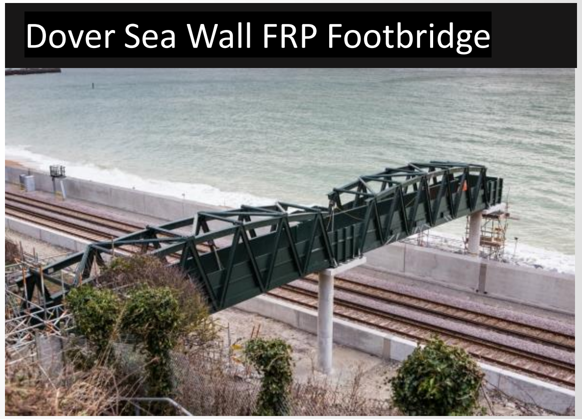
widely used in coastal regions

Steel reinforced concrete

(Cathodic protection the only rehabilitation technique proven to stop corrosion in salt-contaminated concrete structures according to U.S. Federal Highway Administration)

GFRP-RC Secant-Pile Seawall for Hurricane Resilience, Florida

2022, after Hurricane Ian



Dover Sea Wall FRP Footbridge

Dawlish Station’s FRP footbridge

- **Strength**

	BFRP	*GFRP*	*CFRP*	*AFRP*	*steel*
Tensile strength, MPa	*4840*	*1800-3500*	*2500-4800*	*3000-4000*	*500*
Elastic modulus, GPa	*89*	*72-85*	*240-800*	*62-175*	*200*

Source:
https://doi.org/10.3846/2029882X.2014.889274

Challenges of Adopting Basalt FRP Reinforcement for Floating Substructures

Procurement

- Longer lead times for bent rebar due to manufacturing process

Standardisation

- Recently introduced design standards does not cover basalt
- DNV standard based on older standards and model codes
- Resistance to seawater not included in test standards
- Design guidance needed for fully submerged foundations

  Alkaline resistance test based on Ordinary Portland cement concrete (i.e. low carbon concrete not covered)

Supply chain

- Readiness
- Capacity

Good for repetitive designs

Thermoplastic resins can be reshaped

Basalt FRP included in specifications

DNV standard includes basalt

Specification available under EAD, new ISO standard on its way

Dependent on demand

Applicable Standards for FRP Reinforcement in Concrete

Eurocodes (2nd Generation)

All parts to be adopted by 2028

Structural design

BS EN 1992-1-1:2023

Eurocode 2. Design of concrete structures - General rules and rules for buildings, bridges and civil engineering structures

Published: 30 Nov 2023

Annex R Embedded FRP reinforcement *(carbon and glass only)*

Harmonised technical specification

European Assessment document (EAD)

EAD 260023-00-0301

European Technical Assessment (ETA) ?

ISO/PWI 13197 Specifications for FRP bars and FRP grids *(under development)*

Test standard

ISO 10406-1 Test standard Fibre-reinforced polymer (FRP) reinforcement of concrete — Test methods Part 1: FRP bars and grids

ACI codes and guidelines

Plan until 2027

ACI Committee 440

(Fiber-Reinforced Polymer Reinforcement)

Emerging Technology Documents

1996: ***ACI 440-96 State of the Art Report***

2001: ***ACI 440.1-01 Guide for the Design and Construction of Structural Concrete Reinforced with Fiber-Reinforced Polymer (FRP) Bars***

2003: ***ACI 440.1R-03***

Design Guides

2006: ***ACI 440.1R-06***

2015: ***ACI 440.1R-15*** ***(carbon, glass, aramid)***

2025: ***ACI 440.1R-25***

ASTM specification and test standards

Design Codes:

2022: ***ACI CODE 440.11-22 Building Code Requirements for Structural Concrete Reinforced with Glass Fiber-Reinforced Polymer (GFRP) Bars***

