



Contributions on the Role of Fibre-reinforced Polymers Composites in Structural Rehabilitation, New Innovative Structural Systems, Standardization and Specialized Training

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Abstract. Ensuring structural integrity in aircraft is vital for safe operation. This study explores the application of Structural Health Monitoring (SHM) systems in aviation, focusing on advanced sensor technologies and data processing techniques. We instrumented a representative aircraft component with strain gauges, accelerometers, and acoustic emission sensors to monitor critical structural loads and damage initiation. The key finding is the validation of SHM's capability to enhance safety, reduce maintenance costs, and extend aircraft service life by providing real-time data on structural health. This work emphasizes SHM as essential for modern aircraft maintenance and safety management. This study offers a comprehensive overview of SHM applications in aviation, aiming to elucidate its role, examine various sensor technologies, explore data processing techniques, and showcase practical implementations. We investigate how SHM enhances safety, reduces maintenance costs, and extends aircraft service life. Our research employed a holistic approach encompassing data acquisition, analysis methodologies, and algorithm development. The sensors were strategically positioned to capture data on critical structural loads, vibrations, and damage initiation and progression.

Keywords: Structural Health Monitoring, Aerospace, Reliability, Composite, Sensors.

1 INTRODUCTION

Composite materials, often referred to as fibre-reinforced polymers (FRP) composites, have been widely and successfully applied across multiple industries, including aerospace, construction, infrastructure, automotive, wind energy, defence, maritime, and sports and recreation. Their broad adoption is primarily due to their unique set of properties, such as: excellent mechanical performance; exceptional durability, including resistance to corrosion; lightweight nature; ease of handling and application; and nearly limitless design flexibility in terms of shape.

Composite materials consist of two or more distinct phases: (i) fibres (such as carbon, glass, aramid, or basalt) that exhibit high strength and brittle behaviour, playing a primary role in the composite's mechanical performance (i.e., stiffness and strength), and (ii) a polymeric matrix (such as polyester, vinyl ester, or epoxy) that, although of lower strength, ensures the transfer of stress between fibres and offers protection to the fibres [1].

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M. A. Muflikhun et al. (eds.), *Proceedings of the 10th International Conference on Science and Technology (ICST 2024)*, Advances in Engineering Research 268,

https://doi.org/10.2991/978-94-6463-772-4_13

Although composites began to be developed and applied in industries like naval and aerospace engineering during the 1940s and 1950s, their adoption in the construction sector only gained momentum in the 1980s. This delay in the construction industry's interest was driven by three key factors: (i) significant cost reductions in composite materials, (ii) a growing need for repair and strengthening of existing structures, particularly reinforced concrete structures, and (iii) the rising demand for high-performance, lightweight, and durable materials in new construction, especially under harsh environmental conditions [2].

The use of composites in Civil Engineering can be grouped into four main categories [3]: (i) bridges, (ii) primary and secondary structural components, (iii) internal reinforcement, and (iv) structural strengthening. In these applications, composites are utilized in various forms such as strips, sheets, rebars, tendons, laminates, profiles, sandwiches, and decks [2,3].

This paper summarizes some of the author's contributions to the use of composite materials, primarily in the construction sector. It briefly outlines research efforts in the following areas: (i) strengthening existing reinforced concrete (RC) structures using composites, (ii) developing new structural systems based on composites, (iii) exploring the potential of hybrid fibre-reinforced polymer (FRP) composites, (iv) contributing to the standardization of fibre-polymer composite design, and (v) advancing specialized training in the field. In the next sections, examples of the projects supporting this research are given together the main goals obtained. The research here highlighted was developed with the support of many other researchers and colleagues, who are properly acknowledged at the end of the paper.

2 STRENGTHENING EXISTING RC STRUCTURES USING COMPOSITES: THE R&D PROJECT FRPLONGDUR

The FRPLongDur R&P Project (references: POCI-01-0145-FEDER-016900 and PTDC/ECM-EST/1282/ 2014) aims to advance knowledge on the long-term structural behaviour and durability performance of reinforced concrete (RC) elements strengthened in flexure with CFRP laminates. The project investigates two key techniques: externally bonded reinforcement (EBR) and near-surface mounted (NSM), evaluating their performance under various real environmental conditions. Additionally, the project compares these results with those obtained from artificial accelerated aging protocols. The University of Minho, the National Laboratory for Civil Engineering (LNEC), and Empa - Swiss Federal Laboratories for Materials Science and Technology are the main partners in this research.

