FRP INTERNATIONAL

The official newsletter of the International Institute for FRP in Construction

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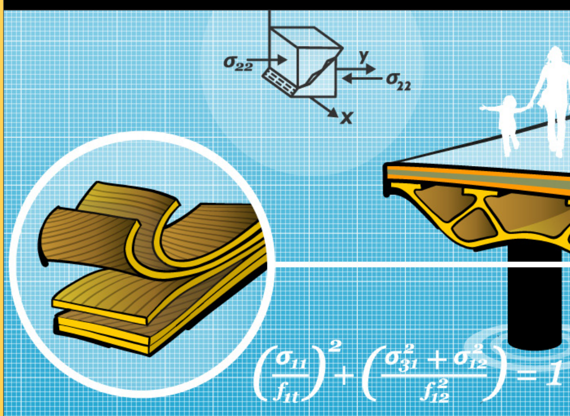

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MESSAGES

Message from the Editor

It gives me great pleasure to present to you the current edition of FRP International. Inside, you'll discover invitations to upcoming conferences, namely APFIS 2024 (Adelaide, Australia), CICE 2025 (Lisbon, Portugal), and FRPRCS-17 2026 (Girona, Spain). Additionally, a reminder to participate in the latest edition of the Photo Competition, with the submission deadline extended to March 31, 2024, awaits you.

This issue also features extended abstracts of the three finalists of the IIFC Best PhD Thesis Award 2023: Inês Rosa (winner), Abdulrahman Zaben (runner-up), and Lourenço Almeida Fernandes (runner-up). Beyond showcasing the exciting research of these young researchers, you are encouraged to explore their recommendations for future research.

In the "Meet the People" section, Prof. Thomas Keller, a leading specialist in the field, shares insights into his main research achievements, heavily influenced by his involvement in various practical projects, and offers guidance to the younger generation of researchers.

The "Composites around the World" section offers three compelling articles: an overview of an applied research project focusing on the use of FRP composites in repairing steel pipelines for offshore oil and gas applications; a case study detailing a hybrid vehicular bridge in Italy, incorporating GFRP rebars and prestressed steel reinforcement; and an overview of the innovative online course "FRPx", offered at TUDelft. This last article marks the inception of our new subsection "Education," dedicated to showcasing educational initiatives in the field of composites, which are crucial for ensuring their widespread and safe application in civil engineering.

Feel free to reach out to one of our editors with your ideas!

Prof. **João R. Correia**
Lisbon University
Portugal

IIFC NEWS

IIFC Events

Invitation to APFIS 2024, Adelaide, Australia

The Ninth Asia Pacific Conference on FRP in Structures (APFIS 2024), will be held in Adelaide, Australia, 8-11 December 2024. APFIS 2024 is jointly hosted by The University of Adelaide and University of South Australia.

APFIS is an international conference series that is supported by the International Institute for FRP in Construction (IIFC). It is relevant to researchers, academics, students, manufacturers, consultants, contractors and policy makers. Its aim is to showcase research, development and application of fibre-reinforced polymer (FRP) composites in the built environment.

The inaugural APFIS conference was held in Hong Kong in 2007. Since then, it has been held in Seoul, Korea (2009), Hokkaido, Japan (2012), Melbourne, Australia (2013), Nanjing, China (2015), Singapore (2017), Gold Coast, Australia (2019), and Shenzhen, China (2022, online).

APFIS 2024 will contain a variety of technical and social activities. On the technical front, there will be keynote presentations, panel sessions, general session presentations, workshops, and site visits. There will also be special issues containing selected conference papers published by Journal of Composites for Construction and Advances in Structural Engineering. There will also be Best Paper Awards presented. On the social front, there will be a welcome reception, conference banquet as well as ample opportunities to network with colleagues and friends.

The conference will be held at the **Hilton Adelaide Hotel** (www.hilton.com/en/hotels/adlhitw-hilton-adelaide) in the picturesque city of Adelaide, Australia. Delegates (and accompanying partners) are invited to spend time exploring the city and surround. The banquet will be held at the iconic Adelaide Oval (www.adelaideoval.com.au/adelaide-oval-functions-events).

SCHEDULE

Date	Time of Day	Activity	Location
Sunday, 8 December 2024	Evening	Welcome Reception	Hilton Adelaide
Monday, 9 December 2024	Morning	Opening Ceremony	
	Morning and Afternoon	Technical Sessions	
Tuesday, 10 December 2024	Morning and Afternoon	Technical Sessions	
	Evening	Banquet	Adelaide Oval
Wednesday, 11 December 2024	Morning and Afternoon	Technical Sessions	Hilton Adelaide
	Afternoon	Closing Ceremony	

KEY DATES

First Announcement and Call for Abstracts	October 2023
Submission of Abstracts for Review Deadline	15 February 2024
Abstract acceptance	Rolling basis
Submission of Papers for Review Deadline	1 June 2024
Submission of Camera-Ready Papers Deadline	1 September 2024
Conference	8-11 December 2024

Invitation to APFIS 2024, Adelaide, Australia

LIST OF TOPICS

The following is a non-comprehensive list of key topics covered by the conference.

- Materials and products: properties, tests and standards
- Bond behaviour
- Confinement
- Strengthening of concrete, steel, masonry and timber structures
- Seismic retrofit of structures
- Concrete structures reinforced or pre-stressed with FRP
- Concrete filled FRP tubular members
- Hybrid FRP structures
- All FRP structures
- Smart FRP structures
- New FRP materials/systems/techniques
- Inspection and quality assurance
- Durability and long-term behaviour
- Fire performance
- Life-cycle performance, longevity and sustainability
- Design codes and guidelines
- Case studies and practical applications
- Performance of FRP under extreme loading
- Green and natural composites
- Additive manufacturing
- Floating and offshore structures
- Space (extra-terrestrial) structures
- Health monitoring and quality control related to FRP systems

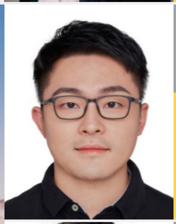
CONFERENCE CHAIRS AND CONTACT INFORMATION

Please address all enquiries to apfis2024@adelaide.edu.au. In addition, please visit the conference website for additional information: https://set.adelaide.edu.au/apfis2024

The website also contains information for sponsorship opportunities. You are very welcome to Adelaide and we look forward to seeing you at APFIS 2024.

Chair
Prof. **Scott SMITH**
The University of Adelaide

Chair
Prof. **Yan ZHUGE**
University of South Australia



Chair
Dr. **Jun-Jie ZENG**
University of South Australia

Chair
Dr. **Tafsirojjaman**
The University of Adelaide

On behalf of the organising committee, we offer you a very warm welcome to Adelaide and we look forward to seeing you at APFIS 2024.

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Invitation to CICE 2025, Lisbon, Portugal

The 12th International Conference on FRP Composites in Civil Engineering (CICE 2025) will be held in Lisbon, Portugal, in 14-16 July 2025. The CICE 2025 will be jointly organized by the University of Lisbon, the National Laboratory of Civil Engineering and the University of Minho.

The conference will take place at the campus of Técnico (Figure 1), University of Lisbon, located in the heart of Lisbon (Figures 2 and 3).

You will find a city that is full of history, is safe and friendly, and has excellent climate and gastronomy.

Alongside the scientific programme, an exciting social programme will be organized, so that participants can enjoy a wonderful city resort just next to Lisbon (Figure 4).

Further information is available in the conference website: www.cice2025.org

We look forward to welcoming you in Lisbon – **SAVE THE DATE!**

Figure 1. The campus of IST-ULisboa.

Figure 2. Torre de Belém, Lisbon.

Figure 4. Palácio da Pena, Sintra.

Figure 5. Website of CICE2025.

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Invitation to FRPRCS-17 2026, Girona (Barcelona), Spain

Associate Prof. Cristina Barris (University of Girona, Spain), together with Professors Eva Oller (Technical University of Barcelona, Spain), Antoni Cladera (University of Balearic Islands, Spain) and Associate Prof. Maurizio Guadagnini (The University of Sheffield, UK),

On behalf of the organizing committee and the International Institute for FRP in Construction (IIFC),

We would like to invite you to the 17th International Symposium on Fiber-Reinforced Polymer (FRP) Reinforcement for Concrete Structures (FRPRCS 2026) to be held in Girona, Spain, in July 2026.

FRPRCS is the longest running conference series on the application of FRP in civil construction. FRPRCS commenced in Vancouver in 1993, and has travelled to Ghent (1995), Sapporo (1997), Baltimore (1999), Cambridge (2001), Singapore (2003), Kansas (2005), Patras (2007), Sydney (2009), Tampa (2011), Guimaraes (2013), Nanjing (2015), Anaheim (2017), Belfast (2019), Shenzhen (2002), and will be held in New Orleans in 2024.

FRPRCS-17 will reflect the state-of-the-art on the use of FRPs as reinforcing solution for new and existing concrete and masonry structures and provide a stimulating international forum for researchers, practitioners, manufacturers, asset managers and representatives of standardization committees to showcase the latest advancements in the field and set future trends.

We look forward to welcoming you in Girona, Spain, during FRPRCS-17 and fostering proactive discussions amongst participants.

IIFC NEWS

IIFC Business

FRPRCS-17 (2026)

The IIFC Executive committee received a total of 5 excellent proposals to host the FRPRCS-17 Conference in 2026. The origins of the proposals were from Germany (2 separate applications), Italy, Spain, and Australia.

The ExCom considered all proposals carefully and decided to shortlist three to present their pitch for hosting the FRPRCS via zoom to all IIFC council members for voting.

Following the voting process we are pleased to announce the FRPRCS-17 conference in 2026 will be hosted by Spain: Cristina Barris (University of Girona), Eva Oller (Polytechnical University of Catalonia), Antoni Cladera (University of Balearic Islands).

Congratulations to Cristina, Eva and Antoni, we look forward to joining you in Spain in 2026 for FRPRCS-17.

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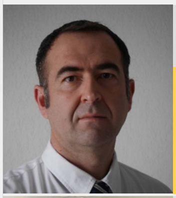
New IIFC Advisory Committee

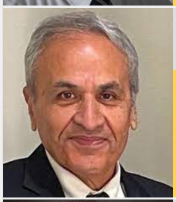
A new IIFC Advisory Committee (AC) was recently elected. The following members will serve for a six-year term:

Scott Smith
University of Adelaide, Australia (Chair of AC)



Emanuel Ferrier
Université de Lyon, France

Thanasis Triantafillou
University of Patras, Greece



Riadh Al-Mahaidi
Swinburne University of Technology, Australia

Jian-Fei Chen
Southern University of Science and Technology, China

Charles E. Bakis
Pennsylvania State University, USA

Renata Kotynia
Technical University of Lodz, Poland

Jin-Guang Teng
The Hong Kong Polytechnic University, China

Zhishen S. Wu
Ibaraki University & Southeast University, Japan & China

IIFC NEWS > IIFC BUSINESS

Call for Photo Competition

The International Institute for FRP in Construction is pleased to announce the 2023-2024 Annual Student Photo Competition! The competition is open to all IIFC student members (a $25 student membership fee applies to non-members).

All current undergraduate and graduate students are welcome to join IIFC and encouraged to participate in the competition.

CONTEST RULES

Submit one high-resolution photograph depicting FRP composites along with a title and brief description before **March 31 2024**. All photos related to FRP for construction are eligible, including (but not limited to) manufacturing, testing, and application. You must own the rights to any photo submitted to the competition. By participating in this competition, you are granting permission to IIFC to use your photo on their website, publications, and promotional material.

CRITERIA

All photos will be evaluated according to the following equally-weighted criteria:

- Aesthetic quality
- Uniqueness/originality
- Highlighting an innovative feature or application of FRP composites

JUDGING

All photos will be evaluated by the international jury listed below. Public voting will determine the People's Choice Award.