2027: ***ACI CODE 440.11-27***

DNV Standards

DNVGL-ST-C502 Offshore concrete structures 2018

Refers to:

- **fib Model Code 2010**

(already replaced by Model Code 2020)

- **ACI**
- **ASTM**
- **ISO**

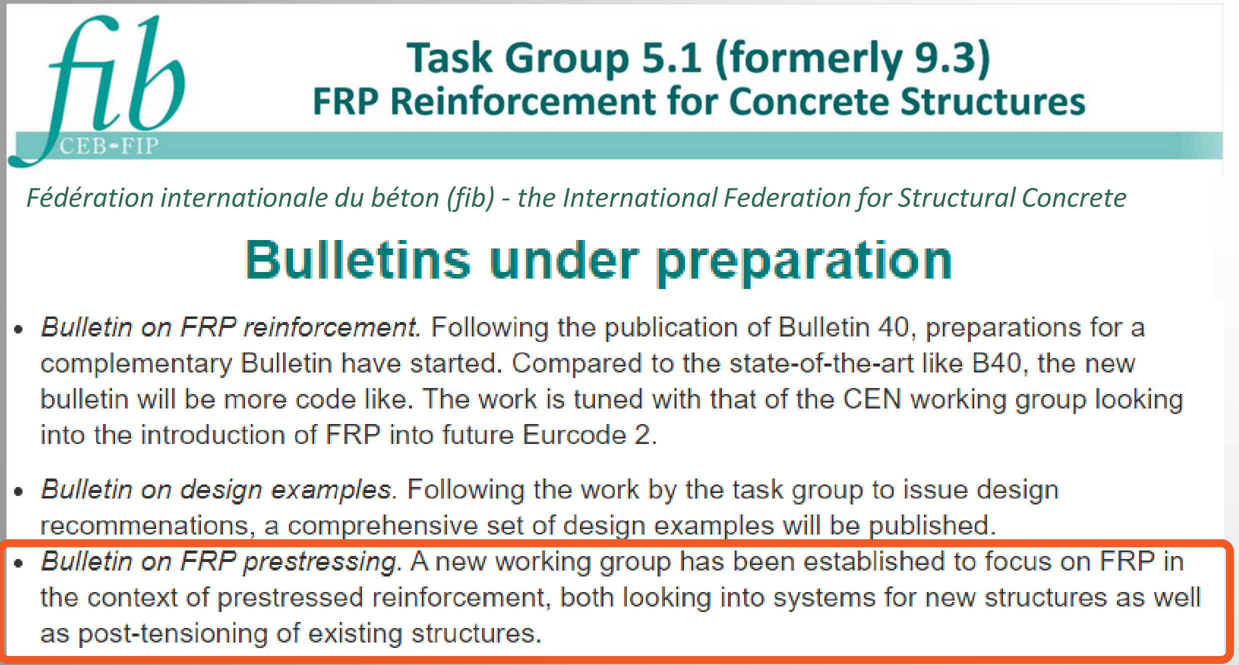
Appendix F provides requirements to content in certificates for FRP bars ***(carbon, glass, aramid, basalt)***

Clause 6.3.1.6 ***For reinforcement consisting of FRP bars, consistent sets of characteristic material parameters and material factors for each limit state, which have been determined by a formal qualification process according to DNVGL-SE-0160, shall be used for design. Material factors for strength and stiffness for the different limit states shall be reported in the product or type approval certificate.***

Possibilities for Use of FRP Reinforcement in Concrete Beyond Current Standards

Prestressed concrete

- Pre-tensioned or post-tensioned
- Use FRP more efficiently (higher stress)
- All fibre types can be prestressed
- Reduced deflections
- Even mild prestressing is beneficial



fib CEB-FIP

Task Group 5.1 (formerly 9.3)
FRP Reinforcement for Concrete Structures

Fédération internationale du béton (fib) - the International Federation for Structural Concrete

Bulletins under preparation

- *Bulletin on FRP reinforcement*. Following the publication of Bulletin 40, preparations for a complementary Bulletin have started. Compared to the state-of-the-art like B40, the new bulletin will be more code like. The work is tuned with that of the CEN working group looking into the introduction of FRP into future Eurocode 2.
- *Bulletin on design examples*. Following the work by the task group to issue design recommenations, a comprehensive set of design examples will be published.
- *Bulletin on FRP prestressing*. A new working group has been established to focus on FRP in the context of prestressed reinforcement, both looking into systems for new structures as well as post-tensioning of existing structures.