The project employs experimental, numerical, and analytical approaches across several dimensions: (i) different scales (material level, meso-scale, and full-scale - see Fig. 1a), (ii) various strengthening techniques (EBR and NSM passive techniques, as well as EBR active techniques), and (iii) a range of environmental conditions, including artificial (accelerated aging) and field (natural aging) scenarios.

To support the experimental component, six testing stations have been established where specimens are exposed for up to 10 years. Fig. 1b highlights five different locations across Portugal (mild Mediterranean climate), each with distinct profiles in terms of temperature and relative humidity. These stations are labelled as follows.

- **E1** – Indoor (reference) environment at 20 °C/55 % RH,
- **E2** – Indoor (reference) with tap water immersion at 20 °C,
- **E3** – Lisbon (Csa climate type, based on the Köppen-Geiger climate classification by [4]), representing a dense urban area in a coastal city,
- **E4** – Serra da Estrela (Csb climate type [4]), a mountainous region at 1600 m altitude, characterized by high thermal amplitudes and freezing winter temperatures,
- **E5** – Elvas (Csa climate type [4]), known for high daily and annual thermal amplitudes, with some of the highest maximum temperatures in Portugal, and,
- **E6** – Viana do Castelo (Csb climate type [4]), a coastal environment.

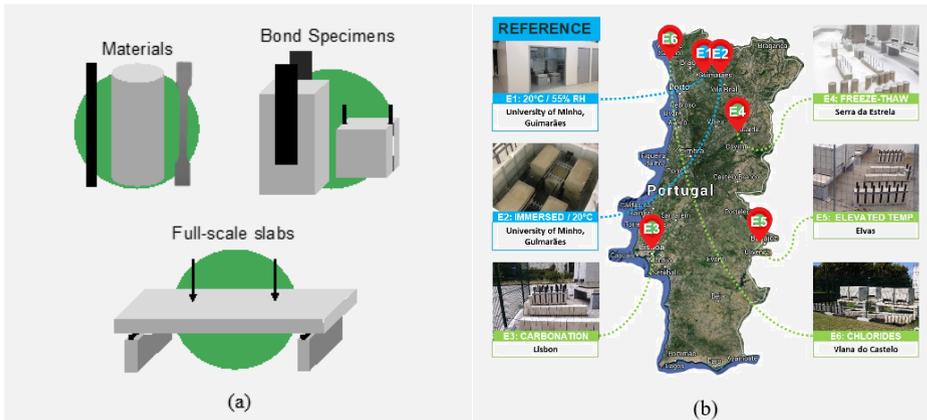


Fig 1. FRP Long Dur Project: (a) type of specimens/scales; (b) Experimental stations used

After 1, 2, 3, 4, 6, 8, and 10 years of aging, material samples and bond specimens are collected for laboratory testing, while periodic monitoring is performed on the RC slabs. After 4 years of exposure to different environmental conditions, the materials and bond specimens showed relatively low to moderate mechanical degradation. In contrast, the structural behaviour of the RC slabs was predominantly influenced by the creep phenomenon.

A detailed description of the project and its outcomes (so far) can be found in the following publications:

- [5] Dushimimana, A.; Sena-Cruz, J.; Correia, L.; Pereira, J.M.; Cabral-Fonseca, S.; Cruz, R. (2024) “Behavior of CFRP composites and epoxy adhesives after long-term exposure to outdoor and laboratory-controlled environments.” *Journal of Construction and Building Materials*, 438: 137201, 20 pp. DOI: 10.1016/j.conbuildmat.2024.137201
- [6] Dushimimana, A.; Sena-Cruz, J.; Correia, L.; Pereira, J.M.; Cabral-Fonseca, S.; Cruz, R. (2024) “Effects of long-term exposure of NSM CFRP-to-concrete bond to natural and accelerated aging environments.” *Composite Structures*, 340: 118174, 19 pp. DOI: 10.1016/j.compstruct.2024.118174

- [7] Dushimimana, A.; Sena-Cruz, J.; Correia, L.; Pereira, J.M.; Cabral-Fonseca, S.; Cruz, R. (2024) “Durability of bond between EBR-CFRP laminate and concrete after four years of natural outdoor and accelerated ageing exposures.” *Journal of Construction and Building Materials*, 427: 136213, 18 pp. DOI: 10.1016/j.conbuildmat.2024.136213