JURY MEMBERS

- Prof. Martin Noël, University of Ottawa, Canada
- Prof. José Sena Cruz, University of Minho, Portugal
- Prof. João Correia, University of Lisbon, Portugal
- Prof. Qian-Qian Yu, Tongji University, China

PRIZES

Competition results will be announced by April 30, 2024. All finalists will be featured in a Special Photo Issue of FRP International, the official newsletter of IIFC. The following cash prizes will also be awarded:

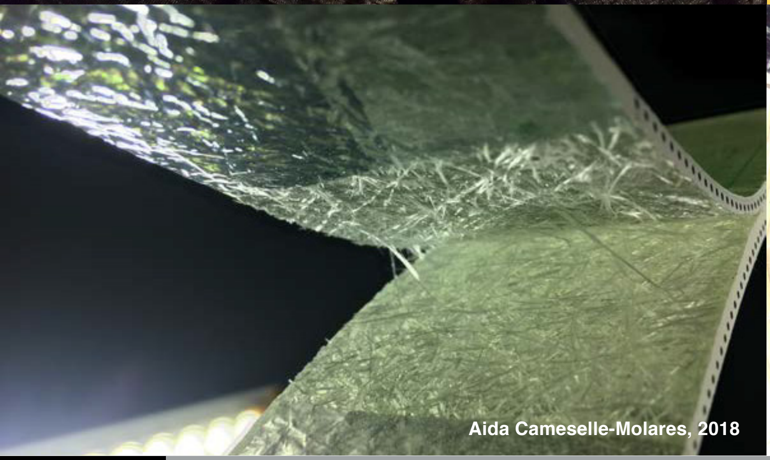
- **1st place: $500 USD**
- **2nd place: $300 USD**
- **3rd place: $200 USD**
- **People's Choice: $200 USD**

SUBMISSIONS

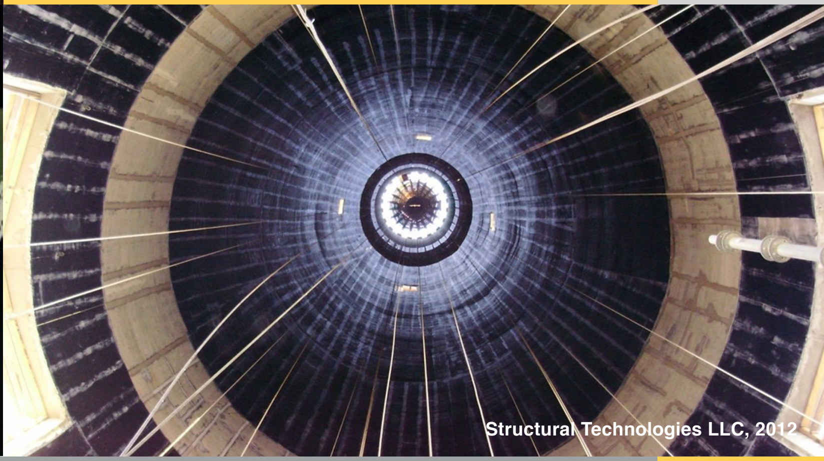
To submit your photo fill in a Google Forms accessible through the IIFC website:

www.iifc.org/awards

Vu Linh, 2018



Aida Cameselle-Molares, 2018



Structural Technologies LLC, 2012

IIFC NEWS

IIFC Best PhD Thesis Award 2023

WINNER

Author: Inês C. Rosa

Affiliation: Civil Engineering Research and Innovation for Sustainability (CERIS), Instituto Superior Técnico, University of Lisbon, Portugal

Email: ines.rosa@tecnico.ulisboa.pt

Title of the thesis: Fire behaviour of concrete structures reinforced with GFRP bars

Institution awarding the degree: Instituto Superior Técnico, University of Lisbon, Portugal

Supervisors: Dr. João P. Firmo, Dr. João R. Correia, Dr. Mário R. T. Arruda

Year of completion: 2022

INTRODUCTION

The use of glass fibre reinforced polymer (GFRP) bars is becoming increasingly considered for reinforced concrete (RC) structures such as bridge decks or maritime structures, where fire is not typically a primary design requirement.

On the other hand, the adoption of GFRP reinforcement in buildings is still not common, mainly due to concerns and lack of information and guidance regarding fire design.

However, and despite the relevance of the subject, few studies had comprehensively investigated the consequences of the severe degradation with temperature of the bars' mechanical properties and bond to concrete on the fire endurance of GFRP-RC structural members.

The main objectives of the thesis were to improve the knowledge about the fire behaviour of concrete members reinforced with GFRP bars, and to propose guidelines for fire design, complementing the (limited) recommendations available in GFRP-RC building codes.

A comprehensive assessment of the topic was made by means of experimental, numerical and analytical methodologies in the following three complementary domains: (i) thermophysical and mechanical characterization of GFRP bars at elevated temperature; (ii) bond behaviour of GFRP bars in concrete at elevated temperature, and (iii) fire behaviour of GFRP-reinforced concrete slabs. In each of these domains, the study compared the performance of different types of GFRP rebars, presenting different surface finishes (sand coated and different types of rib profiles), diameters and geometries (straight and 90º bent bars) (Figure 1).

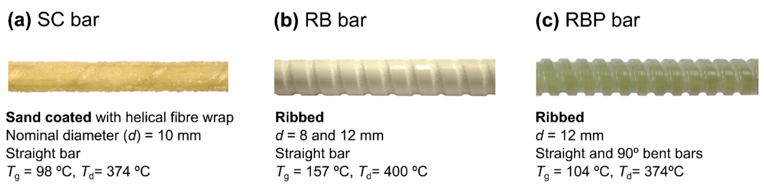


Figure 1. GFRP bars tested in the study.

METHODS AND KEY FINDINGS

The research developed in the first domain provided a wealth of new experimental results which were scarce (or inexistent) in the literature. The extensive campaign performed, comprising a total of 117 tensile tests, allowed to extend the existing database of data regarding the tensile strength and elastic modulus of GFRP bars up to 715 ºC (Figure 2).

The results obtained now comprise a wider range of temperatures likely to be attained during the event of a fire, data which was needed to improve the precision of numerical models simulating the fire behaviour of GFRP-RC members, and to define critical temperatures for GFRP bars.

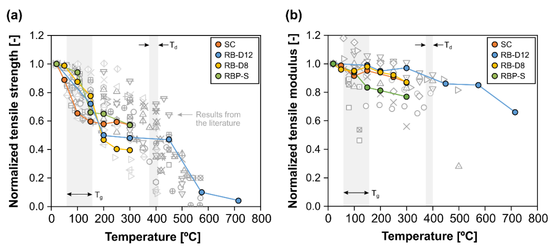


Figure 2. Normalized (a) tensile strength and (b) tensile modulus of GFRP bars as a function of temperature (normalization with respect to 20ºC, ambient temperature); comparison with data from the literature.

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With respect to the second domain, the GFRP-concrete bond behaviour at elevated temperatures, a total of 121 pull-out tests were performed to quantify the bond strength and stiffness degradation with temperature (up to 300 °C) of GFRP bars with different surface finishes, diameters, geometries and embedment lengths in concrete (Figure 3).

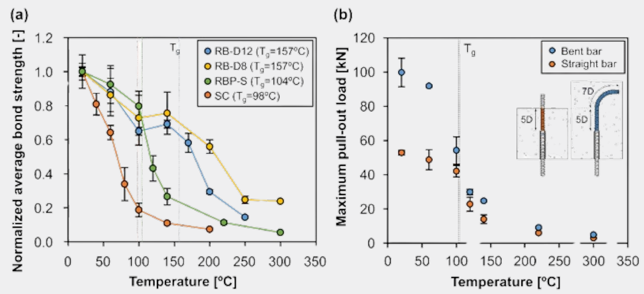

Figure 3. (a) Normalized average bond strength as a function of temperature of straight GFRP bars with different surface finishes and diameters; (b) maximum pull-out load of straight and 90° bent bars as a function of temperature.

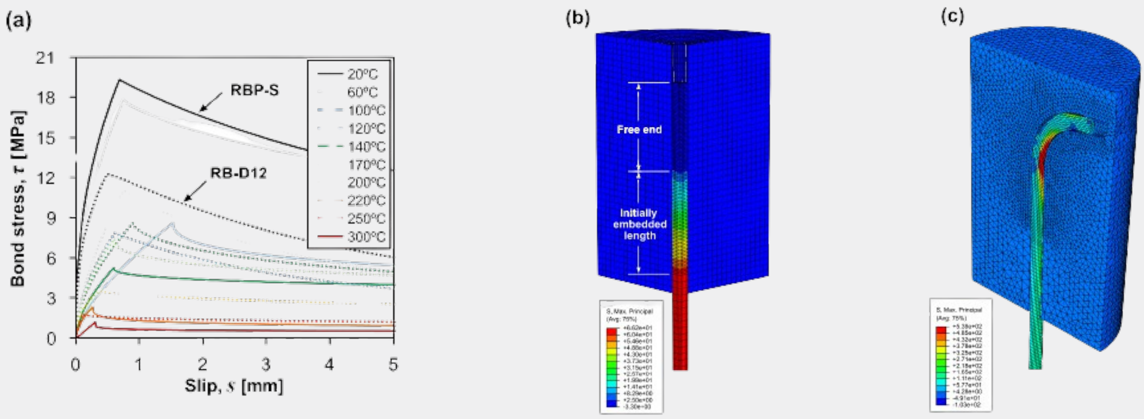

Figure 4. (a) Example of local bond stress-slip laws calibrated for straight ribbed bars; (b,c) numerical modelling of pull-out tests of straight and 90° bent bars.

The numerical calibration of temperature-dependent local bond laws for the different bars (Figure 4a), describing their full bond stress vs. slip response, is one of the most relevant research contributions, as these laws were absent in the literature and are needed to accurately simulate the behaviour under fire exposure of GFRP-RC members.

The numerical simulations of the bond behaviour (Figure 4b and Figure 4c), by means of finite element (FE) models explicitly considering the above-mentioned laws, allowed to model the relatively complex GFRP-concrete interaction at elevated temperatures, especially concerning the behaviour of bent GFRP reinforcement, which had not yet been simulated at high temperatures.

Parametric studies were also conducted, based on which the development lengths required to anchor straight and bent GFRP bars in RC beams and slabs were defined as a function of temperature – this is very useful for the purpose of designing GFRP anchorages.

Regarding the third domain, the thesis provided an in-depth understanding of the fire behaviour of RC slabs comprising GFRP reinforcement and brought new insights about the importance of several constructive details to the fire resistance of these structural members, most of which are not yet covered by current GFRP-RC building codes. In a first stage, fire resistance tests were performed in loaded GFRP-RC slab strips subjected to the ISO 834 standard fire curve (Figure 5).

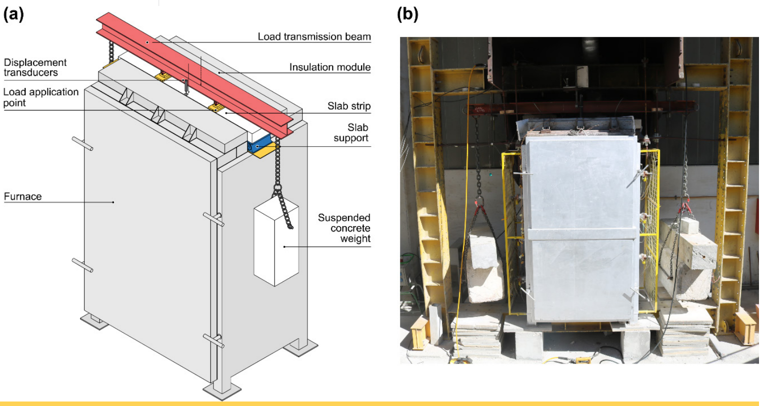

Figure 5. Fire resistance tests setup.

A total of 21 slab strips comprising different materials and detailing configurations were tested to evaluate the influence of the following parameters on their fire behaviour: (i) concrete cover thickness; (ii) presence of straight- or 90º bent tension lap splices directly exposed to fire with different overlap lengths; (iii) presence of "cold" anchorage zones; (iv) type of GFRP bars (with different surface finishes and diameters), and (v) concrete strength. In a second stage, 3D FE models were developed to simulate the thermomechanical fire behaviour of the GFRP-RC slab strips, and to assess in further detail the fire behaviour of GFRP-RC flexural members, particularly with respect to lap splices and anchorage zones.

The temperature-dependent thermophysical and mechanical properties of the bars and concrete were implemented in the models, and the GFRP-concrete interaction was modelled through the local bond laws (independently) calibrated for different temperatures. Based on the experimental and numerical results obtained, design recommendations were drafted concerning (i) the appropriate location and length of tension lap-splices and end anchors, (ii) the potential of using bent reinforcement in the ends of splicing bars to improve the slabs' fire resistance, and (iii) the possibility of adopting lower concrete cover thicknesses than those currently prescribed in current design guidelines, without compromising the fire endurance, thus leading to more economic (and sustainable) designs.

MAIN CONCLUSIONS

The conclusions obtained from this thesis allowed to confirm preliminary results of recent studies which proved that, in spite of the high vulnerability of GFRP bars to elevated temperatures, GFRP-RC slabs can endure over 3 hours of fire exposure with considerably lower concrete covers than those recommended in existing FRP-RC design codes (namely CAN/CSA S806-12), provided that the bars remain well anchored in cool zones of the structure. If this requirement is fulfilled, failure is governed by the tensile strength of the bars at very high temperatures, well above their glass transition temperature (T_g) (Figure 6a).

Moreover, it was shown that the progressive and severe bond degradation of the GFRP bars with temperature must be considered in the design of both cold anchorage zones and lap splices, aiming to prevent premature debonding failures when the bars' temperature increases above their T_g (Figure 6b).