Case Study: Interstate I-75 Highway over Sexton/Kilfoil Drain in Allen Park, MI

Bridge beams prestressed with CFRP Strands

Reference: Nabil F. Grace, , Mohamed E. Mohamed, Marc Kasabasic, Matthew Chynoweth, Kenichi Ushijima, and Mena Bebawy, 2022. Design, Construction, and Monitoring of US Longest Highway Bridge Span Prestressed with CFRP Strands, Journal of Bridge Engineering, Volume 27, Issue 7. https://doi.org/10.1061/(ASCE)BE.1943-5592.000188

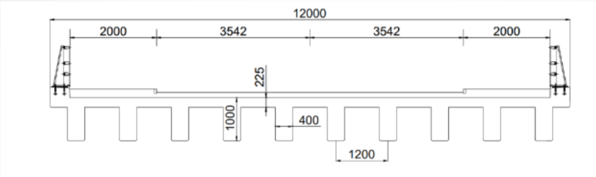
NCC FRP Reinforcement Embodied Carbon Comparative Study

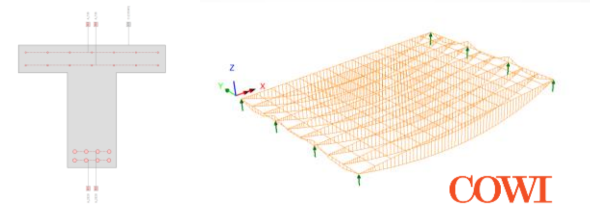
Aims:

- Examine the embodied carbon in concrete structures reinforced with FRP reinforcement compared with functionally equivalent steel-reinforced structures
- Identify possible savings through design

Bridge design study:

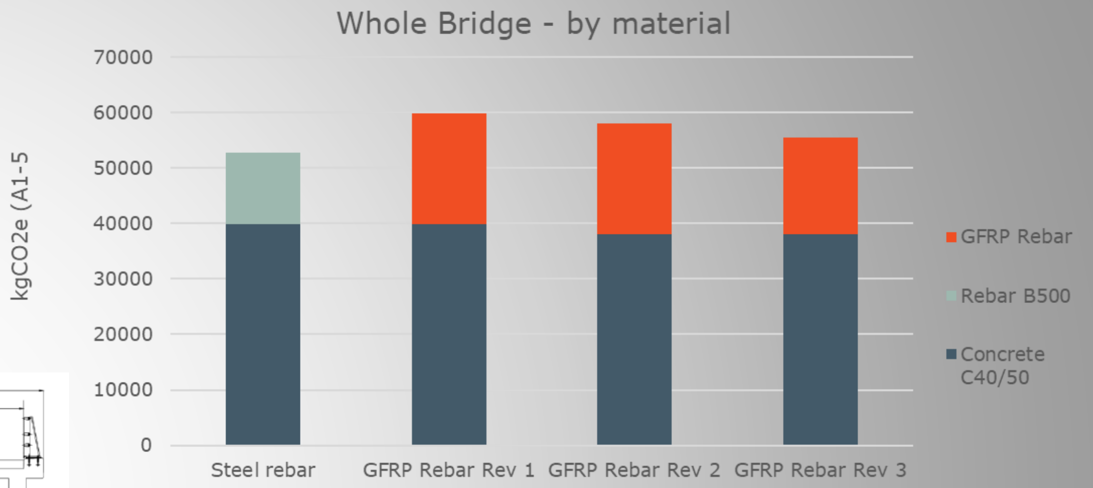
- 15m span "T-beam" deck
- 2D grillage model
- Traffic loading to AASHTO
- Load combinations to ACI318-19
- GFRP design to ACI 440.1R-15