3 DEVELOPING NEW STRUCTURAL SYSTEMS BASED ON COMPOSITES: THE R&D PROJECT EASYFLOOR

The Easyfloor research project (reference POCI-01-0247-FEDER-003480) focused on developing composite sandwich panels for building floor rehabilitation. The project was a collaboration between the company ALTO – Perfis Pultrudidos, Lda., and the Universities of Minho and Lisbon. At the University of Minho, a hybrid sandwich panel was developed, consisting of a top face layer made from steel fibre-reinforced self-compacting concrete (FRC), a core of closed-cell polyurethane (PUR) foam, and a bottom face sheet and lateral webs made of glass fibre-reinforced polymer (GFRP). The project involved several key stages, including (i) design and optimization, (ii) short- and long-term mechanical characterization, (iii) fire behaviour and response and (iv) acoustics performance.

In the development of the hybrid GFRP-FRC sandwich panel, genetic algorithms were employed to create a viable solution that prioritized (i) a lower carbon footprint, (ii) reduced manufacturing costs, and (iii) lightweight properties. These algorithms were designed to find the optimal solution while considering the following boundary conditions: (i) the panel's width had to be less than 500 mm (as required by the manufacturer), (ii) the panel's length was set at 5 m to meet the current demands of the rehabilitation market, (iii) compliance with structural standards, including the verification of ultimate and serviceability limit states, and (iv) an evaluation of the panel's acoustic and thermal performance. Additionally, the panel design incorporated a snap-fit connection system between panels.

The final design is shown in Fig. 2a. However, due to technical issues faced by the ALTO company, a simplified version was adopted that excludes the snap-fit connection – see Fig. 2b. The final solution measures 300 mm in width, 160 mm in height, and includes a 20 mm thick top layer of FRC. The top and bottom face sheets, as well as the lateral webs, consist of a 6 mm thick GFRP profile. The core is made of polyurethane (PUR) foam (130 mm by 290 mm) with a density of 60 kg/m³.

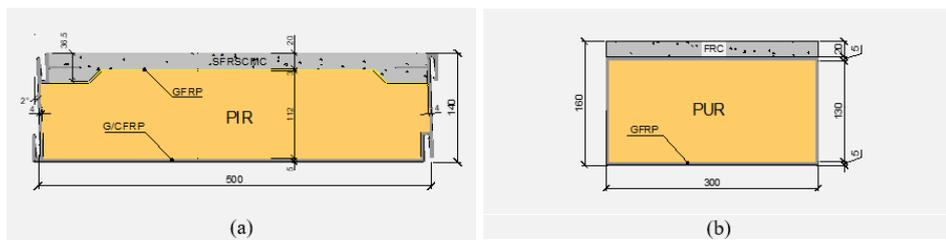


Fig. 2. EasyFloor sandwich panel: (a) design optimized solution; (b) adopted solution due to technical issues. Note: all units in [mm].

The final solution was then submitted to a set of tests, namely (i) short- and long-term mechanical experimental tests with single panels (see Fig. 3a and Fig. 3b), (ii) short-term tests to characterize panel-to-panel and panel-to-wall connections, (iii) fire behaviour (see Fig. 3c) and response and (iv) acoustics performance (see Fig. 3d). The results, supported in numerical and/or analytical simulations, have shown that the proposed panel fulfils the different regulations (structural and functional).

Detailed description of the project and its outcomes can be found in the following publications:

- [8] Proença, M.; Santos, P.; Godinho, L.; Neves e Sousa, A.; Correia, J.R.; Garrido, M.; Sena-Cruz, J. (2024) “Acoustic behaviour of GFRP-PUR web-core composite sandwich panels.” *Construction and Building Materials*, 438: 137195, 15 pp. DOI: 10.1016/j.conbuildmat.2024.137195
- [9] Proença, M.; Garrido, M.; Correia, J.R.; Sena-Cruz, J. (2024) “Experimental study on the fire resistance of all-composite and hybrid web-core sandwich panels for building floors.” *Journal of Composite Structures*, 337: 118071, 12 pp. DOI: 10.1016/j.compstruct.2024.118071
- [10] Silva, T.; Correia, L.; Dehshirizadeh, M.; Sena-Cruz, J. (2022) “Flexural creep response of hybrid GFRP–FRC sandwich panels.” *Materials*, 15: 2536, 25 pp. DOI: 10.3390/ma15072536