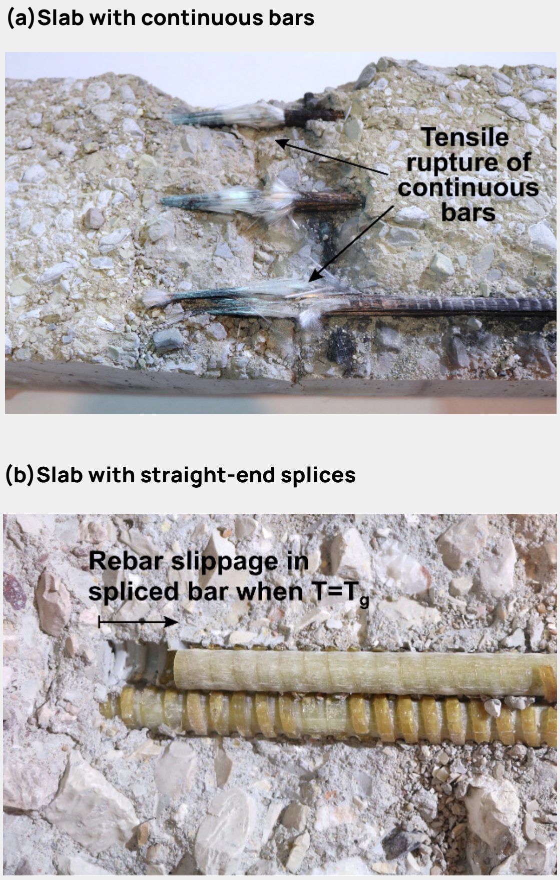

Figure 6. Failure modes of slabs exposed to fire: (a) tensile rupture of reinforcement (midspan section) in slabs with continuous bars, occurring after 2 to 3 hours of fire exposure; (b) slippage of overlapped bars in slabs with straight-end lap splices, occurring within less than 30 minutes of fire exposure.

In this regard, the adoption of bent bars was proven to be beneficial to decrease the cold end anchorage lengths, as well as to significantly improve the bond behaviour in splicing zones, thus increasing the slabs' fire resistance (Figure 7).

The results obtained in this study may contribute to improve existing design guidelines for FRP-RC structures, which currently provide insufficient and overconservative recommendations for their fire design. Ultimately, the findings of this study will also promote a safer, and more economic and sustainable use of FRP reinforcement in civil engineering applications.

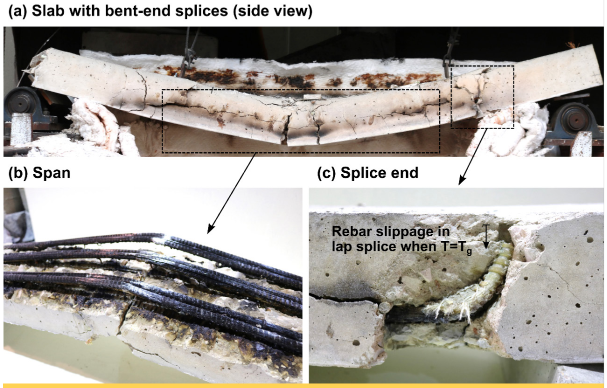

Figure 7. Failure of slab with 90º bent-end lap splices after 75 min of fire exposure, due to slippage of overlapped bars.

FUTURE DEVELOPMENTS

- Characterize the thermal conductivity and specific heat of FRP bars at elevated temperatures;
- Characterize the mechanical properties of FRP bars, in both the longitudinal and transverse directions (emphasis on the thermal expansion coefficients and shear properties), over a broad temperature range, and considering both steady-state and transient-state conditions;
- Investigate the bond behaviour of bent FRP reinforcement at elevated temperature, by means of pull-out and beam tests, to assess the influence of different bar configurations, surface finishes, confinement conditions and gradient temperature distributions;
- Investigate, through experimental and numerical studies, the influence of the following features in the fire endurance of FRP-RC structural members: geometry of hooks in insulated anchorage zones and lap splices location of splicing zones; bar diameter; axial restraint; type of loading, and concrete strength;
- Develop parametric studies to investigate the fire behaviour of FRP-RC members with arbitrary geometry, detailing and concrete cover, aiming to propose detailed recommendations with respect to the design of: (i) thermally insulated anchorage zones; (ii) length, geometry and positioning of lap splices; (iii) definition of critical temperatures for reinforcement, and (iv) minimum concrete cover required for a given fire resistance rate;
- Evaluate the residual (post-fire) behaviour of FRP-RC structural members, together with the data of the residual tensile and bond properties of FRP rebars, to assess the feasibility of repair after fire exposure.

IIFC NEWS

IIFC Best PhD Thesis Award 2023

RUNNER-UP

Author: Abdulrahman Zaben

Affiliation: The University of Queensland

Email: a.zaben@uq.edu.au

Title of the thesis: Hybrid Glulam-FRP Beam with Improved Fire Performance

Institution awarding the degree: The University of Queensland

Principal Supervisor: Dr Cristian Maluk, The University of Queensland, Australia I Semper, London, UK

Associate Supervisor: Joseph M. Gattasa, The University of Queensland, Australia

Year of completion: 2023

INTRODUCTION

The application of timber as a load-bearing structural material, especially in tall buildings, has traditionally raised concerns about its performance during and after a fire. Of particular relevance to the performance of mass timber construction during a fire, the reinforcement of timber and Glulam beam elements by using Fibre Reinforced Polymer (FRP) to create Hybrid Glulam-FRP (HGF) beams have been reported to be significantly stronger and stiffer in bending than unreinforced elements of equal size.

In essence, FRP with a relatively higher residual capacity at elevated temperatures, compared to timber, compensates for timber's loss of strength and stiffness at elevated temperatures or even when charring during a fire.

This is a shift in how FRP materials are currently constrained in load-bearing applications where structural integrity must be maintained during or after a fire.This study explores various HGF beam prototypes, predominantly utilizing Carbon FRP (CFRP) reinforcement in tension and compression zones. Innovative rationalized fabrication techniques were conceived aiming to achieve a balance between the industrial manufacturing requirements and the structural performance of the hybrid beams at normal ambient conditions and during or after a fire. While the timber-FRP combination isn't novel, the stud on how hybrids of this nature can enhance fire performance without adding much complexity to manufacturing procedures.

Overall, this study offers insights into the load-bearing capabilities of prototype HGF beams, demonstrating enhanced strength and serviceability. The findings encourage considering FRP (and other manmade materials) in conjunction with timber to bolster load-bearing timber floor systems, potentially introducing these hybrid systems at an industrial scale with minimal impact (temporal and/or economical cost) on current laminated timber manufacturing processes.

MANUFACTURING DETAILS

The study's core objective was to develop HGF beams with improved strength and serviceability, considering both ambient and fire conditions. The challenge lay in efficiently combining reinforcement materials while protecting them from fire effects without altering timber aesthetics.

The Fabrication techniques aimed to modernize the manufacturing of the HGF beams by:

1. Replacing epoxy, as a bonding agent between Timber and FRP, with conventional timber adhesives like Polyurethane or Phenol Formaldehyde, avoiding manufacturing complexities and long-term incompatibility.
2. Avoiding surface installation of FRP reinforcement to prevent rapid heating and preserving the exposed timber's aesthetics.
3. Addressing debonding between timber and FRP due to adhesive softening at high temperatures.

CFRP reinforcements, fabric or strips, were integrated within or between timber lamellas during the Glulam lamination process. This approach didn't significantly complicate typical Glulam manufacturing processes. The iterations of this technique are visualized in Figure 1 and Figure 2.

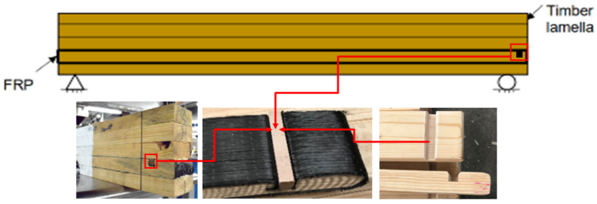

Figure 1. Method of reinforcing glulam beams using CFRP fabric secured around an internal timber lamella.

Figure 2. Method of reinforcing glulam beams using CFRP strips embedded in between timber lamellas.

EXPERIMENTAL METHODOLOGIES

The experimental program aimed to determine HGF beam bending strength and stiffness under normal ambient conditions, residual strength post-heating and cooling, and their behaviour during exposure to fire. This investigation encompassed various parameters: beam depth, reinforcement ratio, position, heating conditions, and charring depth.

Four-point bending tests were conducted in compliance with ASTM D198-15 standards. To ensure precise assessments, all beams were tested inverted, with loading points and the compression side from the bottom and supporting points and tension side from the top (as illustrated in Figure 3). This orientation mitigated flame effects on the remaining timber section, ensuring enhanced repeatability and facilitating clear Digital Image Correlation (DIC) analysis.

During transient experiments, the beams' soffits were exposed to top-mounted radiant panels to receive a fixed incident heat flux. To maintain consistency, adequate cold anchorage zones were provided on each side of the beam.

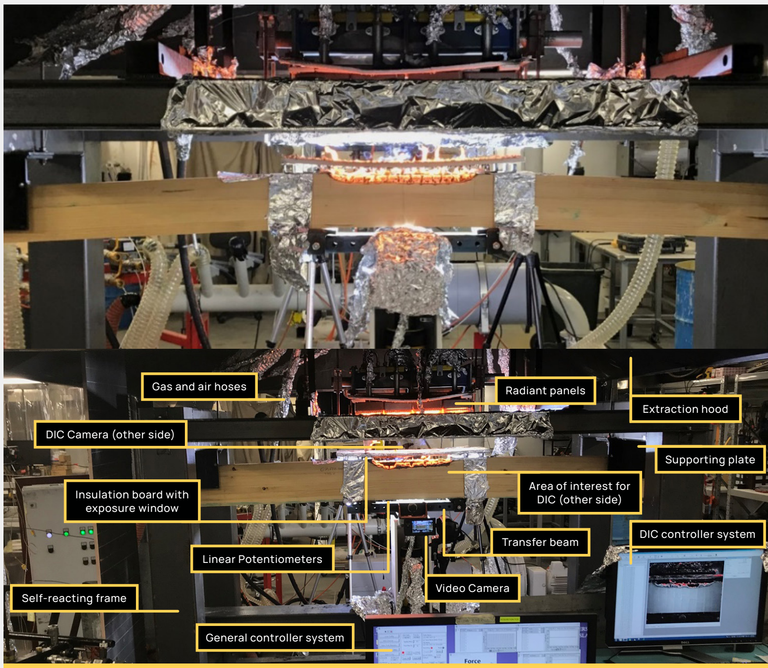

Figure 3. A beam undergoing four-point bending within a self-reacting frame, subjected to top-mounted radiant panels during a transient bending experiment – UQ Fire Laboratory.

RESULTS AND DISCUSION

The load-deflection behaviour of both Glulam and Hybrid Glulam-FRP (HGF) beams, tested under normal and fire-exposed conditions, demonstrated notable enhancements in bending capacity and stiffness owing to the presence of CFRP reinforcement.

Findings highlighted that HGF beams exhibited amplified bending moment capacity and stiffness, showcasing up to a 47% increase in strength under normal ambient conditions and a remarkable 56% enhancement in residual conditions post-fire exposure. Notably, when subjected to heating during loading, HGF beams exhibited over a 175% increase in time-to-failure.

This improvement primarily resulted from two key factors: the consistent mechanical properties of the CFRP reinforcement unaffected by current heating levels, and the partial thermal insulation provided by CFRP strips to the internal timber section, leading to less charring depth compared to Glulam beams after similar heating durations.

The presence of CFRP strips within the timber beams did not yield any detrimental effects. Notably, there was no occurrence of delamination between lamellas, indicating the system behaved as a composite structure. Additionally, no instances of relative slippage or debonding were observed between the timber and CFRP strips. Even in cases of sudden explosive failure in the tension region of some beams, the CFRP strips remained intact and did not peel off.

Consequently, the HGF beams showcased the structural contributions of FRP reinforcement, resulting in superior ultimate bending strength and stiffness for HGF beams compared to control Glulam beams under ambient and fire conditions.

CONCLUSIONS

The research aimed to modernise the manufacturing of Hybrid Glulam-FRP (HGF) beam by focusing on several main aspects. New techniques focused on using conventional timber adhesives, like Polyurethane, to bond Fibre Reinforced Polymer (FRP) with timber, embedding the FRP reinforcement within laminated timber elements to allow their protection from direct fire exposure, and strategically placing reinforcements to prevent debonding and slippage between timber and FRP. These innovations aim to achieve a faster, more efficient fabrication process while minimizing manufacturing disruptions.