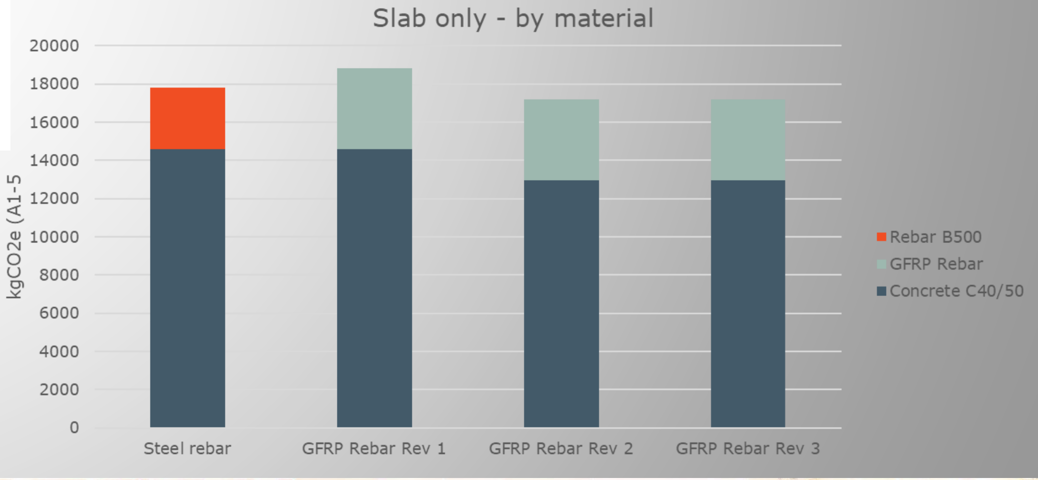


Design scenarios for LCA:

☐ Steel rebar
☐ GFRP Rebar Rev 1 – moderately conservative assumptions
☐ GFRP Rebar Rev 2 – reduced concrete cover
☐ GFRP Rebar Rev 3 – deflection criteria relaxed so that strength governs for beams (from L/800 to approx. L/650)



Life Cycle Assessment (LCA) results
Cradle to Gate



Basalt FRP Reinforced Low Carbon Concrete Trial

national highways

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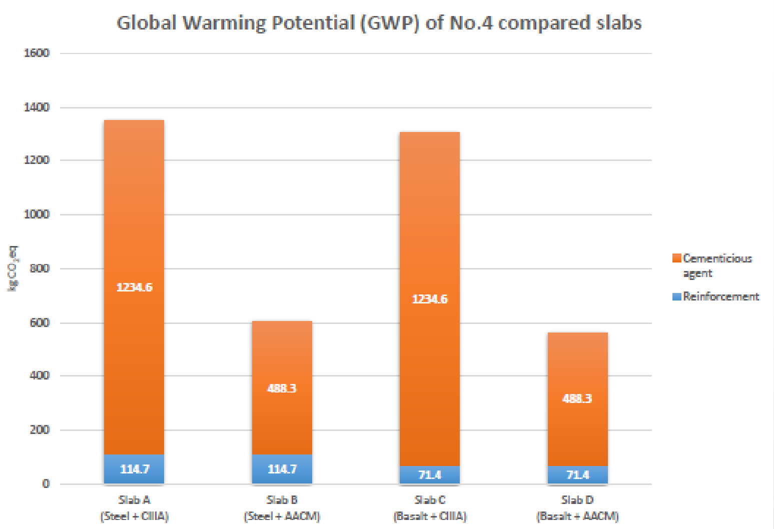
M42 Junction 6 upgrade temporary works used as a test bed for:

Basalt FRP rebar in Alkali Activated Cementitious Materials (AACM) geopolymer concrete

- Assessing the cure, functional properties and structural behaviour against a benchmark of traditional temporary works slabs
- Graphene investigated as a functional admixture
- Comparative Life Cycle Assessment (LCA)
- Roadmap to overcome technology blockers and to enable deployment of novel materials into permanent works



LCA study results based on:

- Average weighted data from UK
- CARES for Steel rebar GWP
- Basalt data from Bastech EPD

Material suppliers: TARMAC A CRH COMPANY BASTECH

NCC Durability Study of Basalt FRP Reinforcement in AACM concrete

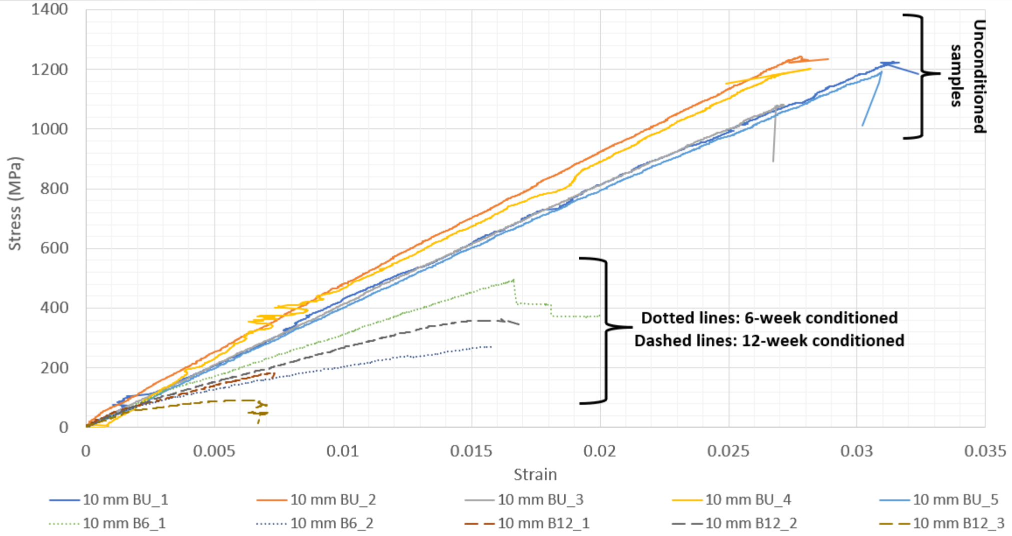
Kostova K., Branfoot C., Clark R., Darby A., Evernden M. and Ke X, (2024). Appropriate Testing Approach for Durability of FRP rebar in AACM Concrete, In Proceedings of Fibre-Polymer Composites in Construction (FPCC 2024), 5 Sep 2024, Milton Keynes, UK

- **Experimental investigation, following the ASTM standard accelerated aging test protocol for alkali resistance of FRP rebar in Ordinary Portland Cement (OPC) concrete, adapted for AACM concrete**
- **Basalt FRP rebar specimens were tested in tension (fibre-dominated) and shear (matrix-dominated) after 6 and 12 weeks of conditioning**

Cement casting

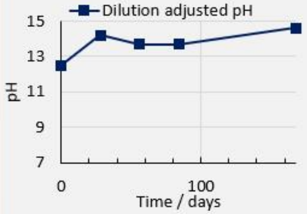
Pore water expression

Pore water characterisation



*28 day	Masses of salts scaled to 50 L / kg				
	$Ca(OH)_2$	NaOH	KOH	$CaCl_2$	$CaSO_4$
Cemfree recipe*	0.7	0.355	0.165	0.08	0.02
ASTM D7705	6	0.045	0.21	0	0
ISO 10406-1	0	0.4	1.1	0	0