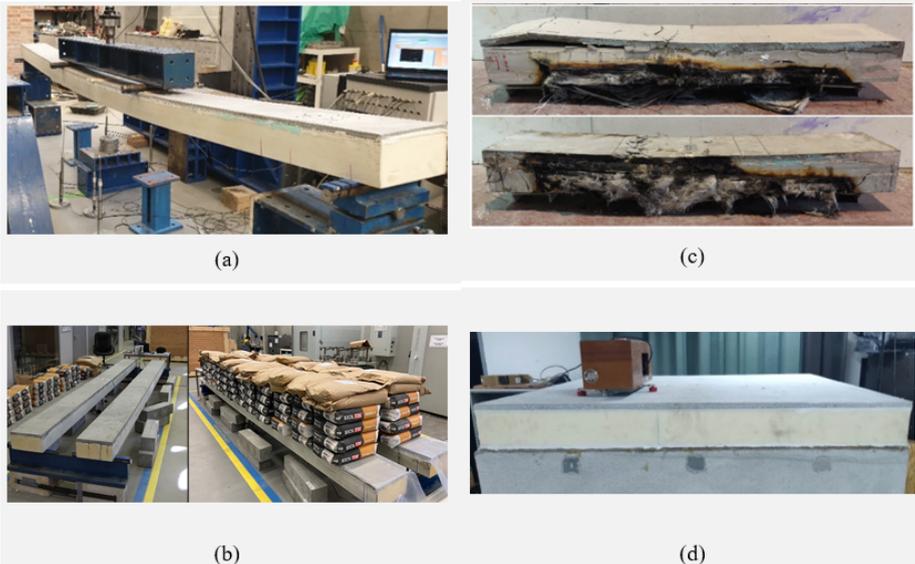


Fig. 3. Characterization of sandwich panel: (a) short-term and (b) long-term creep mechanical characterization of a single panel; (c) final aspect of the panel after fire resistance tests; (d) impact sound pressure test.

4 ENHANCING STRUCTURAL PERFORMANCE WITH HYBRID FRP COMPOSITES: RECENT RESEARCH AND DEVELOPMENTS

Hybridisation in composite materials, particularly in fibre-reinforced polymer composites, involves combining two or more types of fibres within a single polymer matrix. This approach exploits the unique properties of each fibre, producing materials with superior characteristics compared to traditional single-fibre composites. Initially driven by the aerospace and automotive industries, hybridisation has since expanded into civil engineering due to its multiple benefits.

By combining low elongation (LE) fibres with high elongation (HE) fibres, hybridisation offers several advantages: (i) improved mechanical properties such as increased tensile strength, modulus of elasticity, and fracture toughness, depending on fibre combinations and their architecture; (ii) prevention of catastrophic failure, as HE fibres can control crack propagation, resulting in more gradual and predictable failure behaviour; (iii) pseudo-ductile behaviour, with stress-strain curves displaying a plateau after the yield limit, mimicking ductile materials; and (iv) multifunctionality, allowing the incorporation of fibres with specific properties, such as piezoresistivity, for monitoring deformation and fracture [15].

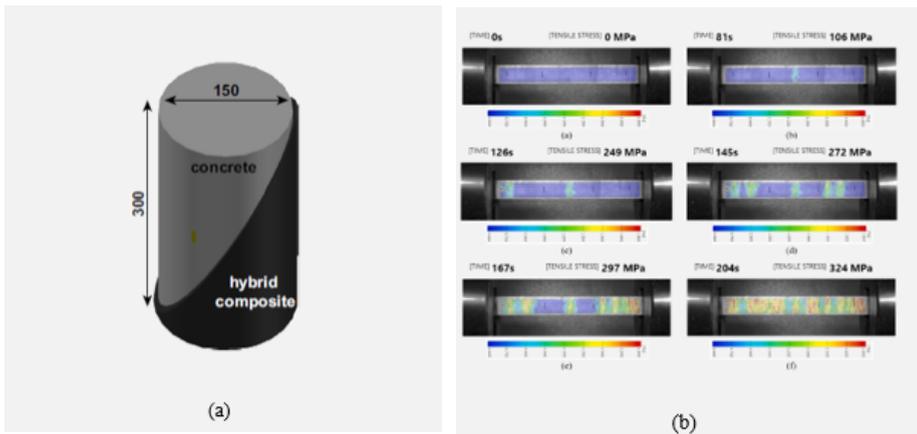


Fig. 4. Hybrid composites: (a) geometry of specimen used to study hybrid FRP jacketing failure; and (b) damage progress observed on hybrid specimens with non-catastrophic failure.