Experimental studies investigated HGF beams' structural fire performance under various conditions. The outcomes offer critical insights into the interplay between structural design, fire resilience, and manufacturing considerations. Incorporating CFRP reinforcement within timber significantly enhanced Glulam beams' bending behaviour, maintaining structural capacity and stiffness under normal ambient conditions and during or after a fire. Parameters such as beam depth, reinforcement ratio, position, heating conditions, and charring depth were examined.

The transient and residual bending capacity of HGF beams during or after a fire showed the substantial contribution of CFRP reinforcement to their strength and stiffness, especially with adequate cold anchorage zones on each side of the beam. No adverse effects, such as delamination or debonding, were observed between the CFRP strips and Glulam beams, affirming the effectiveness of this integration.

RECOMENDATIONS FOR FURTHER RESEARCH

To maximize the utility of hybrid Glulam elements in the modern construction industry, mainly if HGF elements are intended to be used in situations where fire considerations must be addressed, further research in several areas is essential to address future exploration which include:

- Development of **analytical or numerical models** to predict the flexural behaviour of the HGF beams, including ultimate moment capacity and stiffness at ambient conditions and the bending capacity during or after a fire.
- To better understand the performance of HGF beams when fully exposed to fire, more experiments need to be done at **different thermal boundary conditions**. For example, exposing the whole beam span to fire and exposing several sides of the beam to fire.
- Long-term performance assessments are crucial to establish design guidelines. Investigating bond line performance, moisture effects, and material compatibility over time remains pivotal and warrants further experimental exploration.

RUNNER-UP

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Title of the thesis: Fracture behaviour of pultruded GFRP profiles: application to web-crippling

Institution awarding the degree: Instituto Superior Técnico, Universidade de Lisboa

Supervisors: Prof. Nuno Silvestre and Prof. João R. Correia

Year of completion: 2020

INTRODUCTION

This thesis was developed with the goal to better understand web crippling of glass fibre reinforced polymer (GFRP) pultruded beams. Furthermore, the study aimed to address the different failure modes that can occur, (i) web crushing, material failure at the web-flange connection or middle of the web; (ii) web buckling, critical buckling of the web; and (iii) a mixed failure mode, resulting of a combination of the two previous failure modes.

To this end, finite element models (FEM) were developed to correctly simulate web crippling tests. Since previous research had shown that stress-based criteria led to excessively conservative numerical load results for web crippling, the research aimed to experimentally characterize fracture toughness properties, which could be implemented in FEM, to simulate damage progression.

To characterize the fracture toughness properties of each material, experimental tensile and compressive fracture tests were performed for the in-plane transverse direction of the beams. Having characterized these fracture toughness properties, experimental web crippling tests were performed and then simulated with the developed FEM, calibrated with experimentally characterized fracture toughness properties.

Finally, having found a good agreement between experimental and numerical results, the direct strength method (DSM) was implemented to develop design guidelines that can accurately predict the web crippling ultimate load and failure mode of a given profile.

METHODS

The thesis addressed (i) five pultruded GFRP profiles, with four I-section profiles and one U-section profile; and (ii) two web-crippling load configurations, the end-two-flange (ETF), depicted in Figure 1.a); and interior-two-flange (ITF), depicted in Figure 1.b).

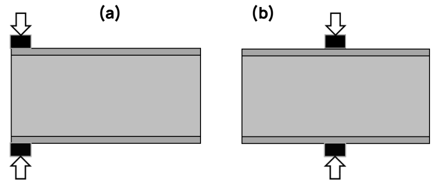


Figure 1. Selected web-crippling test configurations: (a) ETF; (b) ITF.

Fracture toughness tests were initially performed for in-plane transverse tensile loads, through the wide compact tension (WCT) test, depicted in Figure 2.a). This test specimen promoted stable crack growth which is critical for fracture toughness characterization. The specimens were monitored through a videoextensometry system as well as digital microscope, to have precise monitoring of crack growth and crack tip opening displacement. To determine the fracture toughness of each material, data post processing methods were applied to each test. These methods were implemented through FEM, based on crack length, in two different methodologies: (i) by estimating the j-integral for an applied unit load; and (ii) by determining the compliance calibration of each material. Both data processing methods provided similar results.

For compressive damage, the compact compression (CC) test was used, depicted on Figure 2.b), and an inverse methodology was implemented. To this end, FEM were calibrated for different values of transverse compressive fracture toughness, to identify the best fit between numerical and experimental results.

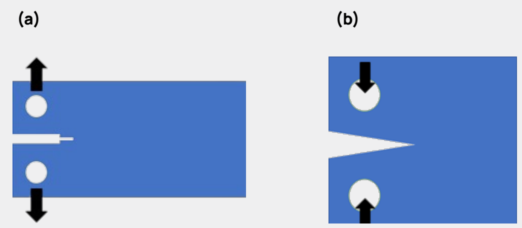


Figure 2. Selected fracture test configurations: (a) WCT; (b) CC.

Having gathered these fracture toughness properties, an experimental web crippling campaign was performed. The specimens were monitored through videoextensometry, as shown on Figure 3.a), to assess the in-plane strains of each specimen, and through displacement transducers and glued extensometers, positioned on at mid-section height, as shown on Figure 3.b), to assess at which point web buckling started to develop.

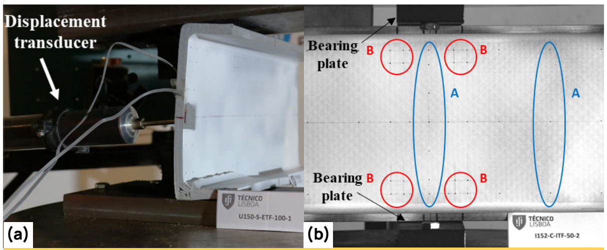


Figure 3. Setup for web-crippling tests: (a) videoextensometry targets; (b) U-section ETF test with strain gauges and displacement transducer installed perpendicularly to the web.

The web crippling numerical models were then developed, based on Abaqus built-in tools, to simulate each of the experimental tests that were performed. Three categories of FEM were developed, (i) geometrically linear damage models (D), where buckling failure cannot occur; (ii) elastic critical buckling models (B), where damage is not considered; and (iii) geometrically non-linear damage models (DB), where a very small imperfection is introduced to combine damage progression and buckling failure.

These three categories of FEM were used to expand the result database and to define the DSM for web crippling, applied to I-section profiles. The DSM method was initially tested for numerical results only, showing a very good accuracy to replicate the numerical results. As a following step, approximate expressions were calibrated for web crushing and web buckling failure, in order to implement the DSM without the need to develop FEM for each specific case.

RESULTS AND DISCUSSION

The fracture toughness tests showed very different trends for tensile and compressive loads. In tensile tests, the fracture toughness results increased exponentially with the level of fibre reinforcement in the in-plane transverse direction of the beam; whereas the compressive fracture toughness results showed no clear trend with transverse oriented fibre content. Figure 4 presents a summary of tensile and compressive fracture toughness results.

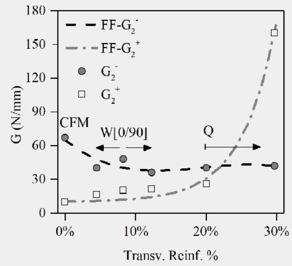


Figure 4. Evolution of fracture toughness results for tension and compression as a function of transverse reinforcement percentages, complemented with fitting functions (FF).

By differentiating the energy release rate results as a function of crack tip opening displacement, it was also possible to have an estimate of the cohesive law of each material. The cohesive law can be implemented in numerical models to simulate damage progression in greater detail. These results are shown in Figure 5.

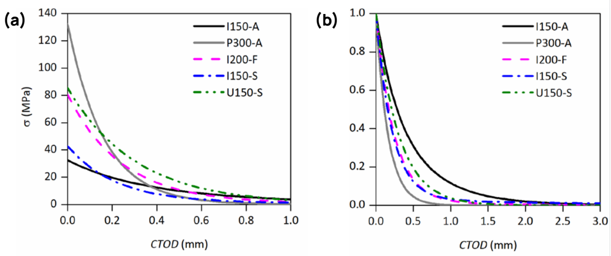


Figure 5. Laminate level cohesive laws: (a) J-integral based cohesive laws; (b) J-integral dimensionless laminate level cohesive laws.

Based on these fracture toughness properties and a simplified linear cohesive law, the experimental web crippling tests were successfully simulated by FEM developed with Abaqus built in tools. The DB models showed a good agreement to specimens that showed web crushing failure, buckling failure and also mixed mode failure. Figure 6 depicts experimental and numerical loads (D and DB models), for four different materials.

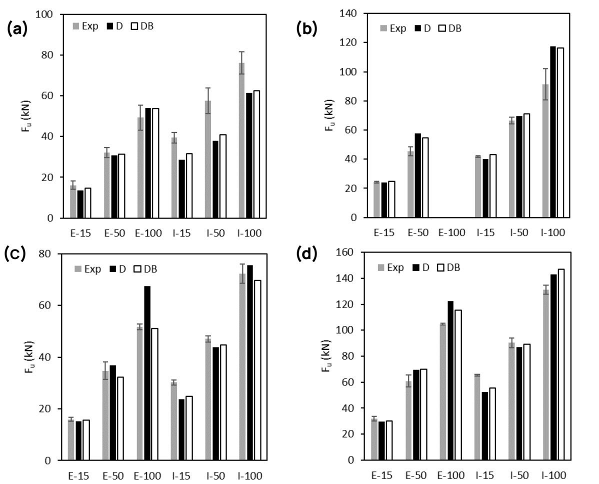


Figure 6. Experimental and numerical ultimate loads, including geometrically linear (D) and non-linear (DB) models: (a) I150-A; (b) I150-S; (c) I152-C; (d) I200-F.

The proposed DSM expression, based on the approximate expressions that were developed, was able to successfully predict the experimental results. The DSM expression was compared to, (i) Figure 7.a) illustrates the fit between numerical and DSM results; and (ii) Figure 7.b) depicts the fit between experimental and DSM results.

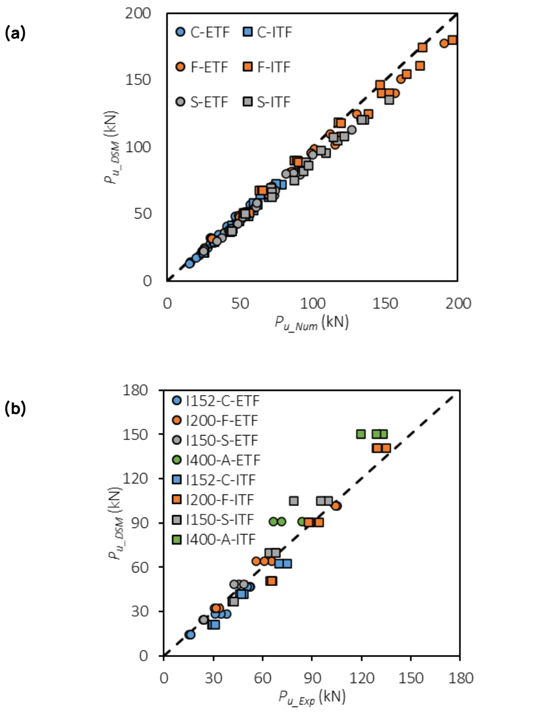
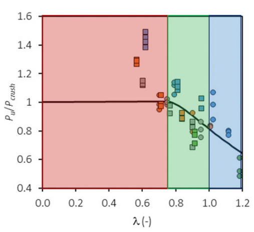


Figure 7. DSM results: (a) DSM (Pu_DSM) vs. numerical DB (Pu_Num) ultimate loads.; (b) DSM (Pu_DSM) vs. experimental (Pu_Exp) ultimate loads.

It can be concluded from Figure 7 that the proposed DSM expression shows a good agreement to numerical and experimental results. Regarding failure mode prediction, Figure 8 depicts this additional result from the DSM, which consists of slenderness (λ) thresholds that can help determine the failure mode of a given specimen.



- For λ < 0.776, web-crippling is triggered by **web crushing**
- For 0.776 ≤ λ ≤1.0, web-crippling is triggered by the **interaction** between web buckling and web crushing
- For λ > 1.0, web-crippling is triggered by **web buckling**

Figure 8: Slenderness thresholds for web crushing, mixed mode and web buckling failure modes.

CONCLUSIONS

The main contributions of this study can be divided in three main topics:

1. an accurate methodology was proposed to characterize the in-plane transverse fracture toughness properties and cohesive laws of GFRP pultruded materials, for tensile and compressive loads;
2. numerical models were successfully implemented to simulate web crippling failure of GFRP pultruded beams. These models simulated well the experimental ultimate loads as well as the experimental failure modes;
3. a DSM based design expression was proposed and found to have a good agreement to experimental results. The DSM expression provided accurate predictions of experimental ultimate load and also set slenderness thresholds that can be used to predict the failure mode of a given specimen.

FUTURE DEVELOPMENTS

The future developments of this study can be divided into the two main topics of the study, fracture toughness characterization and web crippling failure.

