# FRPRCS17

## 17TH INTERNATIONAL SYMPOSIUM ON FIBER-REINFORCED POLYMER (FRP) REINFORCEMENT FOR CONCRETE STRUCTURES

6-8 JULY 2026
GIRONA, SPAIN

# BOOK OF ABSTRACTS

International Institute for FRP in Construction

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# Preface

It is with great pleasure that we present the Book of Abstracts for the 17th International Symposium on Fiber Reinforced Polymer Reinforcement for Concrete Structures - FRPRCS17 - the longest running conference series on the application of FRP in civil construction.

The global construction industry is at a critical turning point. The dual challenges of aging infrastructure and the pressing need for sustainable, climate-resilient development require innovative materials and forward-thinking engineering solutions. For decades, FRP composites have been at the forefront of this evolution, transitioning from novel materials into mainstream solutions for the internal reinforcement of concrete structures and the external strengthening and repair of critical infrastructure.

FRPRCS17 brings together a vibrant, international community of researchers, practitioners, manufacturers, and policymakers. The work presented within this book of abstracts highlights the latest advancements in:

- **Advanced Materials and Durability:** discussing the latest development in the manufacturing, characterisation and use of organic- and inorganic-matrix composites, thermoplastic composite and hybrid solutions; and investigating long-term performance under extreme environmental conditions.
- **Design Codes & Specifications:** bridging the gap between cutting-edge research and the implementation of robust, standardized predictive models; and exploring the integration of artificial intelligence and structural reliability assessment methods.
- **Innovative Applications:** showcasing the latest advancements in the design and implementation of smart FRP and TRM composites for self-monitoring applications.
- **Sustainability & Life-Cycle Assessment:** quantifying the low-carbon benefits of FRP/FRCM solutions in a circular economy.

A key highlight of this year's program is the inclusion of dedicated special sessions. The abstracts compiled in this volume represent the extensive contributions of authors from over 42 countries, each having undergone a rigorous peer-review process by our international scientific committee. Our sincere thanks go to the special session proposers, whose initiative brought a series of highly impactful and diverse contributions to this year's program. We also extend our deepest gratitude to all authors and reviewers for their invaluable time and dedication to maintaining the technical excellence of FRPRCS17. Your passion and curiosity continue to push the boundaries of FRP in civil engineering applications.

We also wish to express our sincere thanks to our sponsors, supporting partners, and keynote speakers whose generosity and expertise made this event possible. We trust that these proceedings will serve as a valuable reference, inspiring new ideas, sparking technical debates, and forging lasting collaborations that will shape the future of our field and drive it in exciting new directions.


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# Keynote lectures

# FRP COMPOSITES IN CONSTRUCTION: A THREE-DECADE JOURNEY AND FRP'S ROLE IN MAINSTREAM

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**ABSTRACT**

It was in the middle of the 1990s that I decided to shift my main research focus from metal shell structures to the structural application of fibre-reinforced polymer (FRP) composites in civil engineering. At that time, the latter was an emerging field for researchers in civil and structural engineering, and the FRPRCS conference series had been launched only a few years earlier. Three decades have now passed, and significant advances have been made in the research and application of FRP composites as a structural material in civil engineering. In this presentation, I will first provide an overview of my personal research journey over the past three decades within the broader context of the field, focusing on the key issues we have addressed. I will then examine the current status of the field with regard to the question of whether FRP is now a mainstream structural material in construction.

The initial focus of my research was on understanding the behavior of structures strengthened with FRP systems—first reinforced concrete structures and later metallic structures—with the ultimate goal of developing theoretical models that capture such behavior and design methods based on a strong mechanics foundation. With regard to the use of FRP in new structures, I have explored three topics: the combined use of FRP, steel, and concrete to create a new type of hybrid structure, concrete structures made with seawater and sea sand and reinforced with FRP rebars, and the coating of steel rebars with filament-wound FRP for corrosion resistance.

Through a review of my personal research journey in this field, I also aim to convince the audience of the following assertion: the use of FRP in structural strengthening is now a mainstream option, but the situation is different for FRP in new structures. This means that when a structure is being strengthened, external FRP reinforcement is routinely considered as one of the viable solutions. In contrast, such a mainstream status is far from being achieved in the use of FRP for new construction. I will also elaborate on my views regarding the obstacles that limit the wider application of FRP composites in new construction and highlight key issues that the research community should address in the coming decades. If these obstacles can be properly resolved, FRP composites will be accepted as a mainstream material for new structures.

**KEYWORDS**: FRP composites; Personal journey; Strengthening; New construction; Mainstream applications.

# ENHANCING FATIGUE SERVICE LIFE OF AGING CONCRETE BRIDGES USING FRP

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**ABSTRACT**

The long-term reliability of concrete bridges in modern transportation systems is compromised by structural deterioration under heavier daily traffic during bridges' designed service lives. Adanced composite materials based on fiber-reinforced polymer (FRP), either externally bonded or near-surface mounted, offer a great solution to improve the fatigue behavior of aging concrete bridges with fewer signs of debonding and lower stress ratio in prestressing strand if used, thus elongating the fatigue life of the aging concrete bridges.

To fully understand the important fatigue-specific issues of strengthened structures, a comprehensive study was undertaken from both the experimental and analytical prospectives. Included in this presentation are the major findings related to the local interfacial bond, the flexural and shear behavior of strengthened bridges such as the strain redistribution among various steel/FRP/concrete materials, deflection and crack progression throughout fatigue life, and how those affect and lead to the final failure modes of a structure. This systematic investigation also led to verified reliable predictive means for such complex behavior up to failure. A set of thus derived fatigue life coefficients accounting for important design parameters such as bond strength and reinforcement ratios were further incorporated into fatigue life design formula for a practical fatigue life-based design framework of FRP-strengthened concrete bridges.

**KEYWORDS:** Fatigue; Concrete; Fiber reinforced polymer (FRP); Service life.

# ADVANCED SOLUTIONS USING COMPOSITES FOR SEISMIC LOSS REDUCTION

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**ABSTRACT**

The post-earthquake response of buildings is of paramount importance for the seismic resilience of communities in earthquake prone areas. The frequent occurrence of strong earthquakes and their devastating effects have drawn the attention to the damage prediction and economic loss estimation. After recent earthquakes worldwide, the structural engineering profession has renewed interest in understanding and quantifying the benefits provided by strengthening solutions applied at large scale to prevent structural collapses and significantly reduce future direct and indirect losses.

The existing structures may be affected by strong signals of deterioration, and they often need to be upgraded to meet new mandatory seismic design requirements or to allow a change of use of the building. Applications of innovative materials for retrofitting and upgrading existing structures have been rapidly grown in past years because of their several advantages with respect to traditional strengthening systems. Often seismic upgrading involves buildings partially or completely occupied and short-term disruption of occupants becomes a crucial aspect and controls the design. These remarks have introduced new challenges in the development of novel advanced solutions using composites for seismic upgrade of deficient existing buildings that can be applied wholly from the exterior of the building. The experimental validation of such solutions and the relevant calibration of reliable design formulations is a crucial aspect for future seismic risk mitigation. The study outlines the basic principles of advanced solutions using composites applied on existing structures to avoid the most common brittle and premature failure modes. Details on the experimental investigations on full scale specimens or real subassemblies aimed at confirming the effectiveness of these solutions are presented and discussed with due attention to the calibration of reliable design formulations and the analysis of their impact on the potential reduction of future losses at large scale. Finally, an insight on the main still open issues and future perspective for future investigations on the use of advanced materials for seismic upgrade is presented.

**KEYWORDS:** Fatigue; Concrete; Fiber reinforced polymer (FRP); Service life.

# FRP materials and products

# NON-CONTACT MEASUREMENT TECHNIQUE FOR THE TENSILE PROPERTY EVALUATION OF LARGE-DIAMETER GFRP BARS

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**ABSTRACT**

This study presents a comprehensive tensile behavior evaluation of large diameter (36 mm - #11) glass fiber-reinforced polymer (GFRP) bars pultruded by two distinct manufacturers, referred to as Type A and Type B. Based on ASTM D7205, Traditional tensile testing methods typically rely on mechanical extensometers to measure strain within a fixed gauge length. Regardless of its effectiveness, extensometers have limitations, including localized measurement, potential slippage, and safety concerns due to sudden, explosive broom-type failures typical of GFRP bars. These limitations can lead to incomplete characterization of the bar's strain distribution and failure progression. Consequently, a modern, non-contact measurement technique, Digital Image Correlation (DIC), was employed to perform tensile testing of #11 GFRP bars. DIC provides full-field strain mapping that captures the evolution of strain over the entire exposed surface of the specimen in real-time without physical attachment to the bar. Comparative analysis between extensometer-based and DIC-based tests revealed that while both methods produced similar ultimate strain values, DIC identified early micro-damage zones that cannot be detected by relying on traditional methods. Furthermore, DIC enhanced operator safety and eliminated the need to detach sensors before failure. The findings demonstrate that integrating DIC into tensile testing leads to improved accuracy and robustness of data for large-diameter GFRP bars and can be suggested for refining current ASTM testing protocols.

**KEYWORDS**: Glass fiber reinforced polymer (GFRP); Tensile properties; Digital image correlation; Large diameter bar; Non-contact measurement technique.

# INFLUENCE OF ADHESIVE ELASTIC PROPERTIES IN CFRP-TO-CONCRETE DEBONDING STRENGTH


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## ABSTRACT

The effectiveness of Carbon Fiber Reinforced Polymer (CFRP) strengthening systems for concrete structures is often limited by premature failure at the adhesive-concrete interface, which prevents the composite from reaching its full tensile capacity.

This study investigates the influence of adhesive elastic properties on failure modes, ultimate load, and effective bond length. Four adhesives with distinct elastic properties were mechanically characterized and used to bond 1.4 mm thick CFRP laminates (50 mm and 100 mm wide) to a HA-35 concrete prism. The control adhesive is a pure epoxy resin commonly used for CFRP reinforcement commercially known as Sikadur30. The remaining products are a mixture of epoxy and polyurethane in different proportions thus getting increasingly higher elasticity. Those are commercially known as Sikadur370 and Sikadur61 from higher to lower stiffness. A new product under development with intermediate properties between these two was specifically supplied for this research.

The aim of the study is to experimentally evaluate whether the properties of the adhesive can lead to greater effective bond length and, consequently, to higher ductility and potentially higher ultimate debonding load. To this aim, all tests were performed including a Digital Image Correlation (DIC) system for accurate assessment of the debonding process. The use of adhesives with lower Modulus of Elasticity than conventional epoxy products arise as a promising alternative to existing techniques to delay debonding, such as anchorage systems, EBROG and EBRIG. The results can be particularly interesting in the case of structural members in which interfacial debonding failure in Mode I, Mode II and coupled modes are involved.



**KEYWORDS**: CFRP; Adhesives; Failure modes; Elastic properties; Ductility.

# INFLUENCE OF LONG-TERM SUSTAINED LOADING ON THE CREEP PERFORMANCE OF CFRP BRIDGE TENDONS

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**ABSTRACT**

Despite the attractive structural, sustainability and durability advantages of Carbon Fibre Reinforced Polymers (CFRPs) as alternatives to steel for bridge hangers or prestressing cables, the paucity of long-term creep studies on CFRP tendons at high sustained loading ratios currently hinders their fully optimised application in civil engineering infrastructure. Three groups of CFRP tendons (pultruded with the same carbon fibre and epoxy) were loaded at 70% of their ultimate tensile strength (UTS) in custom creep frames for up to 5000 h to assess the influence of long-term sustained loading on their creep performance. Specifically, tendons from Groups "KE" and "PR" were pultruded in 1997, whilst tendons from Group "BN" were pultruded in 2024, and are thus comparatively less aged. In addition, the KE CFRP tendons were prestressed to 45% of their UTS for 18 years, beneath the deck of a working pedestrian bridge in Switzerland, before being unloaded and stored outdoors for 7 years prior to testing for this study. PR and BN tendons were never loaded prior to this study and were continuously stored indoors in a controlled environment. The maximum 100-year predicted creep coefficient was 5.54% which demonstrates the exceptional performance of CFRP bridge tendons under sustained loading at typical service stress levels. Furthermore, no significant differences could be discerned between the three groups of tendons, thus highlighting that sustained loading does not significantly diminish the long-term structural properties of CFRP tendons.

**KEYWORDS**: CFRP; Creep; Sustained loading; Ageing; Durability.

# EXPERIMENTAL STUDY ON THE BOND BEHAVIOR BETWEEN CONCRETE AND BASALT FRP APPLIED BY EBROG TECHNIQUE

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## ABSTRACT

Progress toward sustainable construction requires extending the service life of structures using materials with lower environmental impact. Basalt fibers stand out for their low carbon footprint, good mechanical properties, and durability. However, a key limitation of FRP (fiber-reinforced polymers) for concrete strengthening with externally bonded reinforcement (EBR) systems is premature debonding. To address this, recent research has explored the externally bonded reinforcement on grooves (EBROG) method, which shows promise but has thus far been applied primarily to carbon fiber composites. EBROG also requires more viscous resins, and product variations may influence the FRP–concrete bond.

This study evaluates the bond performance of basalt FRP to concrete through single-shear tests, focusing on applications for shear strengthening of RC beams with short bond lengths. Eleven specimens with a single basalt FRP sheet were tested, considering three parameters: FRP bond length, bonding systems (EBR, EBROG), and two resin types (fluid, thixotropic). The analysis includes load–slip behavior, failure modes, and strain distribution, based on measurements from strain gauges and Digital Image Correlation (DIC).

Results reveal that resin type was the decisive factor in bond capacity in single-shear tests. EBROG did not provide significant improvements compared to EBR when using the thixotropic resin (best-performing in these tests). The anchorage length derived from tests was short (≈50 mm), consistent with the elastic modulus of basalt FRP and a small thickness (only one layer). Further tests with short bond lengths and multiple layers are planned, where EBROG technique is expected to have a greater impact.

**KEYWORDS**: BFRP; EBROG; Shear test; Bond behavior; Structural strengthening.

# MACHINE LEARNING PREDICTION OF REGOLITH-RESIN-FIBRE-COMPOSITE (RRFC) MECHANICAL BEHAVIOUR

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## ABSTRACT

Establishing sustainable lunar infrastructure requires materials that can withstand extreme conditions. Regolith-resin-fibre composites (RRFC) show promise by utilising in-situ regolith with minimal Earth-supplied resin and fibres. This study applies machine learning (ML) regression models to predict RRFC mechanical properties, such as compressive, flexural, and tensile strength, based on variables such as regolith, resin, fibre content, density, and fibre type. Five ML algorithms were evaluated: multiple linear regression (MLR), least absolute shrinkage and selection operator (LASSO) regression (LR), random forest regression (RFR), gradient boosting regression (GBR), and voting regression (VR). MLR and LR represent linear models, while RFR and GBR are decision-tree-based, and VR integrates both linear and nonlinear approaches. Model performance was assessed using mean squared error (MSE), root mean square error (RMSE), mean absolute error (MAE), mean absolute percentage error (MAPE) and R-squared (R2). Results showed MLR and GBR achieved the highest accuracy, with all models maintaining prediction errors within 20% of experimental results. The findings demonstrate that ML provides an efficient, data-driven pathway for optimising RRFC design, accelerating lunar material development.

**KEYWORDS**: In-situ resources utilisation (ISRU); Regolith-resin-fibre-composite (RRFC); Lunar construction materials; Machine learning (ML); Mechanical behaviour.

# CFRP GRID PRESTRESSED HOLLOW CORE CONRETE CEILING

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**ABSTRACT**
Carbon reinforced concrete (CRC) offers significant advantages over conventional steel reinforced concrete, particularly in terms of material strength, self-weight and durability, especially in terms of resistance to corrosion. However, one of the main shortcomings of CRC lies in its deformation behavior and serviceability performance. Prestressing has proven to be an effective strategy to address these limitations. While prestressing with carbon rebars and tendons has been successfully applied for decades, these reinforcement types typically require a relatively thick concrete cover to transmit prestressing forces without local concrete splitting, which can limit their use in thin-walled and material minimized structural elements such as hollow core concrete ceiling. In contrast, carbon grid reinforcement allows for thinner covers, making it a promising alternative.

This paper focuses on the prestressing of carbon grids with direct bonds to concrete, with particular emphasis on the simultaneous prestressing of multiple layers. A series of experimental investigations are planned to evaluate the feasibility and performance of this approach. The experimental program includes bond and transmission of prestressing tests as well as full-scale flexural tests on prestressed concrete slab segments reinforced with carbon grids. The goal is to provide insights into the interaction between carbon mesh and concrete under prestress, highlighting the effectiveness of grid prestressing in improving serviceability while maintaining material efficiency.

**KEYWORDS**: Carbon reinforced concrete; Prestressed concrete; CFRP grid.

# Durability of FRP systems

# FATIGUE BEHAVIOR OF CFRP REINFORCED CONCRETE AFTER EXPOSURE TO FREEZE-THAW CYCLES

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## ABSTRACT

The increasing freight load driven by economic growth and global trade poses significant challenges to pavement construction, demanding innovative, resource-efficient, and sustainable solutions. Carbon fiber reinforced concrete composites, consisting of concrete continuously rein-forced with Carbon Fiber Reinforced Polymer (CFRP), have emerged as a promising alternative for lightweight, durable, and environmentally responsible pavement systems. However, the mechanical performance of CFRP-reinforced concrete under coupled freeze–thaw (FT) and cyclic loading remains insufficiently investigated.

This study addresses this research need by subjecting CFRP-reinforced concrete specimens to re-peated FT cycles followed by cyclic tensile loading regimes simulating traffic conditions. Freeze-thaw-induced damage and microcrack development are evaluated through mechanical testing and morphological analysis.

The results demonstrate the capacity of CFRP reinforcement to withstand deterioration and maintain its tensile performance under severe environmental and mechanical stresses. In contrast, the interface between CFRP and the concrete matrix exhibits progressive deterioration under combined FT and cyclic loading, leading to increased structural deformation. These findings clarify the governing role of interfacial damage in the fatigue response of CFRP-reinforced concrete and provide a basis for improving durability design of pavement system in cold-climate regions.

**KEYWORDS**: Carbon fiber reinforced polymer (CFRP); Freeze-thaw cycle; Cyclic loading; Fatigue; Durability.

# DURABILITY OF HIGH-STRENGTH CFRP-CONCRETE JOINTS UNDER FREEZE-THAW CYCLES IN SALINE ENVIRONMENT

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**ABSTRACT**

The long-term durability of externally bonded CFRP systems remains a critical concern in harsh environments. This study investigates the combined effects of freeze-thaw (FT) cycles and saltwater immersion (3.5% NaCl) on the bond behavior of high strength CFRP-to-concrete joints and the mechanical properties of the epoxy adhesive layer. Single-lap shear tests were conducted on specimens subjected to 0 and 300 FT cycles to evaluate the degradation in bond strength, strain distribution, and failure modes. Complementary tensile tests on epoxy adhesive samples were also performed after the same environmental conditioning. The experimental results revealed a significant degradation in both bond and adhesive properties after 300 FT cycles. Specifically, the failure mode shifted from cohesive failure within the concrete, observed in the control specimens, to interfacial failure at the adhesive-concrete interface after 300 cycles, indicating a deterioration of the interfacial bond. Furthermore, the load-bearing capacity of the joints decreased by approximately 15% after 300 FT cycles in saltwater. On the other hand, the tensile strength of the epoxy adhesive decreased significantly, underscoring its vulnerability to environmental aging. These findings highlight the importance of accounting for environmental durability in the design of CFRP-strengthened concrete structures and provide valuable insights for developing more reliable design recommendations for infrastructure exposed to severe climate conditions.