It has been demonstrated that hybridising high-modulus carbon with E-glass and basalt results in significant hybrid effects, increasing strain at failure and enabling pseudo-ductile behaviour, which prevents catastrophic failure [16]. In FRP jacketing for concrete columns, hybridisation enhanced confinement efficiency and improved compressive performance. Design and analysis models accurately predicted the behaviour of hybrid FRP-confined concrete, improving lateral strain efficiency and preventing sudden failure (see Fig. 4a) [17]. Additionally, the authors showed that hybrid FRP composites (glass/carbon and carbon/carbon) exhibit stable pseudo-ductile

behaviour (see Fig. 4b), with controlled delamination and analytically predicted fracture toughness (GII_c) [18].

Detailed information about the work developed in hybrid composite materials can be found in the following publications:

- [15] Ribeiro F, Correia L, Sena-Cruz J. Hybridization in FRP Composites for Construction: State-of-the-Art Review and Trends. *Journal of Composites for Construction* 2024;28. DOI: 10.1061/jccof2.cceeng-4486.
- [16] Ribeiro F, Sena-Cruz J, Branco FG, Júlio E. Hybrid effect and pseudo-ductile behaviour of unidirectional interlayer hybrid FRP composites for civil engineering applications. *Constr Build Mater* 2018;171:871–90. DOI: 10.1016/j.conbuildmat.2018.03.144.
- [17] Ribeiro F, Sena-Cruz J, Branco FG, Júlio E. Hybrid FRP jacketing for enhanced confinement of circular concrete columns in compression. *Constr Build Mater* 2018;184:681–704. DOI: 10.1016/j.conbuildmat.2018.06.229.
- [18] Ribeiro F, Correia L, Sena-Cruz J. Mode II interlaminar fracture toughness of unidirectional interlayer hybrid FRP composites. CICE 2023 - 11th International Conference on FRP Composites in Civil Engineering, International Institute for FRP in Construction (IIFC); 2023. DOI: 10.1016/j.conbuildmat.2024.138418

5 CONTRIBUTIONS TO THE STANDARDIZATION: THE EUROPEAN TECHNICAL SPECIFICATION CEN/TS 19101:2022

In November 2022, the European Committee for Standardization (CEN) published the Technical Specification CEN/TS 19101:2022, “Design of Fibre-Polymer Composite Structures”. This design specification is a milestone towards the widespread application of composite materials in civil engineering structures.

In 2010, the European Committee for Standardization (CEN) initiated the development of a Eurocode for fibre-polymer composite structures. To achieve this, the Technical Committee 250 (TC250) of CEN established the Working Group “Fibre Reinforced Polymer” (WG4). Between 2010 and 2016, WG4 members developed the Science and Policy Report titled “Prospect for New Guidance in the Design of FRP”, marking the first of three steps toward the creation of the future Eurocode.

In July 2018, CEN/TC250 appointed a Project Team (WG4.T2), linked to WG4, with the goal of developing a Technical Specification (TS) as the second step, building on the previously mentioned report. Project Team WG4.T2 consisted of the following members: João Ramôa Correia (leader), Thomas Keller, Jan Knippers, Toby Mottram, Carlo Paulotto, José Sena-Cruz (from 09/2020), and Till Vallée (until 11/2019). Between July 2018 and October 2021, WG4.T2 developed the Technical Specification CEN/TS 19101:2022, Design of Fibre-Polymer Composite Structures, which was published in November 2022. After a trial period (typically two years), the TS is expected to be converted into a full Eurocode.

CEN/TS 19101:2022 (Fig. 5a) applies to buildings, bridges and other civil engineering structures, either permanent or temporary, providing a general basis for the design of all-composite structures or hybrid structures, combining composite members with members made of other materials. The TS covers three main types of composite

components and members (See Fig. 5b): (i) laminates (used, for instance, as plates or shells); (ii) profiles, and (iii) sandwich panels. These composite components can be made of different types of reinforcing fibres (glass, carbon, basalt, aramid) and thermoset polymeric matrices. Polymeric foams and balsa wood can be used as core materials of sandwich panels. With respect to connections, CEN/TS 19101:2022 applies to bolted, bonded (with thermoset adhesives) and hybrid connections.