Regarding fracture toughness, the longitudinal fracture toughness properties of GFRP materials still need to be characterized. On a different perspective, further research is required to better understand the impact of fibre layups on fracture toughness or the impact of different resin materials.

Regarding web crippling there is also a wide range for future research, namely in assessing with greater detail the impact of material properties, fibre layups and geometrical properties on web crippling failure. The methodology presented herein should be tested for other load cases and profile sections.

Finally, two relevant aspects were not considered in the present study and should be researched in the future, (i) the properties of the web flange junction and their impact on web crippling; and (ii) the impact of initial defects on the web crippling failure of pultruded GFRP profiles.

MEET THE PEOPLE

Prof. Thomas Keller

KEY FACTS

Name: Thomas KELLER

Education: MSc in civil engineering in 1983, PhD in 1992, both at the Swiss Federal Institute of Technology Zurich, ETH

Current affiliation: Swiss Federal Institute of Technology Lausanne, EPFL

Key roles and contributions: Head of the Composite Construction Laboratory, CCLab, Professor of Structural Engineering

SHORT BIOGRAPHY

Prof. Thomas Keller obtained a Civil Engineering Degree from the Swiss Federal Institute of Technology Zurich, ETH, in 1983. Subsequently, he worked at the architecture and engineering office of Santiago Calatrava, where, in 1987, he developed the structural concept of the (200-m span) Alamillo Bridge in Seville (first cable-stayed bridge without back cables). In 1992, he received his doctoral degree from ETH, under the supervision of Prof. Christian Menn. In 1998, he was appointed as a (part-time) Associate Professor and in 2007 as Full Professor of Structural Engineering at the Swiss Federal Institute of Technology Lausanne, EPFL.

Today, Prof. Thomas Keller is the head of the Composite Construction Laboratory, CCLab at EPFL, which he founded in 2000. His research work is focused on the development of material-tailored applications of composites in structural engineering and architecture. He was a founding member of the International Institute for FRP in Construction, IIFC, and a member of the CEN/TC 250 Project Team to establish the European Technical Specification “Design of fibre-polymer composite structures”, CEN/TS 19101, published in 2022.

As a practical engineer, he designed the first composite pedestrian bridge in Switzerland (Pontresina Bridge, 1997, Figure 1), which is also one of the first composite bridges in Europe. Furthermore, he was responsible for the structural design of the five-story Eyecatcher Building (Basel, 1998, Figure 2), which is still the tallest building in the world with a primary composite structure. He also contributed to the design of the free-form multifunctional composite sandwich roof of the Novartis Campus Entrance Building (Basel, 2006) and the hybrid Avançon (vehicular) Bridge with an adhesively bonded composite-balsa sandwich deck (Bex, 2012, Figure 3).

Figure 1. Pontresina Bridge, December 1997: Construction team (students of architecture and TK) on top of 4 kN/m² brick loaded adhesively bonded span (without back-up bolts).

Figure 2. Thomas Keller in Eyecatcher Building, Basel, on third floor (02.2023).

Figure 3. Avançon Bridge, October 2012: Adhesive bonding of composite-balsa sandwich bridge deck onto steel girders, panels with transverse scarf joints in face sheets.

When and how did your interest on FRP composites first develop?

It happened by chance that I got into contact with composites. After completing my PhD on the durability of reinforced concrete bridges and working as a practical engineer in the field of bridge construction, I was appointed as a part-time Assistant Professor at the Department of Architecture of ETH in 1996. At the Institute of Building Technology, Professor Otto Künzle gave me the opportunity to design the Pontresina Bridge, which was the seed from which my interest and activities in composite construction grew. The interest was clearly directed towards new construction and not to strengthening of existing structures, since many activities were already ongoing in the latter field, and new construction was almost untouched.

Are there any emerging technologies or trends in the composites industry that you find particularly exciting or promising?

When I started my activities in composites, the development pointed to a bright future for composite vehicular bridges, numerous such bridges with composite decks were built, mainly in the USA. In the meantime, however, a certain disillusionment happened since concerns about the fatigue resistance of these decks could still not be eliminated. Such limitations do not exist, however, for pedestrian bridges. Pedestrian bridges thus seem among the most interesting applications of composites, since they can take advantage of the excellent mechanical properties and, furthermore, may offer unique architectural features. The use of composites in architecture (building construction) represents another field of potential innovation, based on the freedom of form and possible integration of functions. However, since a close collaboration between architect, structural engineer, building physicist, and manufacturer is required form the beginning of the project, and difficulties such as fire reaction response and resistance may need to be considered, progress in this field is not easy. If such projects are successful, however, they always demonstrate the real potential of composites compared to conventional materials.

Can you describe a particularly impactful project or initiative you've been involved related with FRP composites and its outcomes?

The most impactful project, which guided my journey in composites for construction since the beginning, was the Pontresina Bridge. During its design in 1997, I realised that mimicking isotropic steel structures and associated bolted connections does not allow the use of the full capacity of anisotropic composites.

This experience paved the way to the establishing of the CCLab in 2000, with its focus of research on material-tailored structural concepts and connection technologies, such as sandwich structures and adhesive bonding. Today, sandwich bridge decks and function-integrated sandwich roofs are increasingly implemented, and adhesive bonding has developed to a state-of-the-art technology. As a member of the project team of the above-mentioned European Technical Specification (TS), these experiences gave me the basis for the drafting of the clauses about sandwich panels, fatigue, detailing and adhesive joints. Based on my initiative, the TS does also not use "FRP" anymore, acronyms do not give an identity to our materials > "Composites".

Which individuals or mentors have had a significant influence on your career and what have you learned from them?

I was very lucky to meet outstanding personalities, who guided my way since I studied civil engineering at ETH. From my doctoral supervisor, Professor Christian Menn at ETH, I could learn the principles of conceptual design and understand their significance, as a basis for economic structures, which are also aesthetically convincing. Santiago Calatrava, architect and engineer, was my first employer after my studies and further raised my interests for architecture and its relationship to structural engineering. Professor Urs Meier at EMPA was not far from ETH, and I could always rely on his advice and thus gain confidence on my way. I was also lucky to meet Professor Marie-Anne Erki from the Royal Military College of Canada, who helped me in the design of the adhesive connections of the Pontresina Bridge, and thus paved the way for this meanwhile important research axis at the CCLab.

If you were starting your career today as a young engineer/researcher, what advice would you give yourself?

I would give the following advice to a young engineer/researcher:

1. Search for a field of activity where significant progress can still be made and outcome can be generated, which contributes to solve urgent problems of the society. Take care to not be taken by fancy and unsustainable trends.
2. Focus on what is essential.
3. Always aim for the highest possible standards and outcome quality.
4. Establish a network of peers and always be informed about the latest advances in your field
5. Continuously assess yourself to ensure that you are on the right path.
6. Be tenacious, patient and confident in yourself, the success will not arrive tomorrow.

Personal questions:

What is your favourite hobby outside of work?

You may have a look on www.statuary-in-context.ch and related Blog.

What is/was your favorite trip?

My trips to Madagascar were my favorite ones (which are related to the previous question).

Which are your favourite songs?

Muddy Waters & The Rolling Stones: Baby please don't go - live at Checkerboard Lounge Chicago, 1981

The Blues Brothers & Ray Charles: Shake a tail feather (movie scene 4/9), 1980

Deep Purple: Smoke on the water - live at Montreux, 2006

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COMPOSITES AROUND THE WORLD

Research

Performance of FRP-Repaired Steel Pipelines after Long-Term Exposure to Salt-Spray Environment

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INTRODUCTION

Topside steel pipelines from the oil and gas industry are often exposed to aggressive marine environments, characterized by a saline atmosphere with high relative humidity (RH). Currently, the management of corrosion-induced problems represents around 15 to 30% of the total operation expenses. In this context, fiber-polymer composites (FRP), have been increasingly used over the years in pipeline repair systems, due to their high strength-to-weight ratio, good resistance to environmental degradation, ease of application without interruptions and risk of explosion, and less labor-intensive nature.

Despite their advantages, these repairs may lose performance with time associated to FRP degradation under UV and hygrothermal exposure, as well as to debonding caused by steel corrosion. The composite repair design lifetime is mentioned in standards such as the ISO 24817:2017, but an explicit procedure to predict its performance over time is presently not available, requiring subjective judgement that brings uncertainties to the whole operation.

Within this context, a collaborative project was developed by the Research and Development Center of Petrobras (CENPES) and the Pontifical Catholic University of Rio de Janeiro (PUC-Rio), entitled 'Performance of Repairs in Saline Environments', aiming to fill some of the existing gaps.

The scope included (i) exposure of materials and repaired components to salt-spray environment under different temperatures for up to 1.5 years, (ii) evaluation of physical and mechanical degradation of usual FRP materials adopted and their interface with steel substrate, and (iii) assessment of several non-destructive techniques (NDT) and development of FRP repair inspection protocols. The project started in October 2018 and will be completed by May 2024.

METHODOLOGY

MATERIALS

FRP Specimens

The FRP materials used were provided by three different manufacturers, hereafter denoted as A, B and C. Materials were produced by hand layup technique and were composed of proprietary epoxy resin and either glass (A and C) or hybrid carbon-glass (B) reinforcement. All prismatic specimens were cut from flat laminate plates with a nominal thickness of 6 mm. An overview of the materials used is presented in Figure 1.

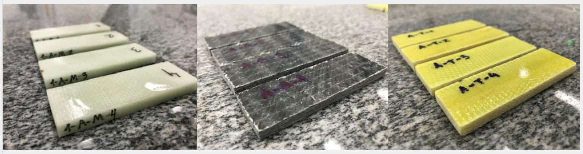

(A) (B) (C)

Figure 1. FRP materials used in the project.

FRP-Steel Joints

Double lap shear (DLS) FRP-steel joints were fabricated using ASTM A516 Gr. 70 steel plates and the same FRP materials described in Section 2.1.1. An illustration of the 380-mm long specimens is presented in Figure 2. Four different methods were used for surface preparation: manual sanding, Monti machine sanding, manual sanding followed by silane application, and Monti machine sanding followed by silane application, always achieving the minimum required roughness. After cutting in the final dimensions, the sides of the specimens were coated with epoxy as an attempt to minimize the corrosion on the sides.


Figure 2. FRP-Steel joint specimens.

FRP-Repaired Pipes

Steel pipe specimens with external FRP repairs were fabricated by the same manufacturers described in Section 2.1.1 (A to C) and considering the surface preparation techniques described in Section 2.1.2. Two reference samples with artificial defects were also fabricated by manufacturer A, for validation of the non-destructive techniques. Figure 3 presents typical samples produced by each manufacturer.


Figure 3. FRP-repaired steel pipe specimens before aging.

METHODS

Aging Protocol

To simulate the marine environment, specimens were conditioned in three independent salt-spray chambers (model EQUILAM SSEQ-Walk-In) operating at temperatures of 35°C, 55°C and 70°C, as illustrated in Figure 4. All temperatures adopted were lower than the material's glass transition temperature (between 90 and 100 °C). The salt concentration in the solution used was 5.0 wt%, according to the recommendations of ASTM B117 standard.


Figure 4. Overview of walk-in salt-spray chambers.

Tests on FRP Specimens

FRP samples were removed from the chambers at pre-defined times and subjected to destructive mechanical tensile, flexural and interlaminar shear tests, to assess the retention of properties with time and aging condition. Moisture content was also measured during aging and, finally, non-destructive tests were carried out as alternative in situ characterization methods, namely: ultrasonic test, terahertz, impulse excitation and colorimetry.

Tests on FRP-Steel Joints

FRP-steel joints were removed from the chambers at pre-defined times and subjected to double-lap shear (DLS) tests according to the ASTM D3528 standard. Before that, ultrasonic inspections were carried out using the same approach used for the pipe specimens (see Section 2.2.2.) to verify for possible discontinuities at the FRP-steel interface. Bi-material mixed-mode bending specimens were also fabricated and tested for the unaged condition, as an attempt to correlate the DLS results with the fracture properties using numerical models. Finally, pictures were taken from the rupture surfaces and image analyses were performed to assess the corroded area during aging.

FRP-Repaired Pipes

Pipe samples with FRP repairs were periodically taken out from the chambers and subjected to the following non-destructive tests using portable tools, namely: shearography, microwave and ultrasonic test. An overview of these test setups is presented in Figure 5. Each technique was previously validated with the reference pipes with artificial defects. To confirm the final results obtained with each the technique, tomography and dissection analyses are currently underway.

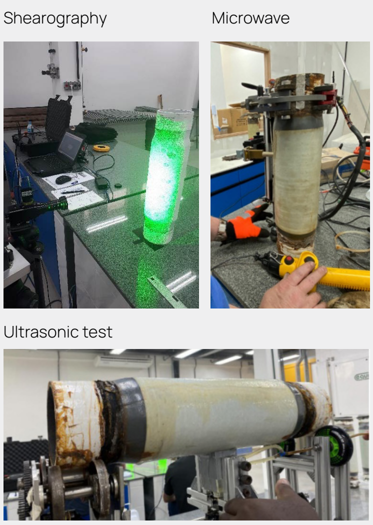


Figure 5. Main non-destructive tests conducted on FRP-repaired pipe specimens.