- ICP-MS
- Ion Chromatography
- pH



University of Bristol PhD research on: **Durability Assessment of Glass & Basalt FRP Bars in Marine Environments**

PhD student: **Asaad Biqai**

Lead supervisor: **Eleni Toumpanaki**

Steel corrosion is the leading cause of degradation for concrete structures near saline environments. It can lead to brittle catastrophic failures and collapses, reducing the structural expected service life. The cost of corrosion for most developed European countries is estimated to be approximately 4-5% of the gross national product [1]. For the UK, the cost of infrastructural repair between April 2015 and March 2021 is about £10.3 billion [2]. What if alternative materials were used to reinforce concrete structures that don't corrode? Why not consider FRP rebars?

This project investigates how glass fiber-reinforced polymer (GFRP) bars used in concrete structures degrade in marine environments. The project examines both the resin and GFRP samples to understand how each component and their composite behaviour deteriorates with exposure time, particularly focusing on interactions at the fiber-matrix interfaces. Accelerated aging is simulated with high temperatures and direct immersion in a saline solution containing sodium chloride and sodium sulfate. Resin samples are tested for tension, shear, and Tg analysis through Dynamic Mechanical Analysis (DMA), and GFRP bars for transverse and interlaminar shear strength after 15 and 30 days of exposure. Moisture uptake is also measured to link it with mechanical degradation. The study finds that resin samples degrade faster in tensile strength initially due to moisture uptake, while transverse shear strength degradation in GFRP bars increases steadily with exposure time. The correlation between resin and GFRP degradation suggests shear testing of resin could assess FRP bar degradation. These results offer insights for developing a durability test protocol for FRP bars in saline environments.


Basalt-Epoxy


Glass-Vinyl Ester


Basalt-Vinyl Ester

Materials & Methods

GFRP Rebar


[4]

VE140 Vinyl Ester


[5]

Testing Methods


Transverse Shear Strength Testing
ASTM D7617 [6]

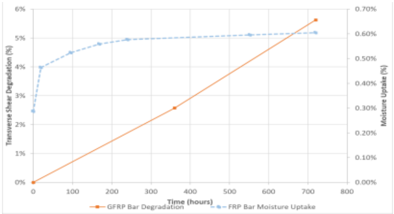

Interlaminar Shear Strength Testing
ASTM D4475 [7]


Tensile Testing
ASTM D638 [8]


DMA Testing
ASTM E1640 [9]


Shear Testing
ASTM D2344 [10]

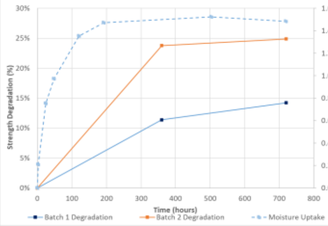
FRP Testing Results



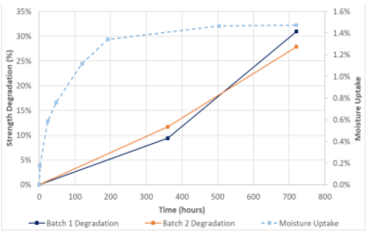
Transverse Shear Degradation with Moisture Uptake