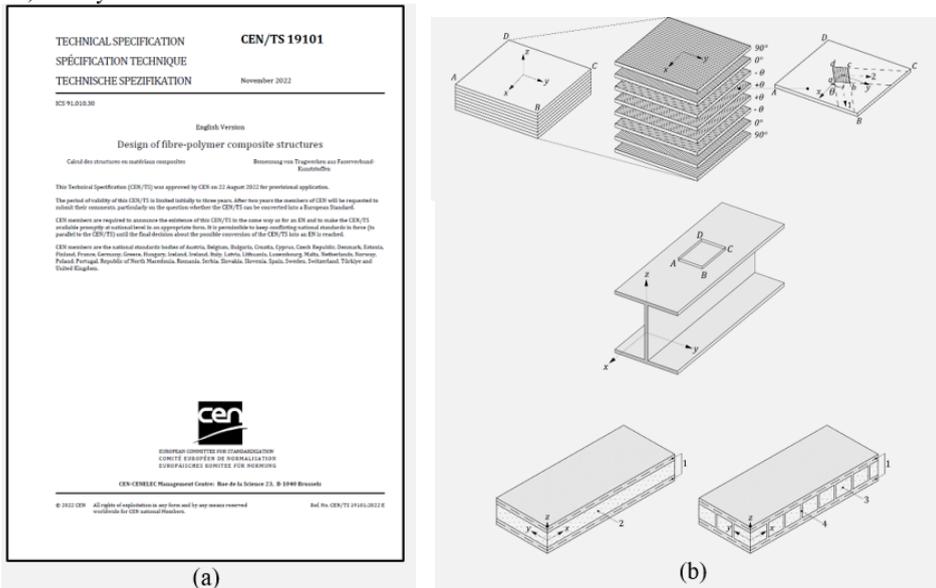


Fig. 5. European technical specification CEN/TS 19101:2022: (a) cover; (b) applications – laminates, profile and sandwich panels (from top to bottom).

Detailed information about the European technical specification CEN/TS 19101:2022 can be found in the following publications:

- [11] Ascione, L.; Correia, J.R.; Keller, T.; Knippers, J.; Mottram, J.T.; Paulotto, C.; Sena-Cruz, J. (2023) “Design of fibre-polymer composite structures (CEN/TS 19101): Overview, commentary and worked examples”, 11th International Conference on Fiber-Reinforced Polymer (FRP) Composites in Civil Engineering (CICE 2023), 24 a 26 de julho, Rio de Janeiro, Brasil, 12 pp. DOI: 10.5281/zenodo.8066346
- [12] Sena-Cruz, J.; Sá, M.; Correia, J.R.; Mottram, J.T.; Keller, T.; Gil Pérez, M.; Ascione, L.; Tromp, L.; Russo, S. (2023) “Design of fibre-polymer composite structures (CEN/TS 19101): Serviceability limit states and creep rupture”, 11th International Conference on Fiber-Reinforced Polymer (FRP) Composites in Civil Engineering (CICE 2023), 24 a 26 de julho, Rio de Janeiro, Brasil, 9 pp. DOI: 10.5281/zenodo.8066441

- [13] Correia, J.R.; Pacheco, J.; Sørensen, J.D.; Garrido, M.; Firmo, J.P.; Keller, T.; Sena-Cruz, J.; Mottram, J.T.; Ascione, L.; Tromp, L. (2023) “Design of fibre-polymer composite structures (CEN/TS 19101): Basis of design and effects of temperature and moisture”, 11th International Conference on Fiber-Reinforced Polymer (FRP) Composites in Civil Engineering (CICE 2023), 24 a 26 de julho, Rio de Janeiro, Brasil, 9 pp. DOI: 10.5281/zenodo.8066317

6 ADVANCED SPECIALIZED TRAINING: THE EUROPEAN MASTER FRP++

The FRP++ (see Fig. 6) is a European Master Course in Advanced Structural Analysis and Design using Composite Materials, offering an advanced integrated educational programme covering the key issues of the Composites industry with a particular focus on (i) materials and manufacturing processes, (ii) mechanics and modelling, (iii) analysis and design, (iv) inspection, diagnosis, repair and strengthening, and (v) sustainability and life cycle analysis [14].