OVERVIEW OF MAIN RESULTS

Performance of FRP Specimens

The results showed that properties degrade during the first ages, stabilizing after a while. Phani-Bose models were used to simulate the behavior for generic time and temperature conditions, as illustrated in Figure 6 for interlaminar shear strength (ILSS). Chemical and physical analyses revealed combined influence of post-cure and water-induced degradation.

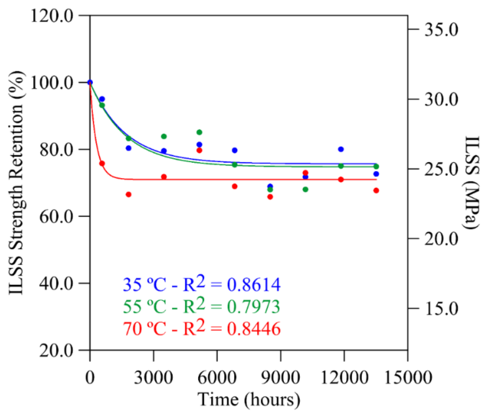


Figure 6. Typical degradation curves for different aging temperatures, fitted with Phani- Bose model.

With respect to the non-destructive tests, all techniques were able to provide indicative parameters of degradation in the composites; ultrasonic and impulse excitation tests provided elastic properties comparable to those obtained from destructive tests. For terahertz, the response spectra were treated and a machine learning technique was used to correlate these signals with the material and aging condition.

Performance of Steel-FRP Specimens

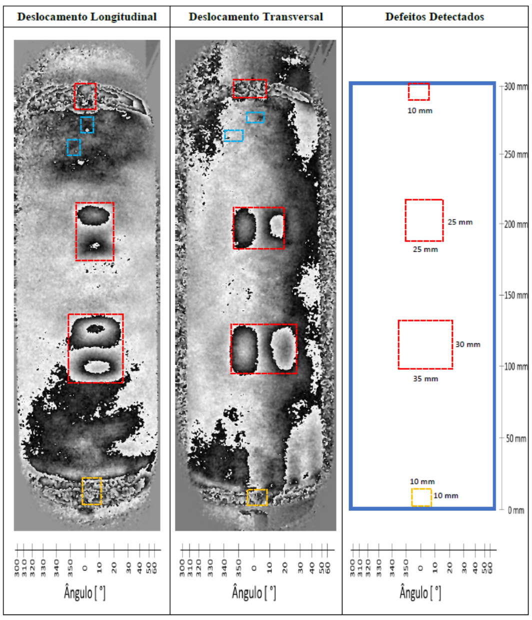
The results showed that the strength of the joints continually reduced over time due to the mainly due to corrosion at the interface. The quantification of the corroded area was possible with the successful aid of image analyses techniques. Mathematical models simulating the DLS configuration in the aged condition are being developed to estimate the individual contributions of corrosion and adhesive degradation to the final reduction of strength. With this approach, a Phani-Bose-type degradation law can be derived for the adhesive, as well as the corrosion rate. The ultrasonic test was also able to review small defects. An overview of the aged DLS specimens is presented in Figure 7.

Figure 7. Aged FRP-steel joints and unaged and aged pipes at 55 and 70 oC.

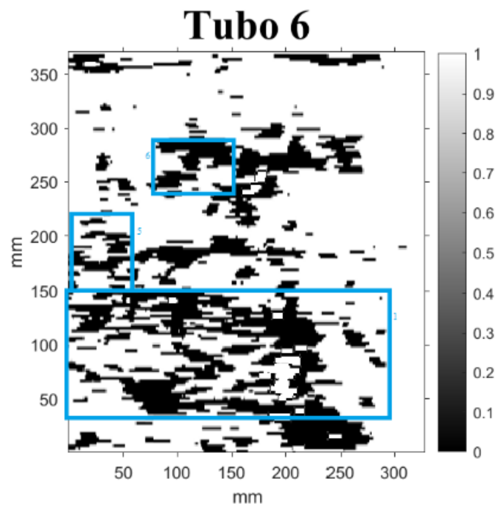
Performance of FRP-Repaired Pipes

In general, however, the results obtained are satisfactory, although variations in the dimensions of the defects have been observed – actual discontinuity areas will only be confirmed after dissection and tomography tests. It was also observed, in some cases, the appearance of defects inside the repair, which may be a consequence of differential repair/metal deformations caused by temperature and moisture absorption. It is worth mentioning that microwave and ultrasonic tests were unsuitable for carbon-based repair materials due to signal attenuation. Typical outputs from main non-destructive tests are presented in Figure 8.

Shearography



Ultrasonic test



Microwave

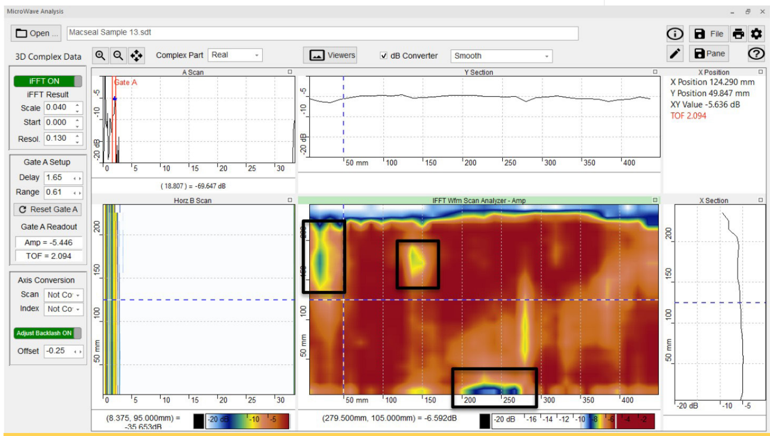


Figure 8. Typical outputs from main non-destructive tests.

CLOSING REMARKS

In all, more than 10,000 specimens were tested over the course of the project. Considering the materials studied and analyses performed, the outputs form one of the largest databases related to aging of FRP-repaired steel. The results allowed the adaption of the ISO 24817:2017 procedures to account for aged properties and corrosion in the design and revalidation of composite repairs. With respect to the execution of non-destructive inspection of FRP-repaired pipes, technical specifications were developed, including information such as equipment, calibration, essential variables and documentation. Finally, it is important to highlight that, despite the large experimental campaign, some gaps still remain and further studies are required to increase the reliability of design procedures and to improve the protocols of inspection techniques.

COMPOSITES AROUND THE WORLD

Industry

Case study: Fontanamare-Gonnesa Bridge, the First Hybrid Bridge in Europe, Gonnesa, Italy

Edoardo Intra
Sireg Geotech S.r.l., Italy

Gabriele Balconi
Sireg Geotech S.r.l., Italy

Year: 2023

Location: Gonnesa, Italy

Owner/Commissioner: Regione Autonoma della Sardegna, Municipality of Gonnesa

Structural Design: Eng. Fausto Mistretta – Secured Solutions

Contractor: Manini Prefabbricati SPA

Products: Sireg Glasspree® TS Glass Fiber Rebars

INTRODUCTION

On the morning of April 2, 2020, the prestressed concrete bridge connecting the provincial road 83 with Fontanamare beach in the Municipality of Gonnesa (west coast of South Sardinia) collapsed while a truck for ecological service was passing through. The collapse was caused by the widespread degradation of the concrete particularly exposed to marine aerosol and the consequent corrosion of the most superficial reinforcement bars. This process increased cracking and material degradation until it reached the harmonic steel of the prestressing cables. Therefore, a new bridge was designed with the ambitious goal of granting a service life of 100 years, while minimizing maintenance interventions over time.

THE PROJECT

The bridge project includes two lanes, one in each direction of travel and a side bicycle/pedestrian track for a total width of 9.10 m; the net span is 22 m, composed of 7 main ribs joined by 5 stringers and a cast-in-place slab. The ribs consist of rectangular section elements having size 50 x 120 cm made of reinforced concrete and prestressed by means of steel strands. The cortical reinforcement is realized using Sireg Glasspree® TS glass fiber bars: the total supply is equal to 21.000 m. This hybrid technology combines the advantages of prestressing with those of glass fiber bars. These ones are corrosion resistant, they provide an expected service life of 100 years and low maintenance costs.

The following design codes were considered in safety verifications:

- D.M. 17 gennaio 2018: “Aggiornamento delle «Norme tecniche per le costruzioni»”;
- Circolare C.S.LL.PP. 21 gennaio 2019: “Istruzioni per l’applicazione dell’«Aggiornamento delle Norme tecniche per le costruzioni”» di cui al decreto ministeriale 17 gennaio 2018”;
- CNR-DT 203/2006: “Guide for the design and construction of concrete structures reinforced with Fiber-Reinforced Polymer Bars”;
- ACI 440.1R-15: “Guide for the design and construction of structural concrete reinforced with FRP Bars”.

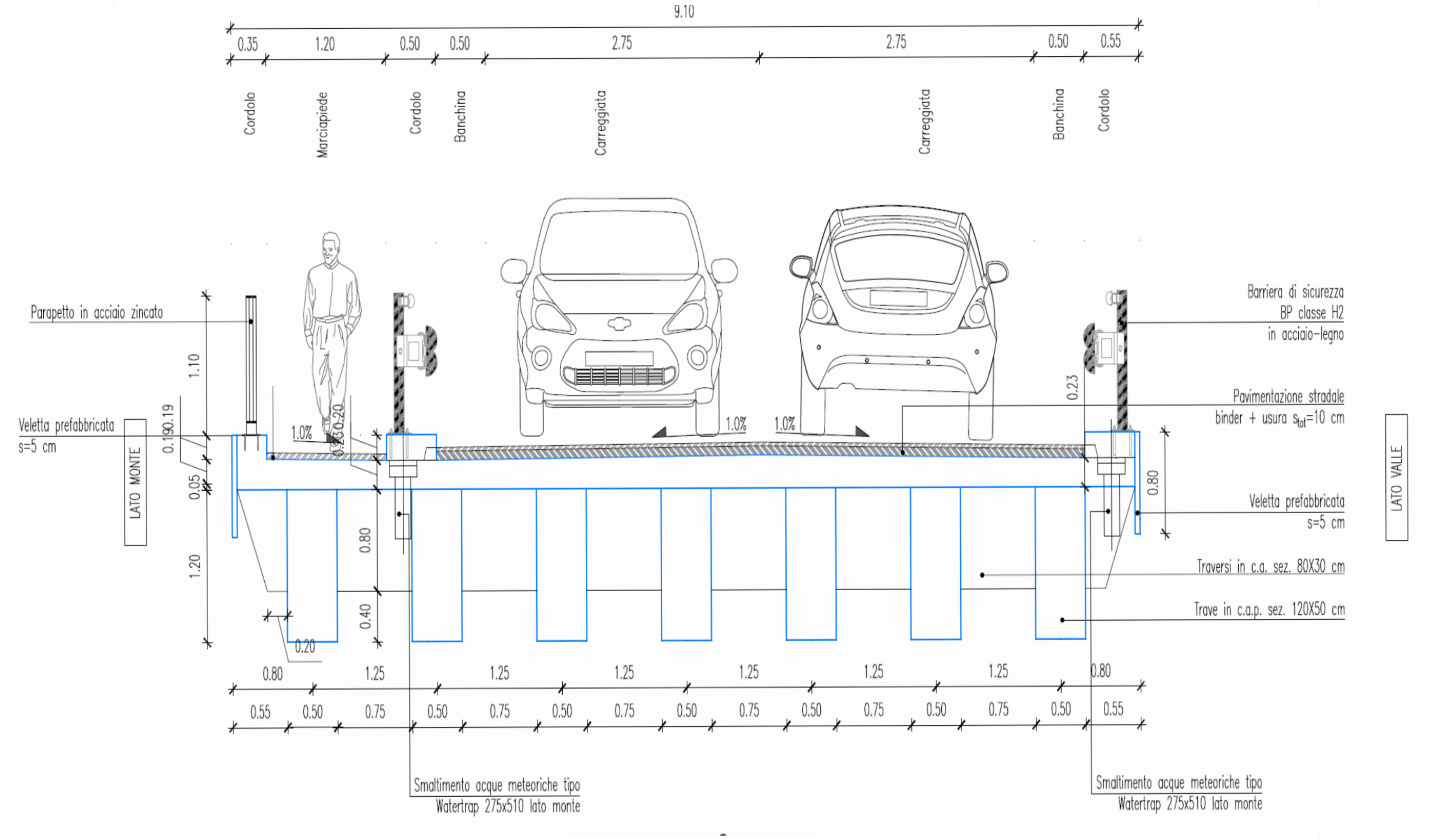


Figure 1. Cross section of bridge deck.