Interlaminar Shear Mode of Failure

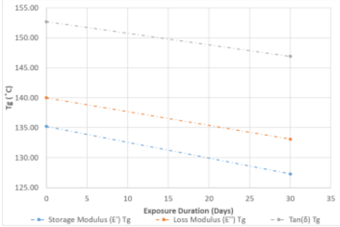
Resin Testing Results



Tensile Degradation with Moisture Uptake



Shear Degradation with Moisture Uptake



Tg Decrease with Saline Exposure

References:
[1] Pritchard, O., Hallett, S., & Farewell, T. (2013). Soil corrosivity in the UK – impacts on critical infrastructure. Infrastructure Transitions Research Consortium.
[2] (2014). Maintaining strategic infrastructure: roads. Department for Transport and Highways Agency.
[3] Composite TECH. (2024, February 28). Retrieved from https://composite-tech.com/2023/10/24/world-experience-of-frp-rebar-use-the-new-era-of-construction-reinforcement/
[4] GFRP Rebars . (2024, February 28). Retrieved from SIREG: https://www.sireg-usa.com/gfrp-rebars/
[5] VE140 Fuel Resistant Vinylester Resin . (2024, February 28). Retrieved from EasyComposites: https://www.easycomposites.co.uk/
[6] ASTM D7617M – 11 Standard Test Method for Transverse Shear Strength of Fiber-reinforced Polymer Matrix Composite Bars
[7] ASTM D4475 – 21 Standard Test Method for Apparent Horizontal Shear Strength of Pultruded Reinforced Plastic Rods By the Short-Beam Method
[8] ASTM D638 – 22 Standard Test Method for Tensile Properties of Plastics
[9] ASTM E1640 – 23 Standard Test Method for Assignment of the Glass Transition Temperature By Dynamic Mechanical Analysis
[10] ASTM D2344M – 22 Standard Test Method for Short-Beam Strength of Polymer Matrix Composite Materials and Their Laminates

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Dispersed non-metallic reinforcement for energy efficient manufacturing of precast concrete

The BEIS Industrial Energy Efficiency Accelerator (IEEA)

Department for Business, Energy & Industrial Strategy
CARBON TRUST
Jacobs
UKRI Innovate UK | ktn

Organisation lead: McC fpmccann

Demonstration partners: B9 SOLUTIONS Renewable Energy & Enviromental Consultants; NATIONAL COMPOSITES CENTRE; QUEEN'S UNIVERSITY BELFAST

Demonstration site:
FP McCann Precast NI,
Knockloughrim,
Northern Ireland

Technology

Conventional approach:

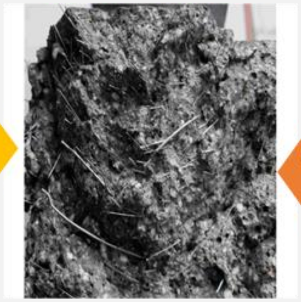
Steel bar reinforced concrete

FRC benefits:

- time, labour and process energy savings,
- lower carbon footprint,
- transport savings,
- overall, lower cost of concrete

Low carbon solution:

Fibre reinforced concrete (FRC) with non-metallic fibre



Addition of BFRPmf to fresh concrete during mixing stage using: automated fibre feeding and dosing equipment

Emerging material: **BFRP macro fibre (BFRPmf)**

Demonstrator

This project aims to validate the use of BFRPmf in precast concrete applications, through laboratory mix optimisation and testing, industrial upscaling, full-scale structural and surface quality testing, and establishing design protocols. The environmental impacts will be quantified through energy monitoring, environmental product declarations and life cycle assessment. It is expected that the project will demonstrate steel reinforcement replacement of at least 25%, leading to 20% reduced energy consumption and 25% lower carbon footprint.