Fig. 6. Website of the FRP++ (<https://msc-frp.org/>) [14]

The Master combines the diverse expertise of leading European Higher Education Institutions (University of Minho, Portugal; University of Girona, Spain; University of Naples Federico II, Italy; and University Paul Sabatier III and INSA Toulouse, France) in the related fields to offer an excellent education proposal oriented to a multidisciplinary understanding of structural Composites through the involvement of specialists from complementary fields (engineers, materials science and others). This partnership allows students to explore a broader range of composite material applications and benefit from the knowledge of industry specialists. Moreover, FRP++ has established a substantial network of associated partners on a global scale, involving over 50 entities, including higher education institutions, industry, research and development institutes, and professional associations. The Associated Partners have a relevant role in Master's activities, namely by (i) providing lectures and seminars, (ii) co-supervise of MSc dissertations and allowing internships of students during the dissertation period, (iii) influencing the course material and syllabus bringing also excellence and innovation and pragmatic and realist thoughts, as well as (iv) assisting graduates' employability prospects.

The FRP++ has a duration of one academic year (60 ECTS), leading to the awarding of a double master's degree. It is held on a rotating basis among partners. Students carry out the entire coursework in one location and the dissertation in another location. The language of instruction and examinations is English.

Through this educational program, students acquire advanced knowledge of structural composites within a research-focused environment. The program emphasizes collaboration with industry and addresses practical challenges in sectors such as construction, aerospace, automotive, and wind energy, where composite materials are increasingly critical. The FRP++ program integrates recent research advances with professional practice, ensuring students are prepared to address both theoretical and applied aspects of composite material design and application.

As an Erasmus Mundus Joint Master Degree (EMJM) supported by the European Union, the FRP++ program offers several types of student scholarships each year, including: (i) Erasmus Mundus Scholarships, (ii) Consortium scholarships, and (iii) Scholarships funded by Associated Partners.

For more comprehensive information about the program and available scholarships, please refer to the official FRP++ website [14].

7 CONCLUSIONS

This paper shows the significant impact of fibre-reinforced polymers (FRP) composites on the structural performance and durability of civil engineering projects. The use of FRP materials, particularly for the rehabilitation of reinforced concrete (RC) structures, has yielded encouraging outcomes with respect to strength, corrosion resistance, and long-term performance under diverse environmental conditions. The development of new structural systems based on composite materials, such as hybrid FRP solutions, offers improved mechanical properties and enhanced failure prevention, making them highly suitable for construction applications.

The research presented highlights the necessity of standardising the design of composite structures through initiatives such as the CEN/TS 19101:2022 technical specification. This is vital for the extensive adoption of composite materials in civil engineering.

Furthermore, specialised training programmes, such as the European Master in FRP++, ensure that the next generation of engineers is equipped with the knowledge to apply these innovations in practical settings, thereby promoting sustainable and high-performance infrastructure.

Credit Authorship Contribution Statement. José Sena Cruz: Resources, Project administration, Investigation, Methodology, Conceptualization, Supervision, Formal analysis, Writing – review & editing. Luís Correia: Support to Project administration, Investigation, Methodology, Conceptualization, Supervision, Formal analysis, Writing – review & editing; minor participation in CEN/TS 19101:2022.

Acknowledgments. This work was partly financed by FCT / MCTES through national funds (PIDDAC) under the R&D Unit Institute for Sustainability and Innovation in Structural Engineering (ISISE), under reference UIDB/04029/2020 (doi.org/10.54499/UIDB/04029/2020), and under the Associate Laboratory Advanced Production and Intelligent Systems ARISE under reference LA/P/0112/2020. Furthermore, the projects FRPLongDur (references POCI-01-0145-FEDER-016900, FCT PTDC/ECM-EST/1282/2014), EasyFloor (reference POCI-01-0247-FEDER-003480) are funded by national funds through the Foundation for Science and Technology (FCT) and co-financed by the European Fund of the Regional Development (FEDER) through the Operational Program for Competitiveness and Internationalization. (POCI) and the Lisbon Regional Operational Program. The project FRP++ (Project no. 101048961) is partially supported by European Union - European Education and Culture Executive Agency. Finally, the authors would like to also acknowledge to the investigators not explicitly referred along the paper, namely (alphabetical order): Filipe Ribeiro, João Pereira, Joaquim Barros, Mário Coelho, Mozhdah Dehshirizadeh, Patricia Silva, Pedro Fernandes, Ricardo Cruz, Susana Cabral-Fonseca, Tiago Silva, Zahir Namourah.

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