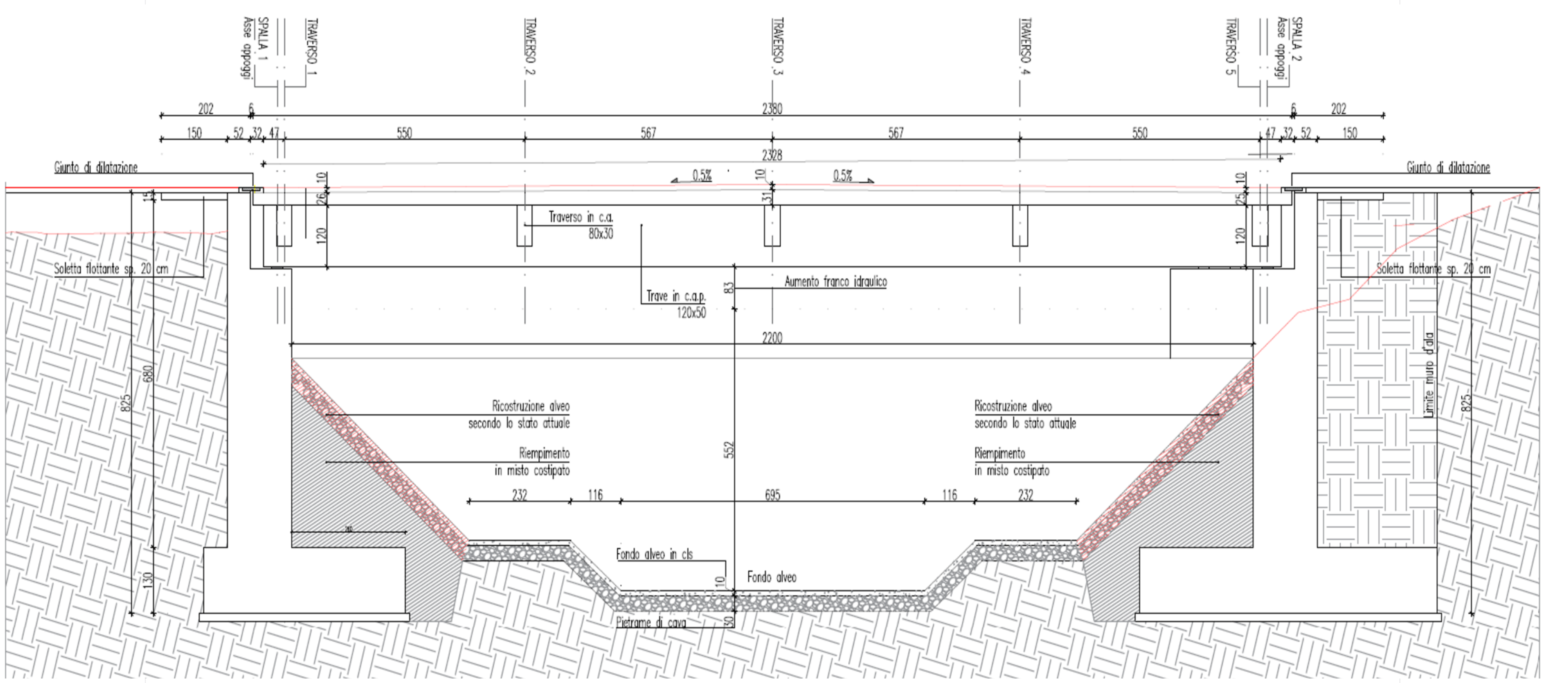


Figure 2. Elevation view of the bridge.

PRODUCTS

Closeness to the sea creates an aggressive environment for classic steel bars and led to the collapse of the bridge. This is the reason why the use of glass fiber bars was planned as reinforcement of the cortical part.

Sireg Glasspree® TS fiberglass bars are made through a continuous pultrusion process; the reinforcing element consists of direct roving "E-CR" glass fiber and vinylester resin (Figures 3 and 4). Available in diameters ranging from 6 to 40 mm, the maximum tensile strength is 1100 MPa and the modulus is equal to 46 GPa; they are externally coated with quartz sand and resin during continuous production process. They are impervious to corrosion and provide an excellent resistance to chemical elements as well. They are transparent to both electric and magnetic fields, and their low weight (2.00 g/cm3) allows for easy handling on the construction site. Sireg Glasspree® TS bars are the first ETA certified bars on the market (ETA certification no. 22/0168).

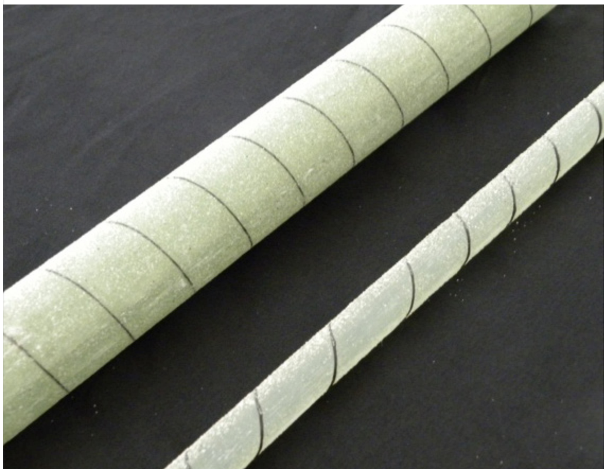


Figure 3. Sireg Glasspree® TS round bars.

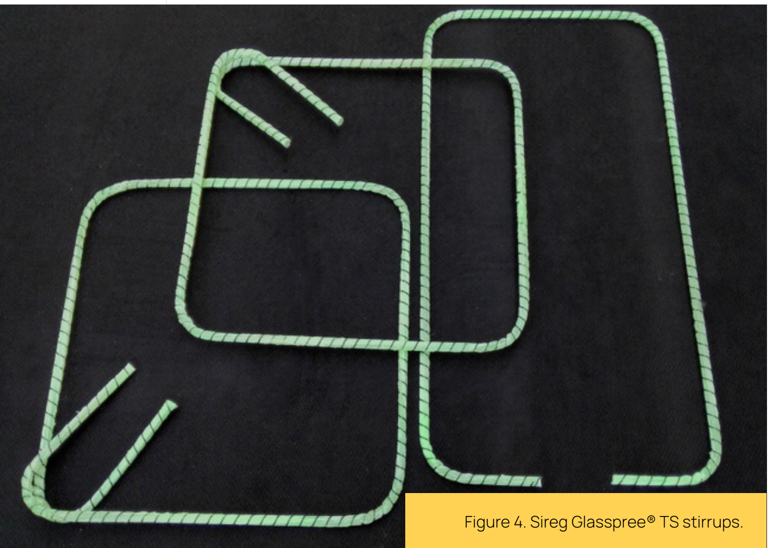


Figure 4. Sireg Glasspree® TS stirrups.

TEST CAMPAIGN

As it was an innovative work, the design and construction phases were accompanied by a thorough laboratory experimental campaign on small-scale prototypes and on a full-scale main rib identical to those of the bridge.

Small-scale tests were carried out in collaboration with the Materials Testing Laboratory of the University of Cagliari: scale prototypes of the bridge ribs (dimensions 20 x 40 x 360 cm) were realized fully reinforced with fiberglass bars designed with the aim of optimizing the static performance of the planned infrastructure.

At Manini Prefabbricati's facility in Bastia Umbra, a full-scale rib was fabricated to investigate both the service limit state and the ultimate flexural and shear capacity of the complete element (Figure 5). Using different test setups, the investigation allowed to quantify the real bending and shear response of the prototype, showing satisfactory results and higher structural performance than expected.

Figure 5. Full-scale testing at Manini Prefabbricati Spa.

NUMERICAL MODELING

The bridge design and the experimental phase have been verified through very sophisticated numerical analysis with the aim of predicting the behavior of the elements subject to the design load stresses and to study their performance to failure. The three-dimensional numerical model created using ASDEA's STKO program and OpenSees replicates the realized structures with the highest fidelity (Figure 6).

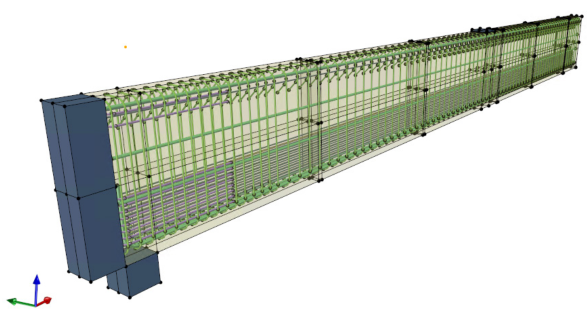


Figure 6. Three-dimensional numerical model.

The model predicted with very good approximation the behavior of the rib in terms of load-displacement curve (Figure 7), crack pattern and residual strain at the end of the test. As described in the experimental campaign, shear tests were carried out both in the central segment and in the support one. Numerical computations made it possible to identify the collapse mechanisms accurately and precisely.

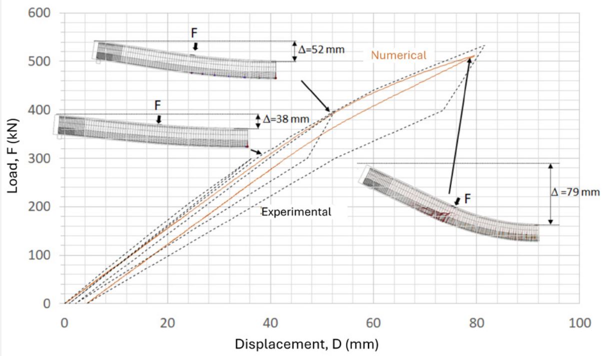


Figure 7. Experimental and numerical load vs. displacement behaviour.

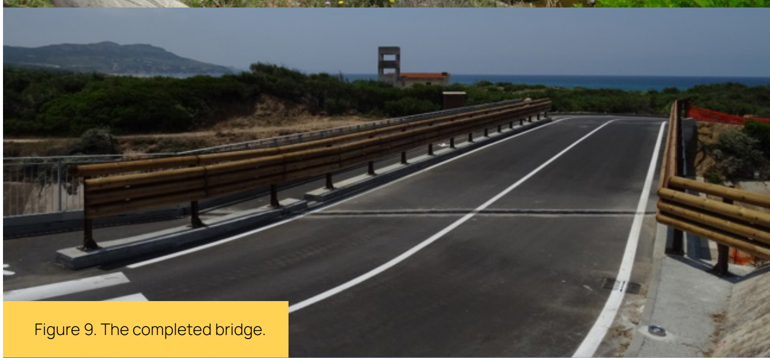


Figure 9. The completed bridge.

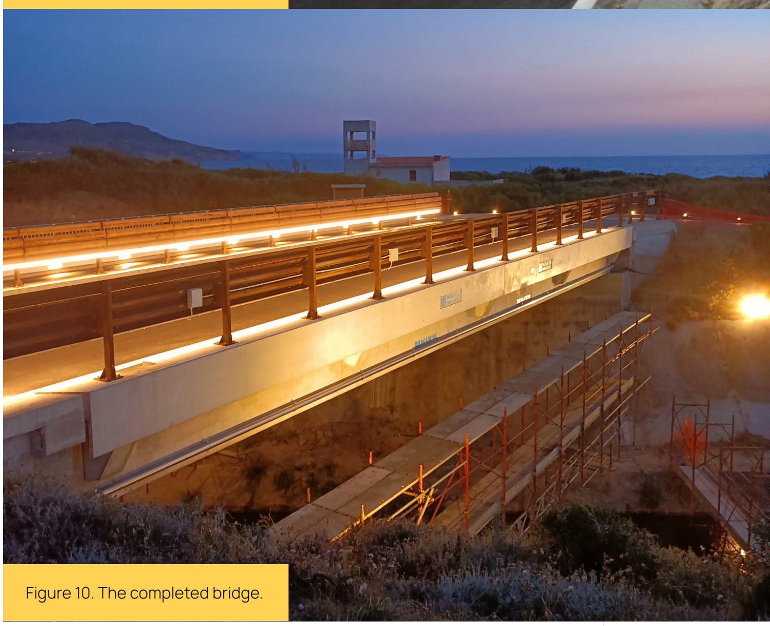


Figure 10. The completed bridge.

REALIZATION

The bridge was built by Manini Prefabbricati using optimized assembly procedures in line with the Accelerated Bridge Construction strategy, aiming to minimize the impact of on-site operations and to eliminate the use of formwork (Figure 8).

The use of glass fiber bars to reinforce the cortical layers and of precast elements with high-performance concrete made it possible to construct an aesthetically pleasant bridge (Figures 9 and 10) with excellent performance in terms of ease of assembly, durability, and environmental sustainability, while retaining the advantages of the traditional adherent cables prestressing.