Structural performance BS EN 14651

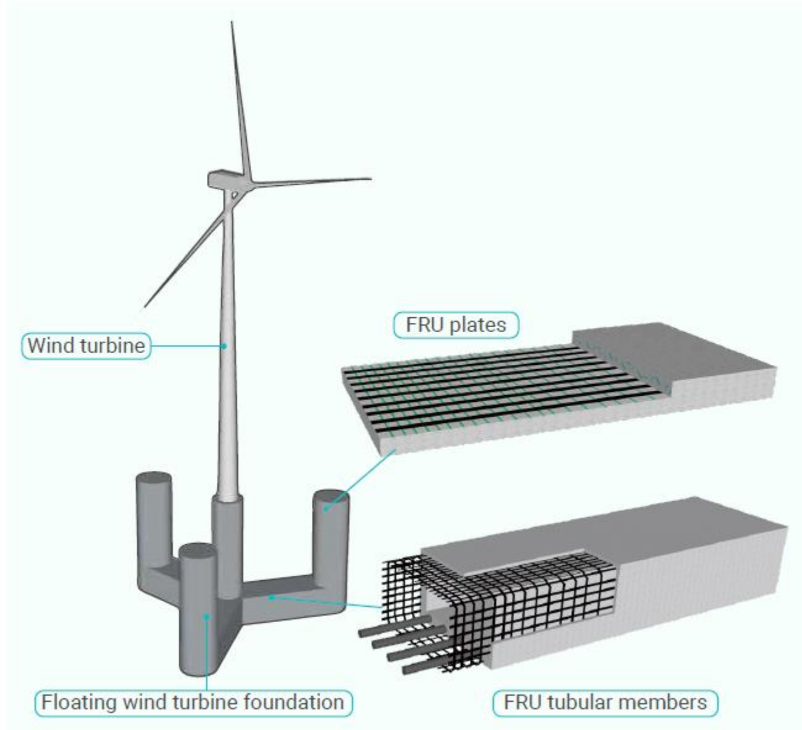
Factory upscale and casting full-scale elements (Trial4 - 1200 mm dia pipe)

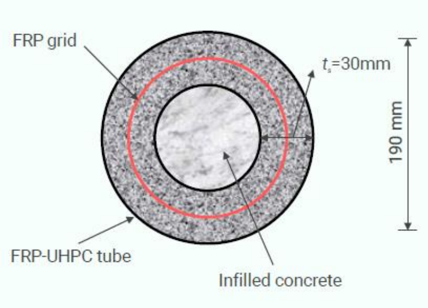
Proposed Designs Offshore Floating Substructures Utilising FRP Reinforced Concrete

Fan T.-H., Zeng J.-J., Su T.-H., et al., (2024). Offshore floating wind turbine foundation revolution enabled by fiber-reinforced polymer (FRP) reinforced cementitious materials. The Innovation Materials 2(2): 100073. https://doi.org/10.59717/j.xinn-mater.2024.100073

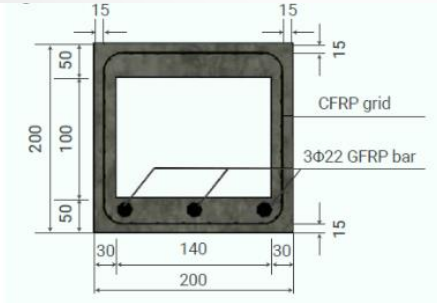
FRP reinforced Ultra-High Performance Concrete (UHPC) = FRU composites

(steel/PE & steel/PE fibres)





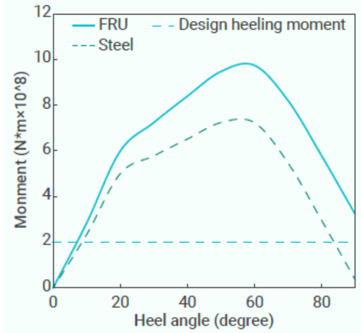
FRU tubular columns



FRU tubular beams

Hydrostatic stability analysis:

FRU foundation has a larger capacity in resisting overturning than original steel foundation.



Hydrodynamic analysis:

surge and pitch of the FRU foundation are consistently smaller than those of the steel foundation, leading to superior stability of the FRU foundation, enhanced power generation efficiency and minimized damage to moorings connected to the foundation

Conclusions

Why use FRP bar?

- Increased service life and resilience
- Remove need for corrosion protection systems
- Readily available technology
- Enables novel low concrete technologies

Where are we?

- Standards development well advanced
- Demonstration projects and real-life structures
- Solutions for offshore wind already considered
- Need full qualification programme for application in floating offshore

What is next?

- Adoption of standard specifications
- Inclusion of durability testing for marine environment
- Develop design guidance for fully submerged structures
- Develop appropriate technical designs