**KEYWORDS**: CFRP-concrete joint; Freeze-thaw cycles; Saltwater; Bond behavior; Environmental aging.

# HOW THE CONCRETE ALKALINE ENVIRONMENT AFFECTS TO THE STRENGTH RETENTION OF GFRP REBARS

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**ABSTRACT**

In aggressive environments, the use of Glass Fiber Reinforced Polymer (GFRP) bars as an alternative to steel in reinforced concrete structures is a strategy to avoid steel corrosion issues. The possible CE marking of the product, a symbol which many products must display to be freely marketed within the European Economic Area that indicates compliance with applicable European legislation, and its consideration in the new generation of Eurocodes are promoting its use in the European Union. This increased use, in turn, leads to a greater need to disseminate and expand knowledge of the material.

GFRP bars have other possible deterioration mechanisms different from those of steel, such as alkaline aging. Concrete is a highly alkaline environment. Free hydroxide ions can degrade matrices with high concentrations of ester groups in their formulation and chemically attack the fiberglass. Material aging due to this process is considered in the design regulations for concrete structures that contemplate reinforcement with bars made of fiberglass-reinforced polymers applying an environment factor that reduces bars' long-term tensile strength. There are also testing standards to determine the long-term loss of material performance through an accelerated aging test in an alkaline solution that simulates the alkaline environment of concrete.

Material specifications, in turn, typically only require tensile strength retention; this article aims to answer the question of whether the alkaline environment equally affects the other strength properties. The results of a study of tensile, transverse shear, and interlaminar shear strength retention after immersion in an alkaline solution following the guidelines of ISO 10406-1 for 1 month and 3,000 hours are presented. The degree of deterioration is quite heterogeneous among the different strength properties, and this heterogeneity increases with increasing aging aggressiveness. A greater correlation of results is observed between tension and interlaminar shear than between tension and transverse shear.

**KEYWORDS**: Glass fiber-reinforced polymer (GFRP); Reinforced concrete structures; Alkali resistance; Strength retention.

# DURABILITY OF EPOXY-IMPREGNATED BASALT AND GLASS FRP BARS IN CONCRETE UNDER THERMAL-MOISTURE CONDITIONING

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**ABSTRACT**

This study investigates the durability of epoxy-impregnated basalt fiber-reinforced polymer (BFRP) and glass fiber-reinforced polymer (GFRP) bars embedded in Portland cement concrete and exposed to water immersion at 20, 40, and 60 °C for 9 months. Experimental results showed that the tensile strength of BFRP decreased by 13%, 20%, and 28% relative to the original tensile strength after 9 months of conditioning at 20, 40, and 60 °C, respectively. Meanwhile, GFRP showed a loss of up to 50% under the same conditioning regimes. Fourier-transform infrared analysis confirmed hydrolysis of the FRP bars, as evidenced by increases in the OH/CH ratios, reaching up to 40% for GFRP samples. Matrix deterioration was assessed by differential scanning calorimetry, with decreases of 7% and 20% in the glass transition temperature for BFRP and GFRP bars, respectively, suggesting resin plasticization and structural relaxation. Scanning electron microscopy revealed interfacial debonding and progressive matrix cracking as the conditioning temperature increased, with the latter more pronounced in the GFRP bars. The durability and microstructure evaluations indicate that both FRP bars suffered moisture-induced degradation under these conditions, although the deterioration was more severe in the GFRP bars. These results provide insights into the long-term reliability of two types of FRP reinforcement bars in concrete structures exposed to aggressive thermal–moisture environments.

**KEYWORDS**: BFRP; GFRP; Performance; Microstructure; Hydrothermal.

# DURABILITY EVALUATION OF FRP BARS EXTRACTED FROM THE HALLS RIVER BRIDGE AFTER SEVEN YEARS OF SERVICE

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## ABSTRACT

Most durability studies on fiber-reinforced polymer (FRP) bars rely on accelerated laboratory conditioning protocols, yet little evidence exists on their actual performance in service. This paper presents the long-term evaluation of glass FRP (GFRP) bars, basalt FRP (BFRP) bars, and carbon FRP (CFRP) strands used in the construction of the Halls River Bridge in Florida (USA) after seven years in service, embedded in seawater concrete. Testing was conducted on bars extracted from the pile cap test block, forming part of the canal seawall. All three FRP systems retained a substantial fraction of their original tensile capacity after prolonged tidal exposure, with retention levels of approximately 79% for BFRP, 84% for GFRP, and 96% for CFRP. SEM observations confirmed these trends, where GFRP and CFRP retained a dense and well-bonded microstructure, and BFRP exhibited extensive resin loss and fiber–matrix debonding concentrated near the bar exterior. These results provide rare field-validated evidence of the durability of FRP reinforcement in seawater concrete. The reinforcement evaluated was manufactured prior to the implementation of performance-based alkaline durability verification procedures. Overall, resin durability, interfacial quality, and manufacturing characteristics significantly influenced long-term performance.

**KEYWORDS**: Fiber-reinforced polymer (FRP); Durability; In-service performance; Degradation.

# DURABILITY OF PRESTRESSED EBR-CFRP SYSTEMS: TEN-YEAR PERFORMANCE OF STRENGTHENED RC SLABS

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**ABSTRACT**
The externally bonded reinforcement (EBR) with fiber-reinforced polymer (FRP) materials technique is nowadays a state of the art for the strengthening of reinforced concrete (RC) structures. When the FRP laminate is prestressed, the advantages of external prestressing are combined with those of the EBR method, leading to significant improvements in stiffness, crack control, and load-carrying capacity, mainly at serviceability limit state loading conditions. Among the various FRP options, carbon FRP (CFRP) laminates are most frequently used for strengthening applications. To ensure the effective use of prestressed CFRP laminates, suitable end-anchorage systems are required to transfer the high shear forces developed at the laminate ends and to prevent premature debonding. Among the available anchorage solutions, the mechanical anchorage (MA) has proven to be particularly effective. The present study extends previous research on RC slabs strengthened with prestressed CFRP laminates and exposed to natural environmental conditions for over ten years. The experimental program involved 2.6 m-long slabs strengthened according to the EBR technique with MA systems, tested under four-point bending and compared with reference specimens previously tested shortly after strengthening. The influence of long-term environmental exposure on stiffness, cracking behavior, and ultimate capacity was assessed. Results demonstrated that the MA system retained a substantial strengthening capacity after a decade of exposure, confirming the long-term durability and structural reliability of prestressed EBR-CFRP systems for concrete structures.

**KEYWORDS**: Prestressed CFRP; Externally bonded reinforcement (EBR); Mechanical anchorage; Gradient anchorage; Durability.

# PERFORMANCE OF FRP BARS IN ULTRA-HIGH STRENGTH SEA-SAND CONCRETE IN COASTAL ENVIRONMENTS

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**ABSTRACT**
Due to the shortage of river sand, non-desalted sea-sand has emerged as a promising alternative for use in ultra-high strength concrete (UHSC), leading to the development of sustainable sea-sand UHSC (UHSSC). However, steel reinforcements cannot be directly used in sea-sand concrete due to corrosion risks. The combined use of high-strength, corrosion-resistant fiber-reinforced polymer (FRP) reinforcing bars and UHSSC is a promising and sustainable solution for coastal and marine construction. This paper presents a comprehensive investigation into the performance of FRP bars embedded in UHSSC exposed to coastal environments. Four types of FRP bars, both bare and embedded in UHSSC, were conditioned at a wharf in Zhanjiang, China, across four distinct coastal environments: atmospheric, splash, tidal, and underwater zones. A total of 148 specimens were tested to evaluate their tensile, horizontal shear, and bond properties before and after exposure. The results indicate that the failure modes did not change after up to one year exposure. More significant degradations in the tensile strength and horizontal shear strength of bare FRP bars were experienced in the tidal and underwater zones than other zones. In contrast, the FRP bars embedded in UHSSC exhibited minimal degradation in tensile, shear, and bond performance after one-year coastal exposure. This study provides new evidence for the validation of the durability performance of FRP bars as internal reinforcement in natural coastal environments.

**KEYWORDS**: Ultra-high strength sea-sand concrete; Fibre reinforced polymer (FRP) bars; Durability; Field exposure; Coastal environments.

# TOWARD HARMONIZATION OF DURABILITY EVALUATION OF GFRP BARS FOR CONCRETE REINFORCEMENT

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**ABSTRACT**

Glass Fiber Reinforced Polymer (GFRP) bars are an effective non-metallic and corrosion free rein-forcement used in concrete structures that are manufactured and used globally. Design codes, guides, material specifications and test methods have been developed to provide qualification criteria to support its use in the construction sector. As part of this qualification, durability testing in the form of accelerated conditioning in alkaline environment forms a fundamental part of this qualification criteria.

This paper presents a comparative review of the main durability provisions for GFRP bars across international codes and guidelines. To illustrate the implications of these differences, experimental results of GFRP bars exposed to alkaline solutions per ISO-10406-1 and ASTM-7705 are compared.

Discrepancies in interlaminar shear strength retention demonstrate how the difference in the test parameters directly influences durability outcomes. The study aims to underscore the critical need for harmonized durability testing for FRP bars. Establishing common accelerated conditioning protocols to correlate material performance and service conditions will provide a consistent basis for specification, enhance reliability in structural design, and ultimately support the global adoption of FRP reinforcement.

**KEYWORDS**: Fiber-reinforced polymer (FRP); Alkaline resistance; Durability testing; Accelerated aging; Standards comparison.

# Innovative composite systems & solutions

# EXPERIMENTAL INVESTIGATION ON THE SKEW TENSION BEHAVIOR OF TEXTILE REINFORCED CONCRETE

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**ABSTRACT**
Textile-reinforced concrete is widely applied in both retrofitting and new structural designs as it enables minimal concrete covers due to corrosion resistance. The textile is typically oriented orthogonally and aligned with the member geometry. Cracks, however, may intersect the orthotropic material at oblique angles, creating skew tension that is known to reduce the textile's load-bearing capacity. The extent of the reduction is not clearly established in the literature.

To facilitate a better comprehension of the exhibited behaviour, we analysed the tensile performance of thin textile-reinforced concrete members under the influence of skew tension in association with the textile deformation rather than discussing the damaging effects in dependence on the crack angle or crack kinematics. For this purpose, 12 specimens (400 × 100 × 22 mm) with varying textile reinforcement orientations and artificial crack angles (0°, 30°, and 45°) were tested in a uniaxial tensile test setup. This setup generated distinct deformations relative to fiber strand orientation.

The experimental results indicate an apparent reduction in the reinforcement's tensile load-bearing capacity. Both textile orientation and notch orientation significantly affect tensile strength, with reductions of up to 81% due to combination of tensile and shear loading of the fiber strands. Compared to other research, this article suggests focusing on the impact of longitudinal and transverse deformation of fiber strands rather than on crack-opening and sliding kinematics.

**KEYWORDS**: Uniaxial tensile test; Textile-reinforced concrete; Skew tension; Crack angle; Textile reinforcement orientation.

# TENSILE BEHAVIOUR OF BASALT AND GLASS FIBRE TEXTILES FOR USE IN TEXTILE REINFORCED CONCRETE

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**ABSTRACT**
Textile Reinforced Concrete (TRC) is a cement-based composite material enhanced with bidirectional textile fabrics, offering significant advantages in structural reinforcement, thin-walled architectural panels, and precast construction components. This study presents a comprehensive experimental analysis of the tensile behavior of basalt and glass fibres, as well as their respective textile configurations, with a particular focus on key mechanical properties such as tensile strength and Young's modulus. To measure tensile strain, a digital image capture technique was implemented, and a custom Python-based algorithm was developed to extract strain values from the captured image sequences. Furthermore, Scanning Electron Microscope (SEM) images were digitally processed to determine the precise cross-sectional areas of the yarns, contributing to a more accurate mechanical characterization. The tensile test results for both individual yarns and complete fabric assemblies showed correlation with manufacturer-provided data, validating the reliability of the experimental procedures. These findings confirm the effectiveness of basalt and glass textiles in TRC applications and demonstrate that image-based strain measurement is a precise, non-contact method suitable for advanced material testing. The experimental data generated serve as a valuable reference for selecting appropriate fibre textiles and optimizing the design of TRC elements, promoting their use in both structural and non-structural engineering solutions.

**KEYWORDS**: Textile Reinforced Concrete; Basalt fibre; Glass fibre; Tensile behaviour; Image-based strain measurement; Mechanical properties.

# EXPERIMENTAL STUDY ON BASALT TRM-TO-CONCRETE BOND UNDER INTERMEDIATE STRAIN RATE

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**ABSTRACT**

The bond behaviour between Textile Reinforced Mortar (TRM) composites and their concrete substrate is a decisive factor in the efficiency of strengthening interventions. While extensive research has addressed TRM performance under quasi-static conditions, the response under intermediate and high strain rates remains largely unexplored. In particular, no studies to date have characterised the dynamic TRM-to-concrete bond, despite its fundamental role in governing load transfer and structural performance under impact or blast scenarios.

This study presents the first experimental investigation of the bond performance of Basalt TRM (BTRM) systems applied to concrete substrates under intermediate strain rates. Quasi-static and impact bond tests were conducted using a modified beam test setup, made of two concrete prisms, a hinge, and the composite installed on the underside of the beam. The dynamic loading was induced by controlled drop-weight impacts at varying heights, ie 400, 600, 800, and 1000 mm. The impact force was recorded via a high-frequency accelerometer (100 kHz) and validated using high-speed imaging and Digital Image Correlation (25 kHz), enabling detailed assessment of strain development and failure mechanisms.

The results highlight the strong dependence of bond performance on strain rate, with improved bond performance, at strain rates between 0.7 and 7.5/s and modified failure patterns observed at higher loading rates. This work provides the first insights into BTRM bond behaviour at intermediate strain rates, addressing a critical knowledge gap and contributing towards the development of testing guidelines for TRM systems under dynamic loading.

**KEYWORDS**: BTRM; Impact testing; Intermediate strain rate; Concrete.

# EFFECTS OF STRAIN RATE ON THE BOND BETWEEN CARBON-FRCM STRIP AND CONCRETE SUBSTRATE

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**ABSTRACT**
Fiber-reinforced cementitious matrix (FRCM), comprising fiber reinforced polymer (FRP) grid embedded in inorganic matrix such as cementitious mortar, has emerged as a viable option for strengthening and repairing concrete and masonry structures. The effects of high strain rate (SR) on the bond between FRCM reinforcement and concrete substrate, which is essential for loading scenarios such as earthquakes and vehicular collisions, remains scarcely explored. In this study, the effects of SR was studied experimentally using 12 single lap shear specimens, each consisting of a concrete block bonded to a carbon-FRCM (C-FRCM) strip. The objective was to assess the effects of SR and bond length ($L_b$) on the bond characteristics of FRCM-concrete joints. Two variables were studied, namely; SR using three load rates (0.20, 20, and 2000 mm/min) representing quasistatic forces, vehicular impact, and earthquake excitations; and bond length ($L_b$) of FRCM strip, using four $L_b$ values; 75-, 150-, 225-, and 300-mm. Results indicate that increasing the strain rate increases the ultimate load ($P_u$) across various $L_b$ values. The highest increase in $P_u$ was 139.6% when the load rate increased from 0.2 to 2000 mm/min. Four failure modes were observed, namely debonding at concrete-mortar and textile-mortar interfaces, textile slippage, and textile rupture. An effective bond length of 150 mm was established from the $P_u$ - $L_b$ relation and was found not to be affected by strain rate.

**KEYWORDS**: FRCM; Bond; FRP; Strain Rate; Strengthening; Debonding.

# INTRODUCING A NOVEL MULTI-PURPOSE STAY-IN-PLACE FORM FOR CONSTRUCTION AND REPAIR INDUSTRIES

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**ABSTRACT**

Conventional fiber-reinforced polymer (FRP) repair techniques typically require extensive surface preparation before installation, increasing both cost and construction time. This paper introduces a newly developed product by the author that offers significant advantages for new construction, as well as for the repair and strengthening of existing structures both above and below water.

The system consists of pultruded glass FRP (GFRP) panels that are 3 ft (914 mm) wide and can be manufactured in any length. The outer face of each panel is smooth, while the inner face features protruding T-shaped profiles, 1.5 in. (38 mm) tall, which serve as integral reinforcing elements. This inner surface is grit-coated to enhance bond strength with concrete. The panels can be joined by overlapping edges or using L-shaped connectors to form stay-in-place formwork of virtually any configuration. Once bolted to the host structure, the annular space behind the panels is filled with a cementitious grout. The flexural strength of the system—equivalent to that of 20 mm, 500 MPa steel bars spaced at 120 mm—often eliminates the need for conventional reinforcement. Additionally, the impervious nature of the panels removes the need for waterproofing membranes.

Since its introduction two years ago, this technology has been successfully deployed in numerous projects worldwide, including the repair of timber, concrete, and steel seawalls and bulkheads; strengthening of bridge decks, girders, and pier walls; extension of seawalls for sea-level rise protection; and construction of fire- and water-resistant roofs and floors.

**KEYWORDS**: Repair; Strengthening; Formwork; Sustainability; Waterproof.

# FLEXURAL BEHAVIOR OF ULTRA-HIGH-STRENGTH ECC THIN PANELS REINFORCED WITH CFRP/GFRP BARS

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## ABSTRACT

Thin panel systems for modular and marine structures require corrosion-free reinforcement and reliable crack control. This paper examines ultra-high-strength engineered cementitious composites (UHS-ECC) solid (40 mm) and hollow (60 mm) thin panels reinforced with CFRP or GFRP bars and tested under monotonic four-point bending. Load–deflection response, reinforcement strains, and digital image correlation (DIC) are used to quantify FRP strain utilization and to relate utilization to governing failure mechanisms. Adopting hollow geometry increased flexural efficiency while keeping a similar net cross-sectional area, raising peak load from 28.6–29.2 kN to 67.8–69.2 kN for CFRP and from 21.6–23.5 kN to 66.1–67.5 kN for GFRP. CFRP-reinforced panels were section-strain-limited: CFRP strains at peak were 0.44–0.50% for solid panels and remained below about 0.7% in hollow panels, indicating a compression-controlled ultimate state rather than CFRP rupture. GFRP-reinforced panels mobilized substantially higher strains, reaching 1.51–1.83% in solid panels and approaching the rupture strain in hollow panels. DIC showed flexure-dominated multiple cracking in solid panels, whereas hollow panels developed diagonal strain localization in the shear spans, leading to flexure–shear interaction when reinforcement utilization was high. The results highlight that improving FRP utilization in UHS-ECC thin panels is inseparable from controlling the associated failure mode, particularly for hollow sections. These findings provide design-oriented guidance for selecting FRP type and section form in thin, durable panelized systems.

**KEYWORDS**: ECC; SHCC; CFRP bar; GFRP bar; Hollow panel; Flexural behavior.

# COMPOSITE ACTION BENEFITS AND DRAWBACKS IN INSULATED WALL PANELS WITH FRP CONNECTORS

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**ABSTRACT**
Precast concrete insulated wall panels combine architectural, structural, and thermal features into a single system. Though commonly used, these panels are difficult to analyze as they act as partially composite elements. The level of composite action is primarily controlled by the material and arrangement of shear connectors that connect concrete layers through insulation. Fibre-reinforced polymers (FRP) have been used as shear connectors in insulated walls since the 1980s with their initial use being non-structural and driven by FRP's low thermal conductivity. Since then, numerous FRP connectors have been developed to provide essentially any degree of composite action in insulated panels. This paper presents a review of FRP shear connectors tested in the literature and gives insights into their contributions to composite action in insulated panels. Results from direct shear push-through tests on FRP connectors are compared to each other. These comparisons focused on connector stiffness and strength. Implications of these properties on composite action and the overall structural response of insulated panels are demonstrated using simplified models that represent panels currently in use in colder regions. Models indicate that larger degrees of composite action, attained from FRP truss or grid connectors, are beneficial for resisting external loads. However, these same benefits create issues with thermal bowing, which means that designers need to understand the degree of composite action they may encounter. Recommendations for composite action based on application are provided.

**KEYWORDS**: Precast concrete; Shear connectors; Composite action.

# FLEXURAL BEHAVIOR OF STEEL BEAMS WITH SIMULATED CORROSION DAMAGE REPAIRED BY CFRP

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**ABSTRACT**
Corrosion of steel beam flanges and adjacent webs leads to significant reductions in flexural capacity, serviceability, and stiffness, particularly in coastal and industrial environments. Conventional repair using steel plates is often difficult to implement, motivating the need for light-weight and durable alternatives. This study examines the effectiveness of carbon fiber reinforced polymer (CFRP) retrofits for a corroded monosymmetric channel-capped steel I-beam. One unrepaired specimen and two repaired specimens were tested, employing either a low modulus fabric or a normal modulus plate. To simulate damage, trapezoidal section loss was introduced at the outer periphery of the flange at midspan. Four-point bending tests on 4.0 m span steel beams measured deflections, strains, ultimate load, and failure modes. The fabric retrofit was applied after both damage and preload to replicate an in-service repair. Relative to the unrepaired damaged beam, CFRP fabric increased the ultimate flexural capacity by 17.2%, the load at first steel yield by 39.3%, and initial stiffness by 8%. Plate retrofits increased ultimate capacity by 20.7% and the load at first yield by 42.8%, with a smaller stiffness gain. Two layers of fabric performed at least as well as 1.4 mm plates. Finite element models were developed and validated, accurately predicting load-carrying capacity and failure modes.

**KEYWORDS**: Carbon-fiber reinforced polymer; Corrosion damage; Steel beams; Repair.

# RECTANGULAR FRP-CONCRETE-STEEL DOUBLE-SKIN TUBULAR COLUMNS WITH A T-STIFFENED STEEL TUBE: STUB COLUMN TESTS

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**ABSTRACT**
FRP-concrete-steel double-skin tubular columns (DSTCs) are an emerging form of durable, high-performance structural members. Compared to circular DSTCs, rectangular DSTCs generally suffer from weak confinement of concrete along their flat sides and potential inward buckling of the inner steel tube due to non-uniform confinement. To overcome these limitations, a novel T-section-stiffened rectangular DSTC (TS-DSTC), in which T-section stiffeners are welded to the steel inner tube, has been recently proposed by the corresponding author. This configuration enhances lateral confinement in regions where FRP confinement is weak and simultaneously restrains inward buckling of the steel tube. This paper presents a series of axial compression tests, comparing the behaviour of rectangular TS-DSTCs with conventional DSTCs and FRP-confined plain concrete columns. The results show that TS-DSTCs achieve a stable bilinear ascending load-displacement curve even with relatively low FRP stiffness. Their performance is superior to the other two column forms due to the beneficial interactions between FRP, steel and concrete in this configuration. Therefore, TS-DSTCs offer an efficient, corrosion-resistant structural solution with enhanced ductility, showing strong potential for applications such as bridge piers.

**KEYWORDS**: Fiber-reinforced polymer; Double-skin tubular columns (dstcs); T-section stiffener; Uniaxial compression; Confinement.

# LONG-TERM EVALUATION OF THE SEISMIC RESILIENCE OF CRC- AND RC-REINFORCED BUILDINGS

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**ABSTRACT**

Corrosion-induced degradation in reinforced concrete (RC) structures, often initiating within the first decades of service life, poses a critical challenge to long-term seismic resilience. Existing analytical tools can evaluate structural performance, but they remain limited in predicting how seismic resistance evolves as core material properties deteriorate. To address this gap, we propose a Seismic Resistance Prediction Method (SRPM) developed to capture changes in seismic capacity, including applications to carbon-fiber-reinforced polymer (CFRP)–reinforced concrete (CRC), where reinforcement is non-corrosive. Classical corrosion models are integrated with section strength predictions to assess durability, while nonlinear static pushover analysis (POA) is conducted using SAP2000 and Response2000. Comparative simulations between conventional steel-reinforced RC and CFRP-reinforced CRC highlight clear differences in long-term seismic behavior. Steel reinforcement exhibits substantial reduction in energy dissipation capacity, losing 54.4% after 170 years, whereas CFRP reinforcement shows only a 25.5% decrease over the same period. These findings underscore CFRP's superior durability and its effectiveness in preserving structural integrity under seismic demands.

**KEYWORDS**: Seismic resistance; Ductility ratio; CFRP; Energy dissipation capability.

# NUMERICAL MODELING OF PRETENSIONED GFRP-REINFORCED SEAHIVE® UNITS SUBJECTED TO LINEARLY VARYING PRESSURE

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## ABSTRACT

SEAHIVE® units are modular concrete elements developed for coastal and marine protection applications, for which structural performance under submerged or partially submerged loading may represent governing design consideration. This study presents a numerical extension of previously validated investigations on SEAHIVE® units reinforced with pretensioned GFRP bars, with specific emphasis on their response under linearly varying pressure. The numerical model adopted herein is founded on a formulation that was validated against experimental four-point bending tests reported in earlier work. Building upon this established basis, the model is extended to a partial cantilever idealization representative of submerged boundary conditions that are not readily amenable to laboratory experimentation. Comparative numerical analyses are performed for pretensioned and non-pretensioned reinforcement configurations to examine stiffness evolution, damage development, stress redistribution, and failure characteristics. The model is then extended to represent the serviceability limit state, in which the active earth pressure is calculated and applied to the SEAHIVE® unit, representing a pile-driven condition. This work provides novel insights into the structural behavior of SeaHive® units and demonstrates the significant contribution of prestressed GFRP to their performance.

**KEYWORDS**: SEAHIVE®; GFRP Reinforcement; Prestressing; Failure Mechanism; Abaqus FEA.

# DESIGN CONCEPT FOR THERMAL BREAK ELEMENT FOR PARAPETS WITH GFRP TENSION BARS

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## ABSTRACT

A novel product concept for thermal breakt elements consisting of GFRP tension bars and concrete bearings was developed for the use of GFRP bars. The project goal is to reduce thermal conductivity by minimising the number of support components while efficiently selecting those materials. The verification was provided by means of a comprehensive experimental and analytical procedure. The investigations covered various types of failure for the entire separation element, with a particular focus on the GFRP tension bars as tension components: tensile failure of the GFRP bar, composite failure in cracked and uncracked concrete, and concrete edge failure. The test programme included systematic variations in embedment depth, concrete strength, crack width (0.3 mm and 0.5 mm) and cyclic loading. A total of more than 60 individual and component tests were carried out in order to record the relevant influencing factors and statistically validate them. In addition, the findings from the national building authority approval of the GRP material were used to assess the long-term behaviour.

The evaluation was carried out in accordance with the specifications of current European Assessment Documents (EAD) using conservative assumptions. It was demonstrated that neither increased crack widths nor cyclic loads lead to a significant reduction in load-bearing capacity. The results thus show that the design values of the tensile component meet the safety requirements. The developed method enables reliable design of GFRP tension bars in the context of thermal separation elements for parapet connections and expands the field of application of fibre-reinforced materials in construction. The extensive findings ultimately resulted in a general building authority approval for Germany.

**KEYWORDS**: Thermal break element; Isokorb; GFRP tension bar; Design concept.

# CHARACTERISATION OF WOUND GLASS FIBRE-REINFORCED POLYMER TRANSVERSE REINFORCEMENTS

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**ABSTRACT**
Fibre-reinforced polymers (FRPs) have emerged as corrosion-resistant alternatives to steel in reinforced concrete structures; however, their effective implementation requires reliable transverse reinforcement solutions. A promising approach involves winding continuous FRP filaments around non-metallic longitudinal bars through an automated manufacturing process, producing lightweight prefabricated reinforcement cages (W-FRP). Unlike steel, FRP shear reinforcement exhibits linear-elastic and brittle behaviour, and its performance is governed by stress concentrations at bent regions, making mechanical characterisation essential. This study presents an experimental characterisation of filament-wound glass FRP (GFRP) shear stirrups fabricated via wet winding using a photo-activated vinyl ester resin. Straight strip specimens and closed rectangular stirrups with 1–6 winding layers were manufactured and tested to evaluate tensile and bent-corner performance. The results show an approximately linear increase in ultimate tensile capacity with increasing layer count, with straight strips reaching up to 26.14 kN (6 layers). Closed stirrups exhibited reduced capacity due to corner stress concentration, with bent-corner efficiency ranging from 0.64 to 0.78 relative to the straight tensile strength. The findings provide quantitative insight into the mechanical behaviour and reliability of wound GFRP transverse reinforcement and contribute to improved estimation of design strength for digitally manufactured, non-corrosive reinforcement cages in concrete construction.

**KEYWORDS**: W-FRP, Reinforcement cages, Bent corners, Filament winding, Digital manufacturing.

# EXPERIMENTAL FRAMEWORK TO EVALUATE THE IN-PLANE SHEAR BEHAVIOUR OF UHPC-CFRP COMPOSITE STRUCTURAL PANELS WITH CFRP SHEAR CONNECTORS

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**ABSTRACT**

This paper outlines an experimental framework to investigate the in-plane shear behaviour of innovative composite structural panels (CSPs) designed for future bridge deck applications. The panels incorporate ultra-high-performance concrete (UHPC)–carbon fibre reinforced polymer (CFRP) hybrid face sheets connected by CFRP shear connectors, fabricated using the Vacuum Assisted Resin Transfer Moulding (VARTM) technique. The novelty of this panel system lies in its monolithic integration of UHPC and CFRP, which enhances bond quality and structural continuity compared to conventional layered assemblies. CFRP shear connectors are strategically de-signed to transfer shear forces between the face sheets and the insulating core, enabling composite action under flexural loading. Understanding in-plane shear performance is critical because it governs the interaction between components, which directly influences the flexural behaviour and ultimate capacity of full-scale panels. The experimental farmwork helps to evaluates shear transfer efficiency and failure modes under quasi-static loading. Findings from this experimental framework provide essential insights for optimizing connector design and predicting flexural response, forming the foundation for advanced numerical modelling and design guidelines. This work contributes to the development of lightweight, durable, and high-strength composite panels for next-generation bridge infrastructure.

**KEYWORDS**: CFRP shear connectors; Composite structural panels; Hybrid face sheets; In-plane shear behaviour; UHPC.

# COMPRESSIVE BEHAVIOR OF PULTRUDED-BRAIDED FRP BARS WITH GFRP BRAIDED LAYERS

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**ABSTRACT**

Pultruded fiber-reinforced polymer (FRP) bars are widely used in engineering structures owing to their excellent tensile properties and corrosion resistance. However, their compressive performance is limited by the unidirectional fiber arrangement, which often leads to brittle failure, fiber micro-buckling, and longitudinal splitting. To improve the compressive behavior of FRP bars, this study proposes a pultruded-braided FRP bar in which an outer braided layer is introduced around the pultruded core to provide transverse confinement. GFRP and CFRP were used as core materials, and GFRP braided layers with braiding angles of 30°, 45°, and 60° were considered. Short-column axial compression tests were conducted to investigate the effects of core material and braiding angle on failure mode, load-displacement response, compressive strength, and the strengthening mechanism. The results show that the braided layer changed the failure mode from core-dominated axial splitting to a composite failure process involving the core, braided layer, and their interface. For GFRP-core specimens, the ultimate load increased by 23.3%–56.8% after braiding, and the compressive strength increased from 408.8 MPa to 504.1–640.3 MPa. In contrast, the enhancement effect was less pronounced for CFRP-core specimens. A simplified angle-dependent prediction model was further developed, and most relative errors were within approximately 16%. The results indicate that the pultruded-braided configuration is an effective approach for improv-ing the compressive performance of FRP bars, particularly for GFRP-core specimens.

**KEYWORDS**: FRP bars; Pultrusion-braiding; Compressive behavior; Braiding angle; Theoretical model.

# SUSTAINABLE MINERAL-BONDED COMPOSITES FOR RESILIENT BUILT ENVIRONMENT: OPPORTUNITIES AND TRADE-OFFS

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## ABSTRACT

The rapid escalation of climate change and human activity is quickly reshaping the priorities of the construction industry due to the sharp increase in extreme weather events and military action. Existing assets and infrastructure are vulnerable due to ageing or outdated design criteria. Retrofitting and protecting structures are crucial to making the existing built environment robust and resilient against extreme events such as collisions, explosions, rock falls, and floods, thereby safeguarding human safety and mitigating economic losses. When it comes to acting on existing structures, especially those made from reinforced concrete, mineral-bonded composite materials have proven to be an attractive option, particularly when applied as thin reinforcing layers. Structural composite systems such as strain-hardening cementitious composites (SHCCs) and hybrid composites (e.g. textile-reinforced SHCCs (TR-SHCCs)) offer exceptional toughness and damage tolerance, while protecting against other hazards such as fire and high-temperature sensitivity. However, SHCCs and their variants require large quantities of cement clinker due to the absence of coarse aggregates, and the production processes of synthetic fibres and textile grids are generally energy-intensive. In this study, we critically assess the opportunities in the field of hybrid composites by analysing how different reinforcements (i.e., PE, PET, PP fibres, and carbon, glass, basalt textiles) contribute to their impact resistance. In parallel, relying on robust databases on impact tests, we examine the environmental and economic impact of these technologies, integrating life-cycle assessment (LCA). Our research aims to clearly identify decision-making criteria for retrofitting designs based on finely tuning raw constituents to provide the required performance standards with the minimum environmental impact.

**KEYWORDS**: Textile reinforced cementitious composites; Strain-hardening; Impact resistance; Life cycle assessment; Resilience.

# DEVELOPMENT AND TESTING OF GFRP GROUND ANCHORS

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**ABSTRACT**

The use of glass fibre-reinforced polymer (GFRP) reinforcement in ground anchors represents a promising alternative to conventional steel. The main advantages of their adoption are high corrosion resistance, low weight, non-conductivity, and non-magnetic properties. For temporary applications, an additional advantage lies in the possibility of easily cutting the anchor element during subsequent excavation or reconstruction, which is complicated with traditional steel anchors and therefore represents a significant benefit.

A specific challenge in this application arises from the anisotropic behaviour of GFRP tendons. At the anchorage zone, the matrix surface is subjected to high stresses both along and transverse to the fibres, which may lead to slippage and a loss of load-bearing capacity. To address this issue, a special steel anchor head was developed. It enables safe transfer of tensile forces close to the ultimate capacity of the FRP tendon while minimizing the risk of damage at the anchorage point.

Another key aspect investigated was the bond performance of smooth GFRP tendons with cement grout. To obtain relevant results, the test specimens had to be suitably modified to reflect the different mechanical properties of cement grout (used for borehole injection) compared to conventional concrete, as these significantly affect shear stress transfer and anchorage reliability.

**KEYWORDS**: Ground anchors; GFRP tendons; Steel anchor head; Bond strength.

# DEPLOYING TEXTILE REINFORCEMENT FOR CONCRETE THROUGH THERMAL STIMULATION OF SHAPE-MEMORY MATERIALS

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**ABSTRACT**
Textile-reinforced concrete enables the creation of thin-walled elements. The reinforcement itself is characterised by low weight, facilitating easier handling and assembly on-site. Current textiles, however, are limited in bendability and transportation size, resulting in difficulties for the creation of non-planar shapes. In this paper, we propose a novel concept for deployable textile-reinforcements, utilising shape memory polymers. These composites, consisting of resin, hardener, and filaments, can change their shape in response to thermal stimuli to recover their programmed geometry. Heat required for activation is induced by wires embedded in the reinforcement using Tailored Fibre Placement. The deployment mechanism can be further supported when using wires made of shape memory alloys (SMAs). To investigate the actuation characteristics of such thermo-responsive composites as reinforcements for concrete applications, experimental tests were conducted. Most specimens (six out of eight) demonstrated excellent shape recovery, exceeding 94% of the programmed geometry. Thinner heating wires achieved recovery ratios of up to 97.3%, whilst thicker SMA wires provided marginally superior mechanical support despite reduced foldability. However, spring-back effects of 2.5-8% over time were observed across all specimens, which may pose challenges for practical applications where precise geometric retention is required.

**KEYWORDS**: Textile-reinforced concrete; Self-unfolding; Shape-memory-polymers; Deployability; Shape-memory-alloys.

# FATIGUE PERFORMANCE OF NON-WOVEN FLAX/BIO-EPOXY COMPOSITES FOR SUSTAINABLE PEDESTRIAN BRIDGE DECKS

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## ABSTRACT

Fibre-reinforced polymer (FRP) composites are increasingly recognised as sustainable alternatives to conventional materials, such as concrete and steel, in pedestrian and cycle bridges. However, their long-term fatigue performance under cyclic loading remains underexplored, particularly for randomly oriented non-woven flax/bio-epoxy composites. This consideration is important for these structures, as their lighter weight makes them more susceptible to vibrations and repeated stress. This study investigates the fatigue behaviour of such composites manufactured via vacuum-assisted resin infusion.

Fatigue tests were conducted at a stress ratio of R = 0.1 across multiple stress levels of ultimate tensile strength (UTS). Three standard specimens were tested per level using a servo-hydraulic Instron machine. The results showed a higher mean UTS than the performance of non-woven hemp composites reported in a previous bio-composite pedestrian bridge study. The fatigue tests exhibited a maximum stress of approximately 40 MPa and a maximum fatigue life of ≈3.5 × 105 cycles. The Stress–Cycle (S–N) curves showed the expected inverse trend, with lower stress levels producing longer fatigue lives. The residual tensile Modulus (E–N relationship) remained stable at lower stress levels, suggesting elastic behaviour. At higher stress levels, stiffness decreased due to crack propagation and damage accumulation.

These findings align with known composite fatigue mechanisms. However, the results uniquely demonstrate that low-cost, randomly oriented non-woven flax mats can provide predictable cyclic performance. The study provides new fatigue data on non-woven flax/bio-epoxy laminates, a rarely reported material system.

**KEYWORDS**: Non-woven flax fibres; Bio-epoxy resin; Natural fibre composites.

# MECHANICAL PROPERTIES OF LIQUID CRYSTAL POLYMER FIBER-REINFORCED CEMENTITIOUS COMPOSITES (LCP-FRCC)

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## ABSTRACT

Cementitious materials often exhibit reduced durability in high-humidity environments, thereby shortening structural lifespans. Improving crack control and ductility in newly developed materials has become a primary research scope, underscoring the wide potential of fiber-reinforced cementitious composites (FRCC). To meet engineering requirements for lightweight, high-toughness, and durability, extensive research has been con-ducted on various ECC categories. Fibers such as polyvinyl alcohol (PVA), polyethylene (PE), polypropylene (PP), and aramid continue to attract significant research attention. Liquid crystal polymer (LCP) fibers, as high-strength, high-modulus hydrophobic fibers, have yet to yield sufficient research evidence regarding their performance in cementitious composites. To address the above issues, this study investigates LCP fiber-reinforced cementitious composites (LCP-FRCC). It proposes varying the LCP fiber content (0%, 0.5%, 1%, 1.5%, and 2%) while maintaining the same mix proportions. Mechanical properties, including compressive, flexural, and tensile strengths, were measured at different stages of curing. Microstructural analysis (SEM and CLSM) was conducted to observe fiber distribution and interfacial bonding with the matrix. Results indicate that LCP fibers in cementitious matrices enhance material strength and fracture elongation. These findings provide a basis for the engineering application of LCP-FRCC and offer practical reference for subsequent research on FRCC mix design.

**KEYWORDS**: Fiber-reinforced cementitious composites; Liquid crystal polymer fibers; Mechanical Properties; Microstructure.

# A STATE-OF-THE-ART REVIEW ON USING GFRP AS INTERFACE SHEAR REINFORCEMENT FOR CONCRETE JOINTS

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**ABSTRACT**
Glass fiber–reinforced polymer (GFRP) has gained increasing attention as a viable alternative to steel reinforcement in reinforced concrete (RC) structures due to its lightweight nature and superior corrosion resistance. However, its role as interface shear reinforcement across concrete joints remains insufficiently explored and is not yet fully addressed in current design codes and standards. Research in this area has emerged only within the past decade, with a noticeable increase in publications in recent years. Previous studies have examined the feasibility of using GFRP as interface shear reinforcement and investigated various influencing parameters, including reinforcement ratio, reinforcement stiffness, interface condition (monolithic, intentionally roughened, or non-intentionally roughened), concrete compressive strength, and reinforcement shape. These investigations have demonstrated the potential of GFRP reinforcement to effectively contribute to shear transfer across concrete interfaces. This state-of-the-art review summarizes the progress achieved to date and identifies the critical research gaps that must be addressed for the broader implementation of GFRP as interface shear reinforcement in design practice. Moreover, experimental results available in the literature were compared with theoretical predictions derived from the available equations to evaluate the accuracy of the available equations.

**KEYWORDS**: Shear-friction; Dowel action; Concrete cold joint; Monolithic concrete joint; Push-off test.

# INTERFACE SHEAR CAPACITY OF GFRP-REINFORCED CONCRETE JOINTS WITH DIFFERENT INTERFACE CONDITIONS

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## ABSTRACT

Interface shear reinforcement plays a critical role in ensuring effective load transfer across concrete cold joints. With the growing use of glass fiber-reinforced polymers (GFRP) in various structural applications—attributed to their superior corrosion resistance, high strain capacity, and high strength-to-weight ratio—their role as interface shear reinforcement remains insufficiently addressed in existing design provisions. This study investigates the structural performance of GFRP reinforcement in cold-jointed reinforced concrete (RC) through an experimental program comprising six push-off specimens, with an interface area of 150 mm × 180 mm (27,000 mm²). The investigation focuses on the influence of interface surface conditions, including intentionally roughened, as-cast, and smooth interfaces. The load-response curves for slip and crack opening were analyzed. Results indicate that GFRP reinforcement substantially enhanced the interface shear capacity and reduced the likelihood of sudden failure of both intentionally roughened and non-intentionally roughened cold joints. Additionally, intentional roughening of the interface substantially increased shear load capacity while concurrently reducing slip and crack opening relative to as-cast and smooth GFRP-RC joints. Comparisons with design provisions revealed that the Canadian Highway Bridge Design Code provided conservative predictions for GFRP–RC specimens, whereas the equation of the American Association of State Highway and Transportation Officials for GFRP–reinforced concrete overestimated the interface shear capacity.

**KEYWORDS**: Shear-friction; Dowel action; Concrete cold joints; Push-off test.

# LONGITUDINAL SHEAR BEHAVIOR OF COMPOSITE SLABS WITH GFRP PERMANENT FORMWORK

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**ABSTRACT**
Composite slabs with permanent Glass Fiber Reinforced Polymer (GFRP) formwork offer a durable alternative to traditional steel decks, particularly in corrosive environments. However, the shear bond behavior at the GFRP-concrete interface remains a critical design aspect due to the lack of natural mechanical interlocking in pultruded profiles. This article presents an experimental analysis of the longitudinal shear resistance of composite slabs comprising trapezoidal GFRP forms and steel fiber reinforced concrete (SFRC). The interface was treated using a sand-coating method to promote adhesion. The experimental program involved testing three full-scale slab segments using an adapted push-off configuration designed to isolate shear stresses and eliminate normal forces typically present in vertical arrangements. The results indicated a brittle failure mode governed by longitudinal slip at the interface. Although limited to three specimens, the study provides preliminary insights into the longitudinal shear behavior. The specimens achieved an average shear bond strength of 0.12 MPa. Although variability was observed in the experimental results, the obtained shear resistance is comparable to values reported for traditional steel deck systems with similar geometries. The study validates the feasibility of using GFRP profiles with sand treatment to promote composite action and demonstrates the effectiveness of the adapted push-off test in characterizing interfacial behavior. The results provide fundamental data for the design and development of composite structures.

**KEYWORDS**: GFRP; Steel fiber reinforced concrete; Composite slabs; Longitudinal shear; Push-off test.

# FRP reinforcement for concrete structures

# COMPARATIVE DIC-BASED SHEAR TRANSFER ANALYSIS OF GFRP AND STEEL-REINFORCED CONCRETE T-BEAMS

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**ABSTRACT**
This paper presents a comparative analysis of shear transfer mechanisms in two T-shaped reinforced concrete beams with dense transverse reinforcement: one with GFRP bars (TG-120) and one with conventional steel bars (TS-120). Both beams shared identical cross-sectional geometry ($b_w = 250$ mm, $h = 400$ mm) and were tested under three-point bending. Digital Image Correlation (DIC) was used to measure crack opening, slip, and shear angle along the critical diagonal crack. Strain gauges on stirrups provided direct measurements of the transverse reinforcement contribution. The shear capacity at peak load was decomposed into five transfer mechanisms: aggregate interlock, residual tensile stress, dowel action, compression zone, and stirrup force. The model achieved good agreement with experimental results ($V_{cal}/V_{exp} = 1.00$ for TG-120 and 1.05 for TS-120). GFRP reinforcement reduced the shear capacity by 20% compared to steel. In TG-120, the stirrup contribution accounted for 67% of the total calculated shear force versus 80% in TS-120, while aggregate interlock provided a relatively higher share in the GFRP beam (25% vs. 15%). GFRP stirrups utilised only 50–57% of their tensile strength due to bend-corner rupture, contrasting with the near-yield stress levels in steel stirrups.

**KEYWORDS**: GFRP reinforcement, Shear behaviour, Digital Image Correlation, T-beam, Crack kinematics.

# STRUCTURAL BEHAVIOR OF FRP-REINFORCED SHCC I-MEMBERS WITHOUT SHEAR REINFORCEMENT


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## ABSTRACT

This study investigates the structural behavior of I-section beams made of strain-hardening cementitious composites (SHCC) internally reinforced with glass fiber-reinforced polymer (GFRP) bars and without shear reinforcement. Although the combination of SHCC and FRP has demonstrated significant potential in enhancing the performance of reinforced cementitious members, their use in slender I-section beams without transverse reinforcement remains a scarcely investigated topic in the literature. To address this gap, an experimental program was conducted, including material characterization, four-point bending tests, and Digital Image Correlation (DIC) for full-field strain and crack monitoring. The results revealed two distinct failure mechanisms: one beam reached flexural failure through rupture of the GFRP bars, while the others failed in shear at the web–flange junction. These outcomes highlight that shear behavior is a critical governing parameter for slender SHCC–GFRP I-members, strongly influenced by geometric constraints and fiber distribution within the SHCC matrix. Load–deflection curves exhibited a bilinear response associated with SHCC tension-stiffening, and DIC analyses recorded the transition from distributed cracking to crack localization at higher load levels. Overall, this work presents the first experimental evidence on the mechanical behavior and failure modes of slender SHCC–GFRP I-section beams without shear reinforcement. The findings underscore the importance of shear transfer in thin webs and demonstrate the sensitivity of this structural system to local variations in fiber mobilization, providing valuable insights to support future modeling efforts and the design of thin-walled hybrid SHCC–FRP structural elements.



**KEYWORDS**: Strain-hardening cementitious composites (SHCC); Glass fiber-reinforced polymer (GFRP); I-section beams; Structural behavior; Digital image correlation (DIC).

# PREDICTION OF SHEAR RESISTANCE OF BEAM REINFORCED WITH GFRP REINFORCEMENT

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## ABSTRACT

Since the 1970s, fiber-reinforced polymers (FRP) have been employed across numerous sectors, including aerospace, sports, automotive, and others. In the early 1950s, the construction industry was acknowledged for its potential applicability. They are commonly employed in the construction sector as direct reinforcement in areas exposed to adverse or chemically aggressive conditions. This research project investigates the use of glass fiber-reinforced polymer (GFRP) stirrups alongside longitudinal GFRP reinforcement in structural components. This study examines the feasibility of utilising an alternative to traditional steel reinforcement in concrete structures. Stirrups are the initial components to deteriorate once the concrete cover is compromised by carbonation, and this application is appropriate for bridges subjected to harsh environments with chlorides from deicing salts. Stirrups are the initial components to undergo corrosion due to their proximity to the surface.

This article primarily focuses on assessing the shear resistance of a concrete element reinforced with GFRP shear reinforcement. In addition to the reduction in tensile strength that occurs at the bend location, certain challenges arise when attempting to develop a computational model that accurately depicts the effect of GFRP stirrups on shear resistance. This study aims to examine the shear capacity of a concrete element reinforced exclusively with GFRP. The results of this study were computed in accordance with the existing standards and guidelines.

**KEYWORDS**: GFRP stirrups; Design of GFRP for shear; Shear resistance.

# MODELLING OF PREMATURE FAILURE OF DEEP BEAMS LONGITUDINALLY REINFORCED WITH INTERNAL FRP BARS

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**ABSTRACT**
Deep concrete beams longitudinally reinforced with internal fiber-reinforced polymer (FRP) bars can exhibit premature failure when compared to similar steel-reinforced members. Experimental observations show that deep beams without transverse reinforcement, when loaded in four-point bending, can fail suddenly through a shear-induced flexural failure mechanism. This failure mode is characterized by the penetration of diagonal cracks into the pure bending region and subsequent crushing of the concrete above the cracks. This paper investigates the mechanisms governing this brittle failure mode and presents a mechanics-based modelling approach based on a modification of the classical method for flexural strength calculations to account for the reduced depth of the compression zone at failure. A semi-empirical expression for the depth of the reduced compression zone is derived from large-scale test data, relating it to beam shear slenderness and concrete strength. The proposed model captures the premature crushing observed in FRP-reinforced deep beams without transverse reinforcement. The results demonstrate that the gradual loss of aggregate interlock and the limited stiffness of FRP reinforcement promote premature concrete crushing, preventing the full development of the load-bearing capacity of such members. These findings highlight the structural vulnerability of concrete deep beams without stirrups and the essential role of transverse reinforcement in ensuring adequate strength and ductility in FRP-reinforced deep concrete members.

**KEYWORDS**: Deep concrete beams; Brittle failure; Fiber-reinforced polymer (FRP) bars; Mechanical model; Shear strength.

# EXPERIMENTAL VERIFICATION AND THEORETICAL ANALYSIS OF CRACKING IN GFRP-REINFORCED BEAMS WITH RAC

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**ABSTRACT**

The use of Glass Fiber Reinforced Polymer (GFRP) bars as an alternative to traditional steel reinforcement is gaining importance, particularly in structures exposed to corrosive environments. While GFRP offers excellent durability, its distinct mechanical properties, such as a lower modulus of elasticity, present significant challenges for structural design, primarily concerning serviceability limit states. Excessive cracking and deflection in GFRP-reinforced concrete members remain key issues that require further investigation. This paper presents key findings from a completed experimental program focused on the flexural behaviour of concrete beams reinforced with GFRP bars with different surface treatments. Results from a series of tested beams are analysed to evaluate the critical parameters influencing crack formation. The research combines these presented experimental results with a parametric theoretical analysis to provide a comprehensive understanding of the mechanisms. The findings reveal that the low modulus of elasticity of GFRP bars effectively masks the potential serviceability drawbacks of Recycled Aggregate Concrete (RAC). This is crucial not only for ensuring the long-term integrity of the structure but also for maintaining its aesthetic appearance over its service life. Furthermore, this work explores the potential integration of RAC within GFRP-reinforced structures, concluding that this hybrid GFRP-RAC system provides a high level of stability in crack width development despite the reduced stiffness of the concrete matrix. Adopting this hybrid material system offers a viable strategy for reducing the environmental impact of construction without compromising serviceability performance.

**KEYWORDS**: GFRP reinforcement; Crack width; Recycled aggregate concrete (RAC); Flexural behaviour; Serviceability limit state (SLS).

# SHEAR PERFORMANCE OF BFRP-REINFORCED CONCRETE BEAMS: EXPERIMENTAL STUDY AND FEM VALIDATION

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## ABSTRACT

Basalt Fiber-Reinforced Polymer (BFRP) bars are increasingly adopted in aggressive environments, but the shear response of BFRP-RC beams without web reinforcement remains insufficiently understood and is often conservatively treated in design. This study integrates an experimental program with finite element (FE) modeling to quantify key parameters controlling shear capacity and to provide validated numerical insight into the governing failure mechanism. A series of BFRP-reinforced concrete beams without stirrups (with minimal steel ties used only for bar positioning) were tested under four-point loading and compared with steel-reinforced control beams. The investigated parameters included shear span-to-depth ratio ($a/d$ = 1.5, 2.1, 2.5), concrete compressive strength ($f_c'$ = 35–70 MPa), and longitudinal reinforcement ratio ($\rho$ = 1.76–4.46%). All specimens failed in diagonal shear, with a clear reduction in capacity as a/d increased and consistent gains with increasing ρ; the highest measured shear capacity was approximately 218 kN for $a/d$ = 1.5, $f'_c$ = 70 MPa, and $\rho$ = 4.46%. A 3D ABAQUS model was developed using concrete damaged plasticity (CDP) for concrete, embedded truss reinforcement for bars, and displacement-controlled loading through bearing plates. The model captured the experimental load–displacement trends and reproduced diagonal shear localization, enabling mechanistic interpretation and limited parametric extension beyond the tested matrix. The combined experimental–numerical findings support improved understanding of shear transfer in BFRP-RC beams without web reinforcement and provide a basis for rational assessment against existing design provisions.

**KEYWORDS**: BFRP bars; Shear; Beams without stirrups; Concrete damaged plasticity; Finite element modelling.

# NUMERICAL STUDY OF GFRP REINFORCED LWC BEAMS

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**ABSTRACT**

Fibre reinforced polymer (FRP) rebars offer multiple advantages in concrete construction such as high tensile strength, corrosion resistance, low weight and magnetic neutrality. Some properties of FRP reinforced elements such as the lack of plastic deformations before failure need to be addressed. The research into the behaviour of FRP rebars and FRP reinforced concrete elements has been ongoing for multiple decades and has produced results that facilitated the construction of many actual structures utilizing the technology. There are, however, many areas that require further study. FRP reinforcements combined with lightweight concrete (LWC) results in structural elements with reduced self-weight. This type of structural element can have reduced transportation and construction costs, as well as larger dimensions due to the reduced density. The goal of the research is to study the behaviour of FRP reinforced LWC beams by conducting numerical simulations based on laboratory experimental results, along with data from experiments on FRP reinforced normal weight concrete. These models are to be used to conduct further analysis on the behaviour of FRP reinforced LWC beams by studying the effect of various parameters such as the potential positive impact of the confinement effect on the concrete in the compressive zone to ensure a more ductile failure of beams designed to fail in compression.

**KEYWORDS**: Reinforced concrete; Numerical analysis; Compression failure; Lightweight concrete; GFRP.

# A HOMOGENISED NUMERICAL MODELLING APPROACH FOR HYBRID BASALT FIBRE-BFRP REBAR REINFORCED CONCRETE

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## ABSTRACT
Basalt fibre-reinforced concrete combined with basalt fibre-reinforced polymer (BFRP) longitudinal reinforcement (rebar) represents a promising sustainable alternative to conventional steel-reinforced systems. While experimental studies have demonstrated the mechanical benefits of fibres and fibre-reinforced polymer (FRP) bars individually, numerical modelling of hybrid fibre-rebar reinforced concrete structural systems remains limited, particularly for basalt-based solutions. Existing approaches often rely on explicitly modelling discrete fibres, leading to high computational cost and limited scalability, or neglect fibre-rebar interaction mechanisms altogether. This paper presents a numerical modelling framework for predicting the mechanical behaviour of basalt fibre and BFRP rebar reinforced concrete structural elements using a homogenised material representation for the fibre-reinforced concrete, coupled with explicit modelling of BFRP longitudinal reinforcement. The fibre contribution is incorporated through equivalent constitutive laws calibrated to represent the composite tensile and post-cracking response, enabling efficient simulation without explicitly modelling fibre dispersion. The numerical model is developed using finite-element analysis and validated against experimental data reported in the literature, covering key mechanical responses such as compressive, tensile, and bending behaviour. Comparisons between numerical predictions and experimental results demonstrate that the proposed modelling strategy can reliably capture load-displacement response, strength, and failure trends of hybrid basalt-based reinforcement systems. The study highlights the influence of fibre-enhanced matrix behaviour on stress transfer, crack control, and interaction with FRP reinforcement. The proposed framework provides a computationally efficient and transferable approach for analysing fibre-FRP reinforced concrete and contributes toward improved numerical representation of sustainable reinforcement systems in structural design and research.

**KEYWORDS**: Basalt fibre-reinforced concrete; BFRP reinforcement; Numerical modelling; Fibre-rebar interaction; Homogenised material modelling.

# NUMERICAL STUDY ON FAILURE MODES IN SLENDER FRP-RC COLUMNS USING FINITE ELEMENTS

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**ABSTRACT**

The fundamentals and standards for the practical design of concrete structures with Fiber Reinforced Polymer (FRP) bars as internal reinforcement have advanced in recent years, but they have not yet reached the same level of detail as Eurocode 2 for steel-reinforced concrete. An important prerequisite for construction with FRP reinforcement to become widely accepted is the availability of design rules for all known components, including short and slender compression members with and without bending moments. The well-known nominal curvature method for designing slender columns according to Eurocode 2 has recently been successfully adapted for columns with FRP Reinforced Concrete (FRP-RC). Furthermore, recent studies, have led to a proposal for extending Eurocode 2 annexure R for FRP-RC columns. However, the nominal curvature method does not provide any direct information on the failure mode, the type of equilibrium, the strains in the cross-section and the deformation at limit state. The latter is particularly of interest, as the deflection of FRP-RC columns with FRP bars may exceed that of steel reinforced columns due to the low modulus of elasticity of the FRP bars. This paper presents recent results of various nonlinear Finite Element (FE) calculations of slender FRP-RC columns and discusses the failure modes and the differences to columns with steel reinforcement at different slenderness ratios. Furthermore, the paper compares them with the results obtained using the direct curvature method, which was used to derive the equations for the nominal curvature method for FRP RC columns.

**KEYWORDS**: FRP-RC; Concrete columns; Failure modes; Nominal curvature method; Nonlinear FE analysis; Stability; Buckling; Material failure.

# CAPACITY AND DEMAND OF UHPC-FILLED, GFRP-REINFORCED SHEAR CONNECTIONS BETWEEN ADJACENT BOX BEAMS UNDER AASHTO TRUCK LOADING

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**ABSTRACT**

Accelerated Bridge Construction (ABC) increasingly relies on prefabricated structural components to reduce construction time and traffic disruption. Adjacent precast concrete box beams are commonly used in these systems because they enable rapid bridge assembly and efficient structural performance. The longitudinal connections between adjacent beams, commonly referred to as shear keys or closure joints, play a critical role in ensuring load transfer and composite action under vehicular loading. This study experimentally investigates the behavior of shear key connections filled with ultra-high-performance concrete (UHPC) and reinforced with glass fiber–reinforced polymer (GFRP) bars. Two full-scale specimens representing adjacent box beam connections were constructed and tested under transverse shear loading. The first specimen contained one layer of GFRP bars projecting from the precast segments and spliced within the UHPC joint, while the second specimen incorporated two layers of projecting GFRP bars located at the top and bottom of the flange and spliced within the joint. The tests evaluated cracking behavior, failure mechanisms, and ultimate load capacity. Results showed that cracking initiated at the beam–joint interface and failure was governed by GFRP bar slip within the UHPC joint followed by localized concrete crushing. Both specimens developed capacities significantly exceeding the factored transverse shear demand predicted using AASHTO provisions, confirming the effectiveness and reliability of UHPC–GFRP shear key connections for accelerated bridge construction applications.

**KEYWORDS**: Accelerated bridge construction; Box beams; GFRP bars; Experimental tests; Demand; Capacity.

# SHEAR CAPACITY OF CONCRETE BEAMS REINFORCED WITH FRP BARS AND BASALT MICROBARS

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**ABSTRACT**
The study was conducted to assess the shear capacity and the mechanical behavior of two-span beams reinforced with BFRP longitudinal bars made of concrete containing basalt microbars. The microbars are manufactured from fibers embedded in resin. They have lengths similar to fibers, but unlike fibers, they are characterized by spatial stiffness, which allows for the production of various microbar shapes. The aim of the study was to analyze the effect of adding basalt microbars to concrete on the shear capacity of beams. The test series included beams constructed with stirrups and beams without stirrups. In order to rationalize the content of the addition the concrete containing 3.5 kg of microbars per 1 $m^3$ of mix, was selected for testing. The tested beams had a total length of 3.20 m and a cross-section of 0.12 m wide and 0.20 m high. Based on the material tests, it was found that the addition of dispersed reinforcement (basalt microbars) to concrete improves its mechanical properties. Improved material properties lead to increased shear and bending capacities of the concrete beams and a reduction in beam deflection. It was shown that microbars control the cracking process and deformations in reinforced concrete beams and they can be effectively used as additional or only shear reinforcement.

**KEYWORDS**: Two-span concrete beam; BFRP reinforcement; Basalt microbars; Shear capacity.

# PUNCHING SHEAR MECHANICAL MODEL FOR FRP RC SLABS W/O SHEAR REINFORCEMENT UNDER CONCENTRIC LOADING


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## ABSTRACT

A punching shear strength mechanical model for reinforced concrete flat slabs with steel reinforcement, previously extended to Steel Fiber Reinforced Concrete, is further extended in this paper to the case of FRP reinforcement. The model is based on the Compression Chord Capacity Model (CCCM) originally developed for beam shear, but adapted to account for the differences in resisting actions between beam shear and punching shear, mainly due to the multi-axial stress state near the support. To extend the model to FRP bars, the significantly lower flexural stiffness of FRP reinforcement compared to conventional steel is considered; as a consequence, the contribution of aggregate interlock at failure is assumed negligible, leading to a slightly modified closed-form design equation. The possibility of flexure-driven punching failures is also addressed, considering in this case the linear elastic behavior of FRP reinforcement compared with the plastic response of steel. Validation of the new extension of the model was carried out by comparing theoretical predictions with results from 86 FRP-reinforced slab tests under concentric loading reported in the literature. In addition, comparisons were made with previously published punching-shear models, most of them of empirical or semi-empirical origin. The proposed model shows satisfactory performance, even though, being derived from a comprehensive preceding mechanical formulation, no coefficients were calibrated against the experimental results. This generality keeps the door open to further extensions and applications of the model to even more complex structural cases.



**KEYWORDS**: Concrete slab without shear reinforcement; Punching-shear strength; Fibre reinforced polymers; Slab-column connection.

# PUNCHING SHEAR MECHANICAL MODEL FOR FRP RC SLABS WITH SHEAR REINFORCEMENT UNDER CONCENTRIC LOADING

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**ABSTRACT**

A mechanical model for the punching shear strength of reinforced concrete flat slabs with flexural and shear Fiber Reinforced Polymer (FRP) reinforcement is presented. The model is developed as an extension of the Compression Chord Capacity Model (CCCM), originally formulated for steel-reinforced slabs and subsequently adapted to RC slabs with or without shear reinforcement, as well as to FRP-reinforced slabs slabs without shear reinforcement. The proposed extension accounts for the lower stiffness and linear-elastic behavior of FRP reinforcement, which significantly influence crack widths, stress redistribution, and the effectiveness of shear reinforcement in slab-column connections.

The punching shear resistance is expressed as the sum of a concrete contribution, governed by the behavior of the uncracked compression chord, and a shear reinforcement contribution associated with FRP stirrups or studs intersecting the critical punching crack. Particular attention is given to the effective stress that can be mobilized in FRP shear reinforcement, which is shown to be limited by strain compatibility rather than by material strength. In addition, upper-bound limits associated with maximum shear capacity and flexure-driven punching failure are incorporated to capture governing failure mechanisms.

Model predictions are compared with the limited experimental evidence available for FRP-reinforced slabs with shear reinforcement reported in the literature. Despite the scarcity of experimental data, the proposed model provides satisfactory agreement with test results and correctly identifies the governing failure modes. Owing to its mechanical basis, the formulation offers a consistent framework for future extensions to other specific cases, such as hybrid systems combining FRP bars with steel-fiber-reinforced concrete (SFRC) slabs.

**KEYWORDS**: Concrete slab with shear reinforcement; Punching-shear strength; Fibre reinforced polymer; Slab-column connection.

# POST-FIRE FLEXURAL PERFORMANCE OF GFRP-REINFORCED CONCRETE BEAMS: LAP SPLICE EFFECT

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**ABSTRACT**
This study investigates the post-fire flexural behavior of glass fiber reinforced polymer (GFRP) reinforced concrete beams with continuous and lap-spliced tension reinforcement. Four full-scale beams were cast using a calcareous aggregate concrete mix: two with continuous reinforcement and two with a 1000 mm midspan lap splice designed according to ACI 440.11-22. Two beams were tested under ambient conditions, while the remaining two were exposed to the ASTM E119 standard fire for 260 minutes before being tested to failure after cooling. Under ambient conditions, beams with continuous and lap-spliced reinforcement exhibited similar initial stiffness, but the lap-spliced beams showed reduced ultimate capacity due to bond-induced splitting at the splice region. Fire exposure caused a significant loss of flexural capacity, with the beams retaining only a small fraction of their original strength. Moreover, the failure modes after fire were strongly influenced by reinforcement continuity, with continuous bars failing by rupture and lap-spliced bars failing through splitting for the unexposed beam and slippage in the lap spliced region for the fire-exposed beam.

**KEYWORDS**: GFRP reinforcement; Lap splice; Post-fire flexural performance; Bond degradation.

# EXPERIMENTAL STUDY OF GFRP-REINFORCED LIGHTWEIGHT CONCRETE SLABS UNDER STATIC AND FATIGUE LOADS

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## ABSTRACT

This study investigated the structural performance of lightweight concrete bridge deck slabs reinforced with glass fiber reinforced polymer (GFRP) bars under static and fatigue loading. The objective was to assess the potential of combining lightweight aggregate concrete with non-corrosive reinforcement to create durable and efficient bridge deck systems.

All slab specimens were designed according to the geometry of typical girder bridge decks, with a theoretical span of 2.40 m, a width of 1.00 m, and a thickness of 18 ± 0.5 cm. The variables were limited to the type of concrete (normal-weight or lightweight) and the reinforcement ratio (number and diameter of GFRP bars). In the static program, seven slabs were tested, including three made of normal-weight concrete and four of lightweight concrete. Monotonic loading was applied until failure, allowing for the evaluation of cracking, deflections, capacity, and failure modes. The results confirmed stable performance, sufficient ultimate strength, and progressive failure development. In the fatigue program, seven slabs with identical geometry were prepared. Two served as static reference specimens, while five were subjected to cyclic loading to simulate repeated traffic. Controlled load cycles were applied while stiffness, crack development, and residual deflections were monitored. The slabs showed consistent fatigue performance, without abrupt strength reduction or excessive deterioration of the lightweight concrete matrix.

The findings demonstrate that GFRP-reinforced lightweight concrete slabs provide reliable structural behaviour in both static and cyclic conditions. Their reduced self-weight and high durability against corrosion make them a promising solution for sustainable bridge deck applications, offering long service life with reduced maintenance requirements.

**KEYWORDS**: Lightweight concrete; GFRP reinforcement; Bridge deck slabs; Static loading; Fatigue loading.

# BEHAVIOR OF GFRP REINFORCEMENT AS INTERFACE SHEAR REINFORCEMENT IN HIGH-STRENGTH CONCRETE COLD JOINTS

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## ABSTRACT

This study investigates the shear friction behavior of composite high-strength reinforced concrete (RC) joints incorporating glass fiber-reinforced polymer (GFRP) connectors as shear friction reinforcement. Four double L-shaped specimens were tested under monotonic axial loading using high-strength concrete of 55 MPa. The influence of different shear reinforcement types (i.e., GFRP headed-end bars, GFRP stirrups, steel stirrups, and no reinforcement) was evaluated at a constant reinforcement ratio of 0.66%. One specimen without shear connectors was tested to serve as a baseline. Although GFRP-RC specimens exhibited lower peak loads and a more brittle response than steel-RC counterpart, they showed notable post-peak load recovery due to the linear-elastic nature of GFRP. The results showed that all GFRP-RC specimens achieved comparable cracking loads. However, the GFRP headed-end connectors enabled substantial post-peak recovery, reaching a second peak of approximately 98% of the first peak load, outperforming closed stirrups, which reached 81% of the first peak load.

**KEYWORDS**: Glass fiber-reinforced polymer (GFRP); Shear friction; Composite element; Cold joint; High-strength concrete.

# BOND BEHAVIOUR OF MINERAL-IMPREGNATED CARBON FIBER REINFORCEMENT IN CONCRETE AFTER THERMAL ACTIVATION

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**ABSTRACT**
Numerous studies have shown that curing temperature critically governs cementitious interfacial bond development. Appropriately increasing the curing temperature activates the kinetics of cement hydration, thus enhancing the mechanical properties in a shorter period of time. Under optimized curing temperature and duration conditions, the mechanical property indexes of the traditional 28 d standard curing can be achieved within a few hours, with potentially simultaneous enhancement in interfacial bond strength of reinforced concrete. This study provided an experimental basis for breaking the limitations of the traditional long-term curing periods.
Specifically, this research investigated the interfacial bond behaviour between mineral-impregnated carbon fibers (MCF) and concrete after varying thermal activation temperatures (40 °C and 60 °C) and curing durations (4 h, 8 h and 16 h) by using one-sided pull-out tests at room temperature. At 40 °C, the shear bond strength showed a non-monotonic variation with curing durations, characterized by an initial decrease from 4 h to 8 h followed by a subsequent in-crease from 8 h to 16 h. In contrast, a continuous degradation trend was observed at 60 °C, indicating that elevated temperatures may accelerate interfacial performance deterioration. The shear bond strength after curing at 60 °C for 4 h reached 1.6 MPa, which corresponds to 61% of the 28 d reference group with 2.7 MPa. However, longer curing impairs the bond quality, with strength decreasing as curing extends. This decline likely results from microstructural degradation under prolonged high-temperature exposure, including increased porosity and microcrack formation, which outweigh the early benefits of accelerated hydration.

**KEYWORDS**: Bond behaviour; Mineral impregnation; Carbon fiber reinforcement; Thermal activation; Limestone calcined clay cement (LC3).

# LOCAL BOND BEHAVIOUR OF GFRP LAP SPLICES: A FINITE DIFFERENCE APPROACH

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**ABSTRACT**
Among the different structural aspects governing Glass Fibre Reinforced Polymer (GFRP) performance, lap splice behaviour remains one of the least investigated and most design-sensitive mechanisms. Current design provisions rely heavily on semi-empirical models, which often overlook the local mechanics of bond stress transfer and degradation along the splice length. To address this gap, this study develops a numerical model based on the finite difference method to simulate the force transfer mechanism in GFRP lap splices, incorporating any user-defined bond-slip law to describe the bar-concrete interaction. A parametric analysis investigates the influence of bond-slip law parameters, splice length, bar geometry, and material properties on the evolution of stress and slip. The simulations reveal pronounced non-uniformities in bond stress distribution, with localised peaks that govern slip development and overall splice capacity. The results demonstrate that increases in bar diameter, lap splice length, and concrete compressive strength lead to higher lap splice strength. The method has been proven to be a useful tool for assessing the influence of different bond parameters on splice performance, which is particularly relevant for GFRP reinforcement due to the wide range of bond-slip behaviours associated with the variety of surface treatments available.

**KEYWORDS**: Glass fibre-reinforced polymer (GFRP) reinforcing bar; Lap splice; Finite difference method; Bond behaviour; Numerical simulation.

# INVESTIGATION OF BEND STRENGTH OF GFRP BARS

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**ABSTRACT**

The construction industry has mainly used Glass Fiber Reinforced Polymer (GFRP) bars for straight longitudinal reinforcement; however, more recent applications have also seen their use in stirrups and shear reinforcement. The current study investigates the strength of GFRP bent bars using two different specimen configurations: stirrups and J-bars. The test specimens, consisting of #3 GFRP bent bars, were bonded with concrete near the bent location and subjected to a pullout force until the bar ruptured. A few specimens were also strain gauged to study the change in bar stress along the bend under increasing applied load.

The ultimate strength of bent bars was found to be approximately 53% of the straight bar strength and was independent of the specimen configuration. The observed strength reduction can be attributed to the stress concentrations in the bend portion and the material imperfections introduced during bar fabrication. Code-based equations—such as in CSA, ACI or JSCE—were found to be reasonably accurate in predicting the bend strength. This paper describes the experimental and analytical results in detail, including the bend strength, stiffness and the stress distribution along the bend.

**KEYWORDS**: GFRP bent bar strength; J-bar test; Stirrup test; Bent bar stiffness; Bend stress variation.

# BENT STRENGTH TESTING OF GLASS FIBER REINFORCED POLYMER BARS OF VARIOUS TAIL LENGTH

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**ABSTRACT**

GFRP bars are widely used as embedded reinforcement due to their inherent corrosion resistance. Bending these bars is only possible during manufacturing due to their thermoset resin matrix. Due to fiber kinking and transverse stresses, bent GFRP bars exhibit lower tensile strength than their straight segments; therefore, specialized test setups have emerged to assess the bent strength of GFRP bars. These setups, however, mainly focus on bent strength rather than the bond behavior of the bent bar, i.e., bond stiffness. To gain further insight into the bond behavior of bent GFRP bars, bent strength tests were performed, including slip measurement at both the loaded and un-loaded ends of the specimens. 12- and 16-mm-diameter GFRP bars were tested with tail lengths of 0, 5, and 10 times the nominal diameter (db). Four specimens of each type were tested, for a total of 24 specimens. It was found that, although longer tail length is beneficial, increasing the tail length from 5 db to 10 db increased bent strength by only 5% and 6% for 12- and 16-mm-diameter GFRP bars, respectively. Ultimate slip decreased by approximately 67 and 20% on the unloaded and loaded end side for both diameters, respectively. The findings suggest that a 5 db tail length is sufficient for the tested GFRP bar product to utilize most of its bent strength, due to its elastic be-havior, while there is only minor decrease in serviceability performance. Ductile pullout failure cannot occur, unlike with traditional steel bars, even with zero tail length.

**KEYWORDS**: Bent strength; GFRP; Bond; Laboratory experiment.

# DATABASE CLASSIFICATION OF BOND BEHAVIOUR OF FRP BARS WITH DIFFERENT SURFACE TREATMENTS

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## ABSTRACT

In reinforced concrete construction, the surface geometry of steel reinforcement has been standardized for decades, resulting in well-defined bond-slip relationships and reliable design models. This level of harmonization has not yet been achieved for fiber-reinforced polymer (FRP) bars. These bars are produced with a wide variety of surface treatment configurations, such as ribs, helical wraps or sand coatings and these configurations differ significantly between products. This lack of harmonization leads to a wide scatter in bond-slip behavior and complicates code implementation and comparative assessment. This work presents a systematic attempt to classify FRP reinforcement according to bond performance. A structured dataset is compiled from pull-out tests on GFRP bars with different surface treatments, bar diameters and concrete strengths. From each bond-slip curve, characteristic parameters are extracted, including initial stiffness, maximum bond stress, slip at peak and post-peak behavior properties. These parameters serve as the basis for grouping bars with similar behavior into welldefined categories. The results show that the investigated bar types can be consistently assigned to distinct response classes, providing a transparent basis for comparative assessment and future database expansion. The proposed classification framework supports the selection and calibration of representative bond–slip models and can contribute to future code development and to more reliable serviceability and ultimate limit state verification in FRP-reinforced concrete structures.

**KEYWORDS**: Fibre-reinforced polymer (FRP) reinforcement; Bond–slip behaviour; Surface treatment; Database.

# EXPERIMENTAL INVESTIGATION OF SHEAR FAILURE IN GFRP-REINFORCED CONCRETE BEAMS

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**ABSTRACT**

Despite extensive research, the mechanisms governing shear failure in concrete beams reinforced with longitudinal and transverse glass fibre reinforced polymer (GFRP) bars remain insufficiently understood. The interaction between bending moment and shear force produces a complex stress field, as shear transfer depends on the combined behaviour of concrete, transverse reinforcement, and, indirectly, longitudinal bars. Consequently, parameters such as reinforcement ratios, stirrup diameter, and spacing can significantly affect the shear response. Shear behaviour of beams reinforced with both steel and GFRP were investigated as a part of a broader research at Lodz University of Technology. The experimental program involved single-span, simply supported T-beams made of C50/60 concrete, tested under three-point static loading. To minimize arch action, the shear span-to-depth ratio (a/d) was set at 3.15, representing slender members.

In all beams, nearly vertical flexural cracks developed and propagated diagonally toward the supports. Strain measurements revealed similar flexural cracking loads for almost all of the beams. Then, shear cracks initiated at mid-depth, extending to the longitudinal reinforcement and the compression zone. As loading increased, the cracks advanced through the flange toward the load point, ultimately leading to shear failure.

Lower deflections were recorded with reduced stirrup spacing that increased stiffness. The location and inclination of the critical shear crack were influenced by both reinforcement type and transverse reinforcement ratio. These findings emphasize key differences between the shear behaviour of GFRP- and steel-reinforced beams and highlight the necessity of refining design models for GFRP-reinforced concrete structures.

**KEYWORDS**: GFRP reinforcement; Shear behaviour; RC beams; Experimental analysis; Crack development.

# Strengthening of concrete and masonry structures with FRP

# AUTOMATED STRENGTHENING AND REUSE OF SLABS FOR CIRCULAR CONSTRUCTION

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## ABSTRACT

The reuse of existing concrete components represents a key strategy for conserving resources and reducing $CO_2$ emissions in the construction industry. Horizontal elements, such as concrete slabs, offer particularly high potential for reuse, as they account for the largest volumetric share of existing building stock and are typically downcycled or discarded after demolition. This paper introduces a concept in which such components are extracted from existing structures and renewed through fully automated robotic processes, enabling their systematic reuse within a resource-efficient construction framework. The proposed strengthening method refers to a robotic process chain consisting of shotcrete with carbon reinforcement. It enhances the structural performance of reused elements. Based on results from manually executed strengthening methods, it is anticipated that both flexural and shear capacity could be significantly improved through robotic retrofitting. Digital design and fabrication technologies are expected to allow precise detection of geometric deviations in reused elements and enable adaptive adjustment of material application.

This conceptual approach outlines new structural possibilities for refurbishing existing concrete components while contributing to the advancement of circular construction practices. Robotic renewal with shotcrete and carbon reinforcement has the potential to become an innovative strategy to extend the service-life of slabs, conserve resources, and improve the environmental footprint of the construction sector. This paper presents a conceptual and process-oriented framework without experimental validation.

**KEYWORDS**: Robotic fabrication; Additive manufacturing; Shotcrete; Carbon-reinforced concrete; Concrete recycling; Structural strengthening; Circular construction.

# INVESTIGATION OF FATIGUE FAILURE MECHANISM OF RC DECKS STRENGTHENED WITH GRID-PATTERN AFRP SHEETS UNDER WHEEL LOAD FATIGUE

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## ABSTRACT

The externally bonded FRP (Fiber-reinforced polymer) sheet strengthening method has become a primary countermeasure against fatigue damage in reinforced concrete (RC) decks. Over the past decade, a technique bonding FRP sheets in a grid pattern has been developed, and its effectiveness has been confirmed. Along with this diversification of application methods, several organizations have conducted wheel load fatigue tests, accumulating data on fatigue durability. However, no unified failure mechanism has been found because each organization conducted its own evaluation individually.

In Japan, meanwhile, the road bridge design code transitioned from the allowable stress design method to the limit state design method in 2017, requiring RC deck strengthening design to comply with this performance-based system. Against this backdrop, joint research led by the Public Works Research Institute is revising the design manual for the externally bonded FRP sheet strengthening method based on the allowable stress design concept.

This paper examines the failure mechanism of RC decks with aramid FRP (AFRP) sheets bonded in a grid pattern on the concrete surface, under wheel load fatigue tests, with the aim of developing a fatigue life prediction method. Test results revealed that delamination of the sheets primarily initiated along the distribution reinforcement direction, expanded throughout that direction, and ultimately led to punching shear failure. Furthermore, it was also clarified that the distribution ratio of tensile force carried by the sheets in the distribution reinforcement direction increased significantly just before the failure. These findings give new perspective that contribute to developing a fatigue life prediction method for FRP-bonded RC decks.

**KEYWORDS**: Manual revision; AFRP sheets; RC deck; Sheet delamination; Punching shear failure.

# ANALYTICAL MODELLING AND EXPERIMENTAL VALIDATION OF CORROSION-DAMAGED RC COLUMNS REPAIRED WITH FRP

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**ABSTRACT**
This paper presents an analytical model for predicting the axial load capacity of reinforced concrete (RC) columns pre-damaged by corrosion and subsequently repaired using fiber-reinforced polymer (FRP) composite wraps. The model incorporates the primary effects of corrosion, including the reduction in steel reinforcement cross-sectional area, the decreased confinement effectiveness of corroded steel ties, and the concrete cover strength. Additionally, the model accounts for the confinement contributions provided by both the remaining steel ties and the externally applied FRP jacketing. Governing equations for confined concrete strength and ultimate strain are integrated while considering confinement stiffness ratios and code-prescribed limits on composite confinement stresses. An experimental program was conducted to validate the proposed model. The results demonstrated the effectiveness of FRP wrapping in enhancing the original load-carrying capacity of the corroded columns. A comparison between analytical predictions and experimental results showed good agreement, with an average analytical-to-experimental load capacity ratio of 0.89 and a coefficient of variation of 12%. The findings verify that the proposed analytical model provides a practical and reliable tool for assessing and designing corrosion-damaged RC columns strengthened with FRP composites.

**KEYWORDS**: Corrosion; Concrete; Columns; Repair; FRP.

# EXPERIMENTAL STUDY ON MECHANICALLY ANCHORED EBR CFRP-CONCRETE JOINTS AT ELEVATED TEMPERATURES

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## ABSTRACT

Externally bonded Carbon Fiber Reinforced Polymers (CFRP) are widely used to strengthen reinforced concrete members in flexure and shear because they offer high strength, corrosion resistance, and easy installation. However, these systems are vulnerable to premature debonding, which limits the stress developed in the laminate and undermines service performance. Mechanical anchorage is often introduced to delay or prevent debonding by providing normal pressure and friction, thereby improving utilization of the CFRP. As service temperature increases, the bond response can be altered. Although the temperature effects on unanchored externally bonded systems are relatively well documented, the mechanical robustness of anchored externally bonded laminates at elevated temperatures, including torque retention, adhesive softening, and reduced frictional resistance, has received little attention. This study addresses that gap by investigating the pullout performance of mechanically anchored externally bonded CFRP pultruded laminates at an elevated service level temperature. Twelve single shear specimens were tested, six unanchored and six anchored, with three replicates at 20 °C and three at 75 °C. Anchors were tightened to 10 N·m. The experimental results showed that heating up to 75 °C degraded the bond performance in both systems. For unanchored specimens, the ultimate load decreased by 10% and for the anchored specimens, the ultimate load decreased by 60% and the slip decreased by 10%, which suggests that the anchorage strength was significantly compromised at elevated temperature. The experimental results of the anchored configuration showed good agreement with the existing analytical equation at 20°C.

**KEYWORDS**: Externally bonded; CFRP; Laminate; Mechanical anchorage; Temperature.

# BOND–SLIP RELATIONSHIP FOR FRP SHEET–CONCRETE INTERFACES DERIVED FROM CONCRETE SURFACE FAILURE

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**ABSTRACT**
This paper proposes a new theoretical bond model that can replicate the debonding behavior of fiber-reinforced polymer (FRP) sheets. Unlike traditional methods, the model does not rely on bond stress–slip relationships obtained from bond tests; instead, it is based on fundamental mechanical principles. This study focuses on the failure characteristics of the concrete surface, where debonding of FRP sheets bonded to concrete is represented as a series of continuous saw-tooth fractures. This failure process is divided into a pre-peak and post-peak region, separated by the onset of saw-tooth cracking. By applying the principle of force equilibrium, considering the relationships between slip and strain, strain compatibility, and geometric conditions, as well as the correlation between slip and shear strain, the bond stress–slip relationship at the FRP sheet–concrete interface is theoretically derived by incorporating the energy equivalence condition together with the constitutive laws of the materials. Based on this debonding mechanism, a new bond model, called the "sawtooth model," is proposed. Numerical analysis of the FRP sheet bond test was then conducted using the sawtooth model. The results showed that the load–slip relationship and bond stress–slip relationship were in close agreement with the experimental data. The proposed sawtooth model can thus reproduce the debonding phenomenon.

**KEYWORDS**: Bond stress-slip relationship; Debonding mechanism; FRP sheet; saw-tooth; bond strength.

# MODELLING CRACKING AND DEBONDING IN FRP-STRENGTHENED RC TIES WITH A PHASE-FIELD–CZM APPROACH

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## ABSTRACT

Externally bonded fibre-reinforced polymer (FRP) laminates are increasingly used for the strengthening and rehabilitation of reinforced concrete (RC) structures. While their contribution to flexural and shear capacity has been widely studied, their effect on the serviceability behaviour, tension stiffening, crack spacing, crack width, and delamination evolution remains insufficiently understood. This study presents a 3D finite element (FE) framework in Abaqus for simulating the cracking behaviour of FRP-strengthened RC tension ties with the objective to provide a robust and physically consistent numerical tool for predicting its serviceability behaviour. The model combines a phase field (PF) formulation for concrete cracking with a cohesive zone model (CZM) to describe the bond-slip interaction and potential delamination at the FRP-concrete interface, while incorporating spatial heterogeneity of concrete through stochastic random fields. The numerical results of RC ties are validated against experimental data from tensile tests from the literature showing good agreement in terms of global load-strain response and localized crack development. Furthermore, a parametric investigation explores the influence of the FRP strengthening, in terms of fracture patterns and load-carrying capacity. The results indicate that the crack width and spacing are significantly influenced by the interfacial bond behaviour, underscoring the importance of accurate bond modelling for serviceability design.

**KEYWORDS**: RC cracking; Phase field (PF); Cohesive zone model (CZM); Bond behaviour; FRP strengthening.

# MINIMUM FRP CONFINEMENT REQUIREMENTS FOR FULLY STRAIN-HARDENING CONCRETE COLUMNS

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**ABSTRACT**
This study presents a practical and unified approach to determine the minimum level of fiber-reinforced polymer (FRP) confinement required to ensure a fully strain-hardening axial response in FRP-confined concrete columns. While excessive confinement is an uneconomical approach, insufficient confinement can lead to post-transition strain-softening or strain-softening followed by strain-hardening behavior, compromising structural safety. To addresses this challenge, the present study introduces a practical and unified approach for determining the minimum level of FRP confinement necessary to ensure fully strain-hardening axial behavior in FRP-confined concrete columns. A key contribution of this work is the development of a non-dimensional confinement stiffness-based index, which quantitatively integrates the effects of concrete compressive strength, cross-sectional geometry, including column dimension size, sectional corner radii and aspect ratio, and partially imposed FRP confinement arrangement, such as strip spacing. This index captures the combined influence of these factors on the axial stress–strain response, enabling a clear distinction between columns that exhibit desirable strain-hardening behavior and those prone to post-transition softening. Based on this threshold-based approach, a straightforward analytical expression is derived to estimate the minimum FRP thickness required to achieve fully strain-hardening behavior. The expression provides a practical tool for designers and engineers, allowing the optimization of FRP confinement systems for both safety and cost-efficiency. The study establishes a generalized, unified framework for assessing and optimizing FRP confinement, offering a clear guideline for both research and practical engineering applications in reinforced concrete column design.

**KEYWORDS**: FRP-confined concrete; Strain-hardening; Strain-softening; Confinement stiffness-based index; Minimum FRP thickness.

# INVESTIGATION OF FATIGUE FAILURE MECHANISM OF RC DECKS STRENGTHENED WITH GRID-PATTERN CFRP SHEETS UNDER WHEEL LOAD FATIGUE TESTING

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## ABSTRACT

The externally bonded FRP sheet strengthening method has become a primary countermeasure against fatigue damage in reinforced concrete (RC) decks. Over the past decade, a technique bonding FRP sheets in a grid pattern has been developed, and its effectiveness has been confirmed. Along with this diversification of application methods, several organizations have conducted wheel load fatigue tests, accumulating data on fatigue durability. However, no unified failure mechanism has been founded because each organization conducted its own evaluation individually.

In Japan, meanwhile, the road bridge design code transitioned from the allowable stress to the limit state design method in 2017, requiring RC deck strengthening design to comply with this performance-based system. Against this backdrop, joint research led by the Public Works Research Institute is revising the design manual for the externally bonded FRP sheet strengthening method based on the allowable stress design concept.

This paper examines the failure mechanism of RC decks with carbon FRP (CFRP) sheets bonded in a grid pattern on the concrete surface, under wheel load fatigue tests, with the aim of developing a fatigue life prediction method. Test results revealed that delamination of the sheets primarily initiated along the distribution reinforcement direction, expanded throughout that direction, and ultimately led to punching shear failure. Furthermore, it was also clarified that the distribution ratio of tensile force carried by the sheets in the distribution reinforcement direction increased significantly just before the failure. These findings give new perspective that contribute to developing a fatigue life prediction method for FRP-bonded RC decks.

**KEYWORDS**: Manual revision; CFRP sheets; RC deck; Strengthening; Fatigue.

# EFFECTIVENESS OF PARTIAL CONFINEMENT COVERING ONLY COMPRESSION ZONE

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## ABSTRACT

This study presents the findings of an experimental investigation into the effects of partial confinement of the compression zone in slender reinforced concrete (RC) shear walls using fiber-reinforced polymer (FRP) composites. Slender shear walls, which are widely employed as lateral load-resisting systems in mid- to high-rise structures, are particularly susceptible to premature compression failure and limited deformation capacity under seismic demands. The primary objective of this research is to enhance the structural performance of such elements by applying externally bonded FRP composites as a retrofitting strategy focused on confining the critical compression zones. To facilitate controlled experimental comparison, a simple novel test specimen configuration was developed and proposed specifically for this investigation. The testing regimen involved subjecting the specimens to monotonically increasing loads, allowing for a direct comparison of their performance. The experimental program comprised one unretrofitted control specimen alongside three geometrically identical specimens, each retrofitted with distinct FRP application schemes differing in wrapping configuration and anchorage type. The experimental results consistently demonstrate that external FRP wrapping combined with appropriate anchorage systems significantly improves the deformation capacity of the specimens. The findings underscore the effectiveness of partial FRP confinement as a viable and practical retrofitting technique, offering valuable implications for the seismic rehabilitation of existing RC structures.

**KEYWORDS**: Compression zone; Confinement; Fiber reinforced polymer (FRP); Reinforced concrete shear wall.

# MODEL ASSESSMENT FOR FIBRE REINFORCED POLYMER (FRP) LIGHTLY CONFINED CONCRETE

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## ABSTRACT

Design models for FRP confined concrete are typically calibrated with moderate to heavy confinement ratios ranging between 1.5 and 4. Although concrete lightly confined by FRP has not been specifically investigated, this type of configuration has several structural benefits. For example, with a given strength demand, light confinement could produce larger ultimate strain (deformability), ductility, and energy absorption capacity due to the slow strain hardening development. Given that the demand for concrete strength enhancement in practical retrofit design is usually low and limited by the capacity of adjacent members, there is a strong potential for lightly confined concrete to have wider applications in the strengthening field. Of increasing importance, systems with a lower confinement may also present a more environmentally friendly solution by minimising the materials to achieve the design requirements. Despite these potential benefits a comprehensive understanding of low confinement system has not yet been formed. Experimental results suggest that simple extrapolation of current models to the low confinement range is unreliable because of the distinct dilation behaviour by the low jacket stiffness. To better understand the concrete lightly confined by FRP, test data is collated and analysed to identify key differences in the prediction of ultimate stress and strain and requirements for future research.

**KEYWORDS**: FRP; Confinement; Lightly confined concrete; Ductility; Stress-strain model.

# INVESTIGATION ON THE UTILIZATION AND DETERIORATION CONDITIONS OF THE EXTERNALLY BONDED FRP SHEET STRENGTHENING METHOD

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**ABSTRACT**

The externally bonded FRP sheet strengthening method has been widely applied to the repair and reinforcement of concrete bridge components, such as decks and girders, due to the excellent properties of FRP materials, including high strength, corrosion resistance, and light weight. However, deterioration phenomena such as debonding and delamination, which may reduce strengthening effectiveness and long-term durability, have also been reported. It is necessary to ensure construction quality, improve maintenance practices, and establish procedures to ensure durability, thereby preventing these issues from arising. This paper reports the investigation results on the actual utilization and deterioration conditions of the externally bonded FRP sheet strengthening method applied to concrete bridge members in Japan. This investigation was conducted as part of efforts to revise the manual related to the externally bonded FRP sheet strengthening method for concrete bridge members in Japan. The investigation results revealed that concrete decks were the primary application targets, and carbon fiber sheets were the most commonly used reinforcement material. For concrete decks, grid-pattern application was more frequently used than full-surface application. Furthermore, many deteriorations were confirmed to be caused by poor adhesion at the interface between existing concrete and the FRP sheet, as well as insufficient removal of deteriorated concrete during installation. Based on these results, the investigation study was conducted into the degradation mechanisms and approaches to ensuring durability. On the other hand, many bridge inspection records lacked sufficient descriptions of FRP sheet deterioration, highlighting the need to clarify inspection and documentation items and methods.

**KEYWORDS**: Manual revision, FRP sheets, Deterioration Cases, Utilization Status, Degradation mechanism.

# EFFECT OF ANCHOR LOCATION ON INTERMEDIATE CRACK DEBONDING IN CFRP-STRENGTHENED RC BEAMS

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## ABSTRACT

In strengthened reinforced concrete members that have already experienced loading, the existing crack distribution plays a decisive role in the effectiveness of mechanically anchored externally bonded reinforcement CFRP (EBR-CFRP) systems. This study investigates the influence of anchor placement on the intermediate crack debonding (ICD) capacity of CFRP-strengthened reinforced-concrete beams. A previously developed numerical model for ICD prediction is coupled with a metaheuristic optimization algorithm to identify anchor configurations that maximize the predicted debonding load for a previously tested beam representing a rehabilitation scenario with an established crack pattern.

The results show that anchor effectiveness is governed by local variations of FRP tensile force between adjacent cracks, with anchors placed on the high-force side of critical crack intervals providing the greatest increase in load capacity. The optimized configuration concentrates anchors in regions of higher force gradients near the loading zones, delaying ICD and increasing the predicted load capacity without increasing the number of anchors.

**KEYWORDS**: CFRP; Debonding; Hybrid bonded FRP; Anchor; Flexural performance.

# A COMPARATIVE STUDY ON PERLITE STRENGTHENED RC T- BEAMS ANCHORED WITH U-WRAP AND FIBER ANCHORS

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## ABSTRACT

The use of CFRP materials has been well studied for normal-weight concrete beams. However, the performance of CFRP sheets and anchors has not been fully explored for lightweight concrete beams. Specifically, for Perlite concrete, comparisons of the flexural performance between U-wrap and fiber anchors have not yet been addressed. Accordingly, this study investigates a novel implementation to improve the performance of U-wrap and fiber anchors installed on sand lightweight Perlite concrete beams. Two series were prepared and tested in flexure under four-point loading. The first series included six full-scale T-beams. The first beam served as the control specimen, the second was strengthened with two CFRP sheets only, and the remaining beams were anchored using U-wraps applied in various configurations. The second series consisted of another six full-scale beams with identical details to series one, but the anchored specimens were secured with fiber anchors, using the same anchorage arrangements as in series one. The results showed improvement in the flexural capacity as the number of U-wrap anchors increased. The use of U-wraps resulted in improved confinement of the beam web, contributing to greater load-carrying capacity. However, the increase in the case of fiber anchors did not noticeably enhance the ultimate capacity due to the lack of aggregate interlock. Experimental results were also compared with numerical and analytical models for a deeper insight into sand Perlite concrete behavior.

**KEYWORDS**: Perlite concrete; T-beam; U-wrap anchorage; Fiber anchors; Flexural performance.

# STRAIN BEHAVIOUR OF EXTERNALLY BONDED FRP SHEAR REINFORCEMENT ON PRESTRESSED CONCRETE I-GIRDERS

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## ABSTRACT

I-shaped concrete girders are widely used in bridge and roof constructions. However, strengthening these girders in shear with externally bonded fiber reinforced polymer (FRP) systems can be challenging due to the premature debonding at the web-flange corners of the cross-section. Over time, various anchoring solutions have been developed to mitigate early debonding and enhance the effectiveness of FRP shear reinforcement. These anchorage systems play a crucial role in im-proving the performance of externally bonded FRP systems. This paper investigates the strain behaviour of FRP shear reinforcement on large-scale prestressed concrete I-girders and investigates the effect of FRP spike anchors and epoxy-bonded infill concrete blocks. Additionally, the contribution of shear reinforcement on I-shaped concrete girders is evaluated using the truss analogy, thereby providing insights into the design of FRP shear reinforcement.

**KEYWORDS**: FRP shear reinforcement; I-shape concrete cross sections; Early debonding; Anchorage; FRP strain.

# EFFECT OF HIGH TEMPERATURE AND HUMIDITY ON AXIAL BEHAVIOR OF FRPJACKETED LOW-STRENGTH CONCRETE: A PRELIMINARY EVALUATION

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**ABSTRACT**
Ensuring the seismic safety of structures that have been exposed to high humidity and temperature is a significant engineering challenge, particularly in the context of strengthening existing structures. Fiber-reinforced polymer (FRP) composites have gained widespread use in structural strengthening applications due to their numerous advantages over traditional methods, including minimal adverse effects on the dynamic characteristics of the structure and reduced volumetric losses. However, further research is needed to assess the performance of FRP strengthening systems under varying environmental exposure conditions. This study investigates the influence of high temperature and humidity on the strengthening performance of carbon FRP (CFRP) composites via the experimental campaign of uniaxial compression test of jacketed low-strength concrete cylinders. Low-strength concrete was widely used in existing structures around seismic regions of Turkey. A total of three concrete cylindrical specimens were jacketed externally with unidirectional woven CFRP fabrics and subjected to different temperature and humidity conditions. While some specimens were stored under standard laboratory conditions (24°C, 55% RH), others were exposed to high-temperature and high-humidity conditions (90°C, 80% RH) for certain durations The effects of these exposure conditions on the axial behavior of CFRP-jacketed specimens are evaluated through concentric compression tests. This study provides detailed insights into the effectiveness of CFRP-jacketing on the axial behavior of concrete members that have been exposed to high humidity and temperature.

**KEYWORDS**: Carbon fiber reinforced polymer (CFRP); High temperature; High humidty; Structural strengthening; Low-strength concrete.

# NUMERICAL MODELLING OF HYBRID BONDED CFRP-TO-CONCRETE JOINTS BETWEEN CONSECUTIVE CRACKS

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**ABSTRACT**
The strengthening of concrete structures with Carbon Fibre Reinforced Polymers (CFRP) has grown worldwide. In the case of a flexurally-strengthened reinforced concrete (RC) beam, the CFRP strip is externally bonded to the concrete surface, and the bond between the CFRP and the concrete substrate plays a critical role in the success of the strengthening technique. However, CFRP strips tend to debond prematurely from the concrete. Therefore, mechanical anchorages have been used to delay or even prevent debonding. Known as hybrid bonding (HB), the deboning process of the HB CFRP-to-concrete joints in a flexurally-strengthened RC beam remains poorly understood. Therefore, a numerical model based on the Finite Difference Method (FDM) to simulate the debonding process in HB CFRP-to-concrete joints is proposed. The model is based on a new nonlinear bond-slip relationship that considers the influence of fracture mode I on mode II by using the Mohr-Coulomb criteria. The influence of the loading condition, consistent with the constant or variable bending moment of the beam, crack spacing and position of the mechanical anchorage between consecutive cracks, is analysed. For validation purposes of the model, the results obtained from a series of generated cases were compared with those obtained from the Finite Element Method (FEM). The proposed model was also used to predict the maximum load of an HB RC beam, and a fair agreement was achieved.

**KEYWORDS**: CFRP; Debonding; Intermediate crack debonding; Bond-slip law; Numerical modelling.

# Effect of extreme events on FRP reinforced/strengthened concrete and masonry structures

# REHABILITATION OF DAMAGED REINFORCED CONCRETE COLUMNS WITH EXTERNALLY BONDED FRP

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**ABSTRACT**

The study concerns the post-seismic repair of reinforced concrete columns using PRF reinforcement systems. Fiber Reinforced Polymer (FRP) has been widely applied in seismic retrofitting of concrete structures due to its advantages such as lightweight, high strength, corrosion resistance, and ease of construction. In recent years, numerous experimental and analytical studies have demonstrated the benefits of FRP retrofitting in improving the seismic capacity of RC structures but mainly for retrofitting structures that were not damaged. The paper deals with the analysis of the mechanical behavior of reinforced concrete columns repaired by externally bonding PRF composite reinforcement. The strengthening is designed according to Eurocode 8 part 3 and Eurocode 2 appendix J. The columns were previously tested in combined bending through static and cyclic tests, leading to a 20% loss of strength under horizontal pushing force. The loading includes a constant vertical load of the order of 10% of the compressive strength of the concrete and a horizontal load of the push-pull type. Subsequently, the columns are repaired with a mortar to reconstruct the concrete area that suffered compression damage, and then reinforced by bonding carbon fabrics in the tension zone. The reinforcement is completed with confinement by PRF. The columns to basement is also strengthened by FRP anchor in order to limit the uplift of the columns and increase the tension capacity. The columns are retested to evaluate their performance once repaired. The results demonstrate the performance of PRF reinforcement systems. A FEM model is used to better understand the contribution of FRP.

**KEYWORDS**: RC columns; FRP; Repair; Experimental testing; Seismic retrofitting.

# FRP STRENGTHENING OF RC FRAMES UNDER CYCLIC LOADING

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**ABSTRACT**
This study investigates the cyclic performance of reinforced concrete (RC) sway frames strengthened with fibre-reinforced polymers (FRP). Medium-scale RC specimens were constructed at approximately 1:3 scale of a typical single-storey frame and tested under quasi-static cyclic loading following ACI 374.1 guidelines, with drift ratios applied up to 4.5%. The experimental programme included an unstrengthened control frame, a specimen with combined CFRP plates and GFRP wrapping, and a hybrid system that combined CFRP plates, GFRP wrapping, and mechanical base restraint using steel angles. Load–displacement responses were recorded and analysed to evaluate capacity, drift behaviour, and energy dissipation. The CFRP plate–GFRP wrapping delivered notable improvements, raising peak resistance by around 26% and delaying strength loss. The hybrid configuration achieved the most significant enhancement, with more than 80% improvement in peak resistance and retention of capacity at drift levels where the control had already degraded. Energy dissipation was also enhanced across all strengthened specimens, with the hybrid scheme sustaining fuller hysteresis loops into the large drift range. The novel contribution of this research lies in presenting a comparative experimental dataset that systematically quantifies the seismic performance of different FRP configurations for sway frames. These insights provide new evidence to guide selection of retrofitting schemes aimed at improving the seismic resilience of RC frame structures.

**KEYWORDS**: Reinforced concrete (RC) frames; Fibre-reinforced polymer (FRP) strengthening; Cyclic loading; Drift capacity; Seismic retrofitting.

# EXPERIMENTAL CYCLIC BEHAVIOR OF AN I-SHAPED GFRP-REINFORCED CONCRETE WALL

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**ABSTRACT**
Steel-reinforced concrete structures exposed to highly corrosive environments require frequent maintenance, which results in substantial costs for the governmental agencies in charge of public infrastructure. One potential solution to minimize this issue is the use of Fiber-Reinforced Polymer (FRP) reinforcement bars instead of steel reinforcement due to the FRP's high resistance to corrosion. Nevertheless, the application of FRP reinforcement in columns and walls has remain limited, particularly in seismic-prone areas, due to the brittle behaviour and relatively low stiffness of FRP bars. In contrast, in regions of low to moderate seismicity, the lateral displacement capacity and energy-dissipation of FRP-reinforced concrete members may be compatible with the demands imposed on vertical load-bearing members. As part of a research program aimed at evaluating the performance of concrete walls reinforced with glass fiber-reinforced polymer (GFRP) bars for structures located in low and moderate seismic areas, a scaled 3.5 m high by 1.5 m long I-shaped wall was densely instrumented and subjected to a cyclic lateral displacement protocol under constant axial load. The wall cross-section was designed to maximize the member's lateral stiffness and force capacity. This paper shows some preliminary test results, which indicate a limited but non-negligible nonlinear response and dissipation capacity, primarily driven by extensive concrete cracking. The appreciable deformation capacity of this prototype wall, combined with very limited residual drifts from self-centering response, suggests that the use of GFRP-reinforced concrete walls may be feasible in low-to-moderate seismic hazard regions, where the lateral deformation demands are expected to remain well below the maximum value observed in this study.

**KEYWORDS**: Reinforced concrete wall; Thermoplastic GFRP reinforcement; Seismic response; Reverse cyclic tests; I-shape section.

# POST-EARTHQUAKE RESIDUAL DISPLACEMENT ANALYSIS OF FRP-CONFINED HYBRID REINFORCED BRIDGE COLUMNS

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## ABSTRACT

Residual displacement in bridge columns after severe earthquakes significantly impairs structural serviceability and increases repair costs. To address this challenge, this study investigates FRP-confined hybrid reinforced concrete (HRC) bridge columns that combine external FRP confinement with internal hybrid longitudinal reinforcement of FRP and normal-strength steel bars. The configuration targets improved resilience under near-fault ground motions with strong velocity pulses. A nonlinear finite-element model with progressive material damage in FRP and concrete was developed and rigorously validated against both shake-table and quasi-static experiments. Using this modelling method, sixteen full-scale columns were analysed by systematically varying hybrid reinforcement ratio (FRP-to-steel), conventional steel reinforcement ratio, and FRP confinement height. Twenty-two pulse-type near-fault records were employed to quantify effects of these design parameters on dynamic response characteristics and residual displacement. Results reveal that increasing the hybrid reinforcement ratio substantially mitigates residual displacement, with an optimal range of 0.4–0.6 that balances performance and economy. Conversely, increasing only the conventional steel reinforcement ratio reduces peak displacement but yields marginal decreases in residual displacement. Extending the FRP confinement height provides limited additional benefit for residual-displacement control. These findings clarify the governing mechanisms by which key design parameters affect post-earthquake performance and provide design suggestions for FRP-confined HRC bridge columns subjected to near-fault seismic hazards. The work advances resilience-oriented seismic design for critical bridge infrastructure by innovative applications of FRP materials and a validated computational framework.

**KEYWORDS**: Residual displacement; FRP-confined columns; Hybrid reinforcement; Near-fault ground motions; Seismic resilience.

# FRP prestressed concrete structures

# STRENGTHENING AND REPAIRING PRESTRESSED CONCRETE BEAMS WITH CFRP: A COMPREHENSIVE REVIEW

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**ABSTRACT**

Prestressed concrete (PSC) is widely used in structures such as long-span bridges, where the prestressing force is used to control cracking, reduce deflections, and improve safety and serviceability under loads. However, many PSC bridges suffer from deterioration due to aging, overloading, environmental exposure, and inadequate maintenance practices, which can lead to damage. Since complete replacement is often expensive and disruptive, strengthening and retrofitting efficient alternatives for structural repair. Carbon Fiber Reinforced Polymer (CFRP) has emerged as a leading solution for flexural and shear strengthening and retrofitting due to its high strength-to-weight ratio, corrosion resistance, and ease of application. Many studies have experimentally examined the strengthening of PSC structures using CFRP, with a primary focus on externally bonded (EB) and near-surface mounted (NSM) methods. This study aims to summarize existing literature on CFRP applications for strengthening both virgin and pre-damaged PSC beams under different techniques. It assesses the performance of different CFRP forms (like sheets and laminates) and techniques, examines the costs of strengthening approaches, and highlights their limitations. It also highlights existing knowledge gaps and suggests future research paths to aid in developing design guidelines for FRP-strengthened structures. This review establishes CFRP as a reliable, adaptable, and high-performance solution for extending the service life of PSC structures across diverse conditions.

**KEYWORDS**: PSC beams; Pre-cracking; CFRP strengthening; Flexure; Shear.

# COMPARISON OF FLEXURAL BEHAVIOR OF PRESTRESSED CONCRETE BRIDGE BEAMS WITH DIFFERENT PRESTRESSING STRAND MATERIALS

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**ABSTRACT**

To avoid deterioration, especially in aggressive environments, non-corrosive materials are always sought to substitute for traditional internal reinforcement for concrete structures. Non-corrosive internal reinforcement alternatives include epoxy-coated steel, Fiber Reinforced Polymers (FRP) composite materials, and different types of stainless steel (SS). Successful employment of such non-corrosive internal reinforcement for concrete bridges can alleviate the maintenance and rehabilitation costs burden that strains bridge owners' budgets. Two issues are always raised with the aforementioned non-corrosive internal reinforcement alternatives. First, the ductility of flexural members reinforced or prestressed with these materials has been questioned. Second, the additional cost associated with using them is typically brought up in alternatives discussions. The first issue has been studied and information can be found in the literature. To assist in conducting comparative cost analyses, this paper looks at the differences in the amount of prestressing strands for the aforementioned non-corrosive materials in addition to traditional carbon steel strands. Six bridge designs are selected to cover different span lengths and cross section types. The results show that bridge beams prestressed with Carbon FRP (CFRP) and stainless steel (SS) strands experience substantial deformations prior to failure, albeit less than similar beams prestressed with traditional carbon steel (CS) strands. The lower deformations can be addressed by adjusting the design factors to ensure appropriate reliability index values for this type of behavior. Quantities of CFRP, SS, and CS strands are presented for the six bridges to assist in comparing their initial costs to lifetime maintenance savings as a corrosion mitigation solution.

**KEYWORDS**: Composite materials; Prestressed concrete; Corrosion; Bridges.

# NUMERICAL OPTIMIZATION OF A NOVEL WEDGE-BARREL ANCHOR SYSTEM FOR CFRP BARS

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**ABSTRACT**

In the last few decades, fiber reinforced polymer (FRP) bars have gained popularity in prestressed concrete (PC) applications due to their high durability in harsh environments. Among them, carbon fiber reinforced polymer (CFRP) bars may be considered the most promising thanks to their high tensile strength, high elastic modulus, low creep deformation, and excellent resistance to fatigue. However, despite these advantages, anchoring CFRP tendons to concrete remains challenging due to their anisotropic behavior and low strength in the transverse direction. Compared to bonded anchors, mechanical anchors are generally preferable in practice since they are easy to install and offer the possibility of being replaced after the tensioning phase.

This paper describes the development of a novel wedge-barrel anchor system for CFRP bars. The system is characterized by reusable components made of brass alloy wedges and steel barrel. Preliminary quasi-static tensile tests were performed on CFRP bars anchored with the proposed system, and the results were used to develop and validate a 3D finite element (FE) model. The numerical simulation provided valuable information regarding the contact stress distribution between the bar and wedges. Additionally, the model guided the optimization of the anchor geometry, leading to a more uniform stress distribution with reduced peak stresses.

**KEYWORDS**: CFRP; Prestressed concrete; Mechanical anchor; Wedge-barrel; FE-model.

# BEHAVIOR OF GIRDERS PRESTRESSED WITH UNBONDED CFRP TENDONS: DEFORMATION-BASED APPROACH

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**ABSTRACT**

Over the past few decades, carbon fiber–reinforced polymers (CFRPs) have emerged as a promising alternative to conventional steel reinforcement and prestressing materials in concrete structures, primarily due to their superior corrosion resistance, high tensile strength, and lightweight characteristics. Their use offers an effective solution to problems of environmental durability and service life reduction commonly observed in steel-prestressed bridge girders. Despite extensive research on CFRP applications in structural elements, significant gaps remain in understanding the flexural response of large-scale bridge girders prestressed with unbonded CFRP tendons. This paper investigates the overall flexural behavior of simply supported composite bridge girders prestressed with CFRP tendons, focusing particularly on systems utilizing unbonded configurations. The novel unbonded post-tensioning system introduces analytical complexities due to strain incompatibility between the unbonded tendons and the surrounding concrete. To overcome these challenges, a modified deformation-based analytical approach is proposed and experimentally validated. The study combines detailed analytical modeling with an experimental program involving full-scale composite bridge girders tested under monotonic loading to evaluate flexural behavior, load-deflection response, cracking, and ductility performance. The results demonstrate good agreement between analytical predictions and experimental observations, confirming the accuracy and applicability of the proposed deformation-based approach. Utilizing idealized curvature diagrams, the method efficiently predicts moment capacity, deflection, and ductility/deformability levels across various limit states. The results underscore the potential of CFRP prestressing systems to enhance the strength, durability/deformability, and serviceability of bridge structures, providing a practical and reliable framework for future design and implementation of corrosion-free prestressed concrete girders.

**KEYWORDS**: CFRP tendons; Unbonded prestressing; Post-tension; Deformation-based analysis; Bridge girder; Flexural behavior.

# Design codes and guidelines, regulatory assessment

# AN OVERVIEW OF THE NEW ACI CODE 440.13 ON FRP STRENGTHENING

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**ABSTRACT**
Fiber-reinforced polymer (FRP) systems have long been used to strengthen and retrofit concrete structures. Recognizing their importance, the American Concrete Institute (ACI) first published design guidance for these systems in 2002. Now, to help support efforts to codify repairs to existing structures, ACI has introduced ACI CODE 440.13-24, a mandatory-language standard that covers the design of FRP systems for structural strengthening. Developed to align with ACI CODE 562 on concrete repair, this new code is expected to be adopted by jurisdictions across the globe, establishing enforceable requirements for FRP strengthening. This paper provides an overview of ACI CODE 440.13, including its scope, the materials and systems covered by the code, and applicable strengthening techniques. The discussion will also address how the code interacts with related codes and standards from ACI, ASTM, and other international bodies. Finally, considerations unique to FRP applications—such as fire resistance, bond performance, and inspection requirements—will be highlighted to illustrate how these issues are addressed in the new code. Topics for future editions of the code and timeline for these changes will also be presented. This paper will clearly illustrate how the code will be implemented, the important technical requirements in the code, and practical aspects of the code.

**KEYWORDS**: FRP Strengthening; Codes; Regulatory; Fire; Inspection.

# AN UPDATED DESIGN APPROACH FOR FIBER ANCHORS FOR STRENGTHENING RC STRUCTURES WITH EB-FRP

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## ABSTRACT

As the advantages of anchoring externally bonded fiber reinforced polymer (EB-FRP) have become increasingly apparent, designers are starting to use fiber (spike) anchors to enhance the performance of EB-FRP strengthened members. Recent design codes, such as ACI CODE 440.13 and fib Bulletin 90 now contain preliminary provisions for fiber anchors. In 2019 the authors published a detailed methodology for designing embedded fiber anchors for use with EB-FRP strengthening of reinforced concrete structures. Since then, substantial testing has been conducted around the world to investigate and validate the design methodology, demonstrating excellent correlation of the results with calculated values. As part of all this experimental work, additional facets of design have been identified. Also, the industry has become aware that a standardized approach to determining the material properties of fiber anchors is essential for any design methodology to be useful. In response, ACI Committee 440 will soon publish a material specification to inform the industry about minimum requirements for the constituent materials that comprise fiber anchors and standard test methods to qualify fiber anchors. The authors have revisited the 2019 design methodology considering this new information and have updated the design approach accordingly. This paper describes expected failure modes for embedded fiber anchors, required design parameters and mechanical properties, as well as updated empirical design equations to complement the complete design methodology presented in the 2019 paper.

**KEYWORDS**: EB-FRP; Fiber anchors; Failure modes; Mechanical properties; Strengthening, Design.

# GFRP DEVELOPMENT LENGTH TABLES FOR PRELIMINARY DESIGN

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**ABSTRACT**
When considering steel-reinforced concrete, designers use tables included in design handbooks to quickly estimate development and splice lengths for steel bars during preliminary design. These tables are useful when assessing design feasibility but similar tables for concrete reinforced with glass fibre-reinforced polymer (GFRP) bars are not in wide use. Lack of these resources for GFRP creates barriers for engineers interested in exploring GFRP-reinforced concrete in design practice. This paper presents methods describing how development length tables similar to those used in steel-reinforced concrete design were created for GFRP-reinforced concrete beams. Tables were developed for GFRP bars that comply with either ASTM D7957 or ASTM D8805 with two sets of tables (based on ACI CODE-440.11 and CSA S806 respectively) created. Tables allow for both tension and compression-controlled beams to be considered which adds insights beyond similar tables used in steel-reinforced concrete. The required GFRP tensile stress was found to be the main challenge when creating tables that are reasonably accurate yet simple enough for preliminary design. The methodology used to create these tables is described such that future changes to development length expressions in design codes and standards can be included. Using these charts, even more simplified methods for estimating development length for GFRP-reinforced concrete beams are provided to aid in assessing GFRP's feasibility in a project. With these resources, designers will be able to develop preliminary designs for GFRP-reinforced concrete members quicker than current practice.

**KEYWORDS**: Development length; Design aid; GFRP bars; Codes and standards.

# EVALUATING EXTERNALLY BONDED FRP SHEAR STRENGTHENING MODELS OF RC BEAMS USING THE COMPREHENSIVE MULTI-METRIC COMPARATIVE (CMMC) METHOD


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## ABSTRACT

The accurate assessment of shear strength in reinforced concrete (RC) beams rehabilitated in shear with externally bonded (EB) fibre-reinforced polymers (FRP) remains an ongoing challenge. Different EB models have been developed to predict the EB FRP shear contribution, yet their predictive capability often varies with beam geometries, strengthening configurations, and the absence/presence of transverse reinforcement. Comparisons until now have relied mainly on Mean of strength ratios and Coefficients of Variation (CoV), which, do not convey the overall accuracy, safety, and statistical consistency required for detailed comparison purposes. Using the Comprehensive Multi-Metric Comparison (CMMC) approach, recently devised for evaluating one-way shear strength models for unstrengthened RC beams, this study critically evaluates current EB shear-strengthening models. The CMMC framework uses deviation-, correlation-, and error-based metrics, safety assessments, including failure probability, percentage of satisfactory predictions (*PSP*), fifth percentile of strength ratio ($P_{5th}$), and statistical tests such as Kolmogorov-Smirnov distance, Friedman mean rank analysis, and Pareto front ranking. By extending beyond the typical single- or dual-metric ratings, the CMMC approach enables a balanced comparison of the performance of models in terms of accuracy, safety, and statistical consistency. The findings highlight the importance of using multi-metric evaluation methods in the comparison of EB shear-strengthening models, with greater insight into their suitability for standard codes and everyday engineering practice. Consequently, the proposed analysis shifts the balance towards stronger and performance-based design guidelines and standards for EB FRP shear strengthening.



**KEYWORDS**: Externally bonded; Shear strengthening; Fibre-reinforced polymers; Reinforced concrete beams; Shear model; Comprehensive multi-metric comparison.

# ECONOMICAL DESIGN FOR R/C STRUCTURES ACCORDING THE NEW EN1992-1 ANNEX R

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**ABSTRACT**

In the last ten years the new Eurocode 2 has been developed with new refined regulations and with the inclusion of different new materials. The first time also non metallic reinforcement has been integrated in Annex J (external reinforcement) and R (internal reinforcement). Strength issues have been elaborated to fit as well to international standards (like ISO 14706, ACI 440, CSA S806) as to the European assessment Document. Bond issues and many other regulations are more or less in accordance to the regulations for reinforcing steel.

In the last time several comparative studies are published that the come to the conclusion , that the regulations for strength are way to conservative, while regulations for the crack width or deflections are comparable to other regulations.

In this paper is shown how a performance based strength design can lead to an economical design if all tests which are also needed for the international guidelines are fulfilled or special tests according the EAD are made. Additional rules for economical and safe embedment length design are also included. The author has been member of the TC250 which has elaborated the Annex J and R. He gives background to the safety factors and the needed tests for the determination of the different factors: $C_e$, $C_c$ and $C_t$, studies are given in this work.

**KEYWORDS**: EC2; Annex R; Strength; EAD; GFRP reinforcement.

# Inspection, monitoring and quality assurance

# FAILURE MODE ANALYSIS OF NSM STRENGTHENED CONCRETE BEAM USING COMPUTED TOMOGRAPHY

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## ABSTRACT

The application of fiber-reinforced polymer (FRP) strips for near-surface-mounted (NSM) strengthening of structural concrete elements is constrained by limited access to the concrete surface where the reinforcement is applied. Consequently, it is difficult, if not impossible, to fully assess the bond condition between the FRP strip and the concrete surface through visual inspection alone. This assessment is crucial for verifying the mechanisms of force transfer between externally bonded reinforcement and the strengthened structure. One potential solution to this problem is the use of non-destructive testing (NDT) methods based on computed tomography (CT). This paper presents new inspection methods using CT technology, with a focus on the analysis of the failure mode in an NSM-strengthened beam. In particular, the failure mode and bond behavior are investigated, with emphasis on crack geometry and aggregate interlocking. For this purpose, an XXL-CT device was employed to scan an FRP-strengthened beam following a four-point bending test, and the data were analyzed using image-processing methods.

**KEYWORDS**: Basalt fiber reinforced polymer (BFRP); Carbon fiber reinforced polymer (CFRP); Near surface mounted (NSM); Computed tomography (CT); Non-destructive testing (NDT).

# DETECTION OF GLASS FIBER-REINFORCED POLYMER BARS IN CONCRETE THROUGH NON-DESTRUCTIVE TESTING

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**ABSTRACT**

This research investigates the effectiveness of non-destructive testing (NDT) methods for detecting glass fiber reinforced polymer (GFRP) reinforcing bars embedded in concrete slabs. Locating GFRP reinforcement is more complex than locating steel reinforcement because its dielectric and acoustic properties are similar to those of concrete. A 1.6 m × 1.6 m concrete slab was constructed using GFRP bars, both sand-coated and ribbed, of varying diameters. After pouring and curing, two NDT techniques were applied: ground-penetrating radar (GPR) and ultrasonic pulse echo (UPE). The experimental results highlight the inherent difficulty in distinguishing GFRP signals in a heterogeneous medium. GPR proved to be the most effective method for detecting GFRP reinforcement. However, results were affected by bar size and age of the concrete. Small diameter bars produced weak or, occasionally, indistinguishable hyperbolas, particularly during the early stages of hardening or in areas with high residual moisture. The UPE results were less consistent, with signal sharpness affected by parameters including concrete maturity, moisture content, and the pressure applied to the transducer. These results support the development of practical recommendations for inspecting GFRP-reinforced concrete structures, emphasizing the optimization of acquisition conditions, the selection of an appropriate inspection schedule, and the combined use of GPR and UPE to improve detection reliability.

**KEYWORDS**: Glass fiber reinforced polymer bars; Concrete slabs; Non-destructive testing; Ground penetrating radar; Ultrasonic pulse echo.

# TRANSVERSE STRESS EFFECTS ON EMBEDDED FIBRE OPTIC SENSORS

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## ABSTRACT

Fibre optic sensing is becoming increasingly important for the monitoring of civil engineering structures. In most applications, optical fibres experience primarily uniaxial longitudinal stress. However, in situations such as anchorages or pin-loaded looped straps made of fibre-reinforced polymers, transverse stresses are unavoidable. These stresses lead to cross-coupling and impede the measurement of axial strains and temperature changes. The influence of transverse stresses remains insufficiently understood and is often disregarded, resulting in potentially significant measurement inaccuracies. In this paper, the physical principles of fibre optic sensors are explained and theoretical formulas are derived that account for transverse stresses, allowing for their compensation provided that the stress state in the optical fibre is known. It is also shown that the stress state in the optical glass fibre depends on its coating and on the stiffness of the surrounding material. Experiments were performed on optical fibres embedded in CFRP plates under transverse pressure to compare measured strains with predictions from finite element models. Because optical fibres subjected to inhomogeneous transverse stress exhibit birefringence, the measurement depends on the polarization state of the light. As a result, exact compensation for transverse stresses is generally not possible because the polarization state of the incident laser beam is not known. Nevertheless, the procedure presented here enables the use of fibre optic sensors in challenging applications with high transverse stresses, if the approximate stress state in the optical fibre is known.

**KEYWORDS**: Transverse pressure; Distributed fibre optic sensing; Embedded sensor; Carbon fibre-reinforced polymers.

# NON-DESTRUCTIVE EVALUATION OF REGOLITH-RESIN-COMPOSITE USING ULTRASONIC WAVES

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## ABSTRACT

To support a sustained human presence on the Moon, developing durable habitats is essential. Regolith-resin-composite (RRC), made from lunar regolith and resin, is a promising material due to its unique mechanical properties. Alongside advancements in lunar construction, a reliable non-destructive evaluation (NDE) technique is crucial, as unexpected damage can endanger inhabitants. Ultrasonic is well-suited for this purpose, being one of the most widely employed NDE techniques for assessing structural integrity. RRC materials pose different ultrasonic responses compared with conventional materials. Therefore, this study investigates the variation in ultrasonic wave response under structural loads in RRC materials. Specimens prepared from lunar regolith simulant and epoxy resin were subjected to varying compression at 50 kN/min., followed by ultrasonic testing after unloading. Minor changes were observed in wave speed and peak amplitude. Time–frequency analysis was used to extract energy-based features, with energy concentration changing up to 23.4% at maximum load, indicating greater sensitivity to progressive damage.

**KEYWORDS**: Non-destructive evaluation; Ultrasonic technique; Regolith-resin-composite; Time–frequency analysis; Energy concentration.

# Case studies & successful applications

# ASSESSMENT OF THE SÃO SILVESTRE HYBRID FRP–CONCRETE FOOTBRIDGE AFTER A DECADE IN SERVICE


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**ABSTRACT**

In 2015, the São Silvestre hybrid concrete-composite footbridge was built and installed over the Cáster River in Ovar. This structure was the outcome of a four-year research project (PONTALUMIS), conducted by Alto-Perfis Pultrudidos, Lda. in collaboration with the Universities of Minho and Lisbon.

The project aimed to develop an innovative simply supported hybrid footbridge, with 11 m of length and 2 m of width. The bridge consists of two I-shaped glass fibre-reinforced polymer (GFRP) pultruded profiles, as main girders, bonded and bolted to a 37.5 mm thick deck made of steel fibre-reinforced self-compacting concrete (SFRSCC).

After ten years in service, a comprehensive assessment of São Silvestre's condition was carried out. This included (i) a geometric survey, (ii) damage mapping, (iii) dynamic identification testing, and (iv) static and dynamic load tests. The footbridge's current performance was then compared with its initial structural characterization. Finally, its compliance with the recently published European Technical Specification for the design of fibre-polymer composite structures (CEN/TS 19101:2022) was verified.

Overall, comparison with the initial characterization confirms the adequate structural performance of the hybrid GFRP–SFRSCC concept for footbridges under real service conditions, without showing any relevant signs of degradation from physical, mechanical, or dynamic points of view. Furthermore, the results of the (retro) safety verification showed that the footbridge satisfies all design requirements specified in CEN/TS 19101:2022.



**KEYWORDS:** GFRP pultruded profiles; Steel fibre reinforced self-compacting concrete (SFRSCC); Hybrid footbridge; Service-life; Assessment; Design.

# APPLICATION OF GFRP REBARS IN AN OFFSHORE SIGNAL TOWER AND ASSOCIATED DURABILITY PROGRAM

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**ABSTRACT**

There is a growing interest in the use of Glass Fiber-Reinforced Polymer (GFRP) rebars, particularly in environments that are aggressive to conventional carbon steel rebars, such as offshore sites where chloride ingress represents a significant concern. In addition, for complex on site applications, the lightweight nature of GFRP rebars provides a practical advantage over steel rebars.

For these reasons, GFRP rebars were selected for the reconstruction of two small reinforced concrete (RC) signal towers in France, each several meters high with a diameter of approximately one meter. Because the towers were cast on-site, the reinforcement cages were assembled on land and then transported to the construction site by helicopter. A notable aspect of this project was the implementation of a durability testing campaign, in which GFRP samples are exposed in the field by attaching them to the reconstructed tower. This approach will enable periodic testing of the samples to monitor the effects of the marine and tidal environment over the service life of the new structure.

The presentation will provide a detailed description of this demonstrator project led by three public agencies (DIRM, Cerema, University Gustave Eiffel), highlighting the main advantages and drawbacks observed during on-site operations using GFRPs, in comparison with conventional construction using steel rebars. It will also present the preliminary validation tests on the rebars and the reinforcement design. Finally, the samples intended for durability investigations are described, including their on-site installation and the planned durability monitoring program.

**KEYWORDS**: GFRP rebar; Offshore application; On-site application; Durability investigations.

# NOVEL DESIGN CONCEPT OF FRP REINFORCED AND PRESTRESSED CONCRETE BRIDGES

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**ABSTRACT**
This paper presents a novel design concept for FRP-reinforced and prestressed concrete (FRP-RC/PC) bridges, emphasizing holistic material-appropriate application rather than simple substitution of steel reinforcement. FRP concrete combines the lightweight, thin-walled efficiency of steel with the freeform shaping potential of cast-in-place concrete, enabling structurally optimized, durable, and low-$CO_2$ bridges. The concept is structured around four key principles: (1) thin-walled construction to reduce material and dead weight, (2) monolithic, force-oriented shaping following structural flow, (3) systematic use of prestressing to exploit tensile capacity, and (4) targeted material selection, including hybrid and low-carbon concrete solutions.

A conceptual 30 m pedestrian bridge is designed according to these principles and compared with two conventional alternatives—prestressed concrete and steel—using a cradle-to-gate life cycle assessment (LCA). Results indicate that the CFRP prestressed concrete variant reduces total greenhouse gas emissions by 15 % compared to conventional prestressed concrete and 29 % compared to steel. When considering only the superstructure, emission reductions reach roughly 40–60 %, mainly due to significant material savings and reduced structural weight.

Finally, the paper presents the practical implementation of the concept in an ongoing 76.5 m pedestrian bridge project in Schwerin, Germany, demonstrating technical feasibility. The findings suggest that material-appropriate FRP concrete bridges can achieve high structural efficiency, environmental compatibility, and cost-effectiveness, supporting the development of a distinct structural language for sustainable bridge construction in the 21st century.

**KEYWORDS**: FRP concrete; Prestressed concrete; Material-appropriate design; Sustainable bridges; Life cycle assessment.

# PORT OF GALVESTON USHERS IN A NEW FRP SOLUTION FOR REPAIR OF CORRODED PIER

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**ABSTRACT**
Concrete structures in marine environments are highly susceptible to corrosion, particularly when exposed to saltwater and cyclic wet-dry conditions. Repairing such structures poses major challenges due to limited access and the need for underwater installation methods. This was the case at a major pier at the Port of Galveston, Texas, where nearly 50% of the reinforcing steel in the concrete girders had deteriorated. The bottom of the girders and the deck were only slightly above the low-water elevation, making conventional formwork-based repairs impractical and costly.

To overcome these challenges, the project team implemented a custom-made fiber reinforced polymer (FRP) stay-in-place form system. The panels consisted of a 10 mm thick foam core sandwiched between layers of glass fabric, which were vacuum-infused with vinylester resin to create rigid yet lightweight shells precisely molded to the shape of the girders and deck. On-site, glass FRP reinforcing bars were installed inside the forms before they were positioned and bolted to the structure. The annular space between the existing concrete and the FRP forms was then filled with a cementitious grout.

This innovative repair approach not only reduced costs and installation time but also provided long-term corrosion protection by fully encapsulating the host concrete in a durable 12 mm FRP shell. The resulting composite barrier shields the pier from saltwater intrusion and environmental exposure, extending its service life for decades. The technique has been used widely worldwide by many industrial clients, the U.S. military and the Port of Melbourne, Australia.

**KEYWORDS**: Corrosion; Repair; Formwork; Sustainability; Manufacturing.

# INNOVATIVE USE OF GFRP REBARS IN THE BARCELONA METRO LINE 8 EXTENSION

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**ABSTRACT**

The Barcelona Metro Line 8 Extension represents a landmark infrastructure project in Catalonia, aimed at enhancing regional connectivity through a 4 km underground expansion linking Plaça Espanya to Gràcia. With three new stations—Hospital Clínic, Francesc Macià, and Gràcia—and upgrades to existing nodes, the project is expected to serve over 70,000 daily passengers.

A critical component of this extension involves the use of Glass Fiber-Reinforced Polymer (GFRP) rebars in five soft-eye zones, including one launching shaft and four station interfaces. Approximately 90,000 linear meters of GFRP rebars were supplied, selected for their superior mechanical performance, cuttability and ease of handling in congested reinforcement zones. The client's decision was driven by high-grade material performance — including the use of a 60 GPa modulus of elasticity for the first time in Spain — and indispensable technical support. The project posed significant design challenges due to high structural forces and main bar lengths reaching up to 16 meters, necessitating bundled bar arrangements and complex lapping strategies. Traditional lapping methods would have resulted in excessive congestion. To mitigate this, the design introduced an auxiliary bar system, reducing congestion to four bars per section and enabling successful design validation.

This case study highlights how optimized lapping strategies, high-performance GFRP materials, and consistent, trust-based collaboration between stakeholders contributed to a solution that meets both standard requirements and the project's demanding structural forces. It demonstrates the practical advantages of GFRP reinforcement in urban tunneling applications and underscores the importance of integrated design support between manufacturers and engineering teams.

**KEYWORDS**: GFRP; Softeyes; MoE; 60 GPa; Lapping; Tunneling.

# APPLICATIONS OF GFRP REINFORCEMENT IN TUNNELLING

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**ABSTRACT**
Glass Fibre Reinforced Polymer (GFRP) reinforcement is increasingly adopted in specific structures of underground applications due to its advantages (low weight, high tensile strength, corrosion resistance under aggressive environments and lower embodied carbon). This paper focuses and describes those specific usages where GFRP rebars offer competitive benefits compared to traditional steel reinforcement. In mechanized tunnelling, GFRP soft eyes have become a mainstream solution for reinforcing retaining walls where Tunnel Boring Machines (TBM) excavate through them. In pre-cast concrete tunnel segments, GFRP bars are successfully adopted as edge reinforcement to prevent corner spalling during handling, and there are also cases where GFRP bars are installed at segments joints to resist localized tensile stresses, often in combination with Fibre Reinforced Concrete (FRC). In conventional underground excavation, GFRP longitudinal bolts offer a lightweight and easily cuttable alternative for controlling tunnel face deformations, which results in a widely used solution. Another effective utilization is the implementation of GFRP mesh in tunnel repair and tunnel relining due to its advantages concerning low cover need and low maintenance. These diverse applications highlight the versatility and effectiveness of GFRP reinforcement in improving the structural performance, sustainability and durability of some underground infrastructure.

**KEYWORDS**: Pre-cast segments; Mechanized excavation; Conventional tunnelling; Tunnel refurbishment.

# PERFORMANCE OF LINK SLABS REINFORCED WITH BASALT FIBER-REINFORCED POLYMER BARS IN PEDESTRIAN BRIDGES

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## ABSTRACT

This research investigates the performance of concrete link slab reinforced with Basalt Fiber Reinforced Polymer bars (BFRP). The link slab was incorporated in a pedestrian bridge deck supported by prestressed concrete Florida Slab Beams. The study aimed at evaluating the elimination of deck expansion joints by creating a continuity link slab that made bridge beams partially continuous for lateral and longitudinal load effects along with live loads. The deck span ends were modified, BFRP bars were installed, sensors were installed, and concrete of continuity link slab was cast-in-place between the span ends. The instrumentation of the bridge included surface-mounted and embedded sensors to evaluate the short and long-term performance of the developed link slab. The sensors were installed on both sides of the midline of the link slab to detect strains in the concrete link slab, strains in the BFRP bars, deformation between beams' ends, and monitoring link slab cracking. A data acquisition system recorded the deformations and strains at regular time intervals. The maximum recorded daily strain change due to thermal effects was approximately 600 to 800 micro strains. The recorded data indicated that the developed strains were considerably smaller than the BFRP ultimate strain levels. The study also discussed the effects of live-load, shrinkage and creep restraint of connected span beams, and thermal cycling that can cause link slab cracking. The research team analyzed the results, drew conclusions, and provided recommendations for link slab instrumentation and monitoring systems.

**KEYWORDS**: Link; Slab; BFRP; Monitoring; Bridge; FSB.

# PERMANENT APPLICATION OF LARGE GFRP BARS FOR FLORIDA BRIDGE SUBSTRUCTURES

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## ABSTRACT

As peninsula, Florida bridges are subjected to very corrosive environments. In addition, the foundations of many Florida bridges are subjected to the scour caused by floods after very common heavy rains. The biannual inspections of Florida bridges sometimes discover substantial scour in pile bents substructures that require retrofit.

Crutch bents are a common way to retrofit substructures that have been weakened by scour. Crutch bents typically consist of two piles installed either side of the bridge cross-section, to avoid disturbing the roadway operation, and connected by a concrete cap beam underneath the superstructure at the centerline of the existing bent. The existing bent in distress typically remains in-place.

An elucidating example project is the highway US90 bridge over Aucilla River in North Florida. In this case, the crutch bent was designed by an expert consultant for the Florida Department of Transportation (