The choice of precast concrete ribs and shells, instead of the ordinary formwork, allowed for increased productivity on site, which, due to the ease of installation of fiberglass bars, led to a reduction of construction time of 30 to 40 %.

Figure 8. Slab reinforcement with glass fiber bars and casting.

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COMPOSITES AROUND THE WORLD

Education

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Institution: Delft University of Technology, Faculty of Civil Engineering + Extension School

Name of course: Fiber Reinforced Polymer (FRP) Composites in Structural Engineering – FRPx

Level (BSc, MSc, PhD, professional): Professional

Type of training: online

OBJECTIVES

Fibre-polymer composites (also known as FRP) are used for almost 6 decades in aerospace, automotive and marine applications, having main advantages over metals, concrete and timber by being lightweight and durable. Aging of infrastructure and increase of traffic loadings on bridges, and new hazards on buildings, are main driving forces for innovations in the field of structural/civil engineering. Use of composites for strengthening of existing structures is relatively well-known technology. However, less well documented knowledge exists for design of composites in new components or complete design of load bearing structures. Therefore, engineers in practice usually hesitate to apply composites.

This course focuses on engineering application of composites in infrastructure, where the scale, loading conditions and structural requirements are distinctly different from classical fields of application of composite materials like aerospace, automotive and marine industry.

The main learning objective of this course is to improve design and structural skills of an engineer in a company so that he/she can make a decision, create appropriate detailing and propose the fabrication process of a full-scale composite structure. The goal is to enable and encourage application of the composites in construction sector where it is competitive compared to traditional construction materials.

The course is designed for professionals who may include early-career and senior structural engineers, consultants, reviewers, project managers and decision makers at investors and/or state institutions, who have experience with classical structural engineering materials.

The learning objectives are set such that after successfully finishing the course, the participant will be able to:

- Exploit the advantages of composites with respect to traditional materials in infrastructure and building projects whilst being aware of the limitations that exist for specific applications.
- Make informed selections from the wide range of different FRP materials and production processes suited to a specific application.
- Deliver a realistic design for structures made of composites.
- Perform design verification for simple to modestly complex structural members and joints between members.
- Use analytical and computational methods to analyze structural behavior and obtain results for design verifications of all-composite and hubris structures.

NUMBER OF CREDITS AND HOURS OF CONTACT

The course lasts for 9 weeks with expected workload of participants ranging from 6-10 hours per week. Approximately half of the time is spent on following the course material and another half on working on individual and group assignments. Upon successful completion of lectures and assessment through assignments participants receive certificate. Based on the learning hours the course can be considered as equivalent to 3.0 ECTS credits for bachelor and master courses. Each country has own scheme to convert those to an equivalent professional education credits.

PROGRAM (TOPICS COVERED) AND SYLLABUS

The course is organized in 6 modules over 9 weeks. A brief summary of topics covered in each module is presented below:

Module 1 – Introduction: Examples of applications (new-build, retrofitting), environmental impact of composites, constituents of the composite material, rule of mixtures, laminates.

Module 2 – Structural design: Construction and assembly, developing a composite structural solution, conceptual design, design of materials, joints, composite decks, fabrication methods.

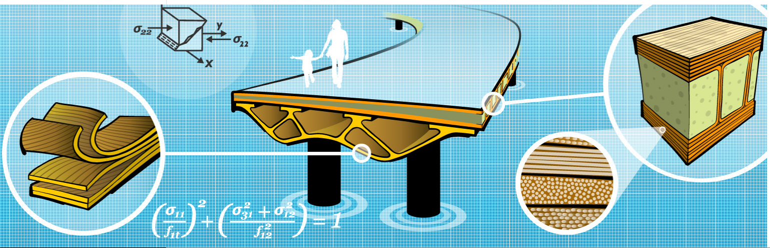
Module 3 – Mechanical behaviour of the material: Orthotropic behaviour, Classical Laminate Theory, failure modes, simulation tools.

Module 4 – Specific behaviour of the material: Durability, effects of the environment by moisture and temperature, influence of production processes on quality and robustness, creep and fatigue behaviour.

Module 5 – Design verifications: Design codes and recommendations, verification of cross sections and members, Verification of joints, finite element analysis (FEA) in design verifications.

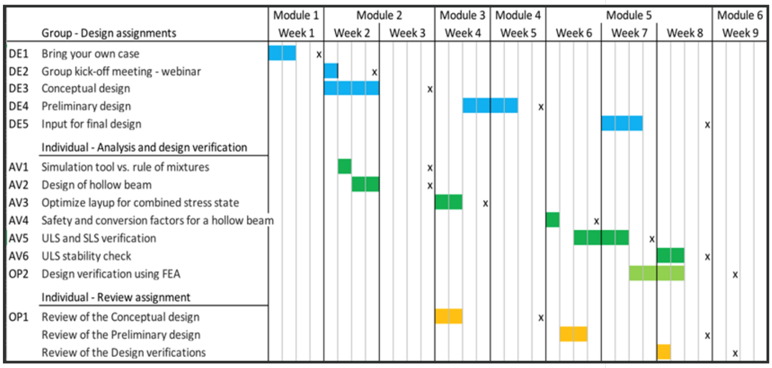
Module 6 – Discussion of the designs and Wrap-up.

Throughout the course participants learn through hands-on exercises divided to 6 individual and 4 group assignments. The goal of the group assignment is to redesign a structure previously designed and/or built by a traditional construction material to a composite structure. The assignment is based on selecting a case of a previous projects that participants provide as input at beginning of the course. Each team consists of 3-4 partipants with different expertise needed to accomplish the design assignment of a real structure as the team. In this way, participants explore the possibilities of using composites for projects in roles that are relevant for them. The assignment is continued in 3 major phases of conceptual, preliminary and final design, each lasting 2-3 weeks. In the group design assignments participants go to a limited extent with complexity of calculations specific for composites, allowing them to focus on a bigger picture of design with composites.



In the individual assignments, however, participants will go deep in aspects of calculations and design verifications of a composite beam as a simplified case study. In the assignment, participants practice aspects of: using CLT to determine and laminate properties and optimize them for a specific loading condition; determine conversion and partial factor for design; verify bending, shear, local and lateral torsional buckling resistance, check deflections and creep of a composite beam and use FEA with Abaqus and Sofistik software packages to calculate stresses, deflections and local and global buckling.

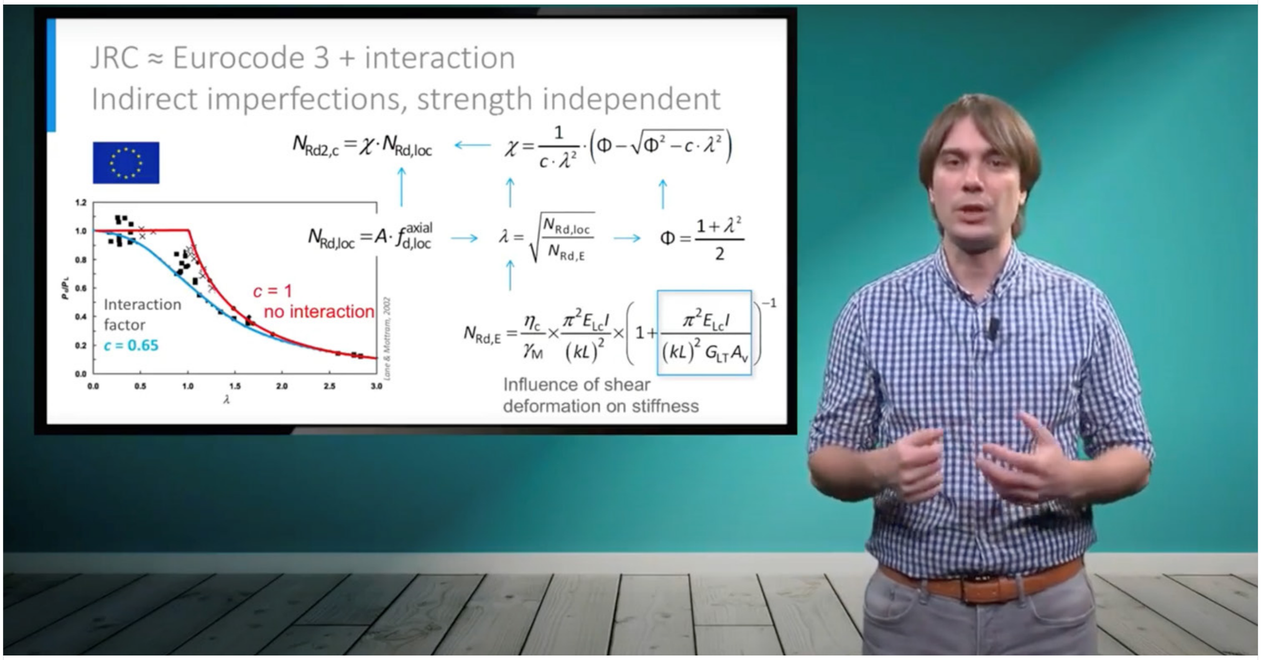
Participants have opportunity to see beyond their own designs through peer review process. Each year about 5 new design assignments are delivered, discussed, reviewed by lecturers and presented by participants. The scope of design often result in bridge designs but also industrial towers, submerged special structures, balconies, building extensions, etc.



TYPE OF CLASSES

Even though the course is delivered completely online, it is not a self-paced online course.

The pace of course is pre-set through sequential weekly opening per topics with associated pre-recorded lectures, reading materials, assignments and quizzes. The pre-recorded lectures are short, 5-10 min each, but dense. They follow the learning objectives that participants are gaining through the group and individual assignments. During the 9 weeks of the course 2 to 3 webinars are organized to discuss questions of participants, present group assignments and introduce new specialized topics and recent updates in the field.



EVALUATION / ASSESSMENT

Participants work in groups on assignments and receive extensive feedback by the lecturing team consisted of total 3 to 4 academics and industry experts. Therefore, the course is limited to approximately 30 participants per run.

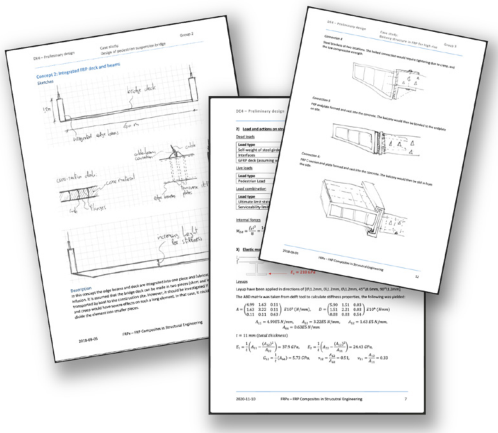
New issue of the course starts every year in October. Assessment is based of personalized feedback on group assignments and corrections of individual assignments. Theoretical background is checked through 10 quizzes during the course. Participants need to have 70% of successfully assessed assignments and quizzes to receive the certificate.

CLOSING REMARKS

So far, the widespread use of composites in buildings and infrastructure projects was held back by lack of knowledge, experience of engineers and lack of clear design guidelines. With new TS19101 published in November 2022 by CEN/TC250 the design guidance has improved significantly. Wide-spread education of engineers is still to be done to allow application of composites in infrastructure and building projects and utilize its benefits for the society.

There are more widely available courses about the use of composite materials in the field of aerospace and automotive engineering. However, aspects and requirements such as scale, laminate composition, nature of loading, environment, life-span and reliability concepts, production techniques and tolerances, quality control, inspection and maintenance are quite different in construction projects compared with aerospace and automotive applications.

This professional education course is unique opportunity for working professionals to obtain set of skills needed to start working with composites in structural engineering. The course had 6 runs so far, with nearly 120 participants from all over the world. The background of participants ranges from bridge engineers, building engineers, municipality and infrastructure ministry engineers, pipeline and profiles producers, general construction consultants, and even several PhD students that had no previous education on composites wanting to quickly jump into the topic.



PUBLICATIONS

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https://doi.org/10.1061/JCCOF2.CCENG-4053

Quasi-Static Cyclic Behavior of CFRP-Confined Geopolymeric Composites
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https://doi.org/10.1061/JCCOF2.CCENG-4138

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https://doi.org/10.1061/JCCOF2.CCENG-4300

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https://doi.org/10.1061/JCCOF2.CCENG-4164

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https://doi.org/10.1061/JCCOF2.CCENG-4247

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Sandra Milev and Jovan Tatar
https://doi.org/10.1061/JCCOF2.CCENG-4239

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Announcements of upcoming conferences, innovative research or products and abstracts from newly-published PhD theses are particularly encouraged. All announcements are duplicated on the IIFC website (**www.iifc.org**) and all issues of the FRP International are also available in the archive at this site. FRP International is yours, the IIFC membership's forum. The newsletter will only be as useful and interesting as you help to make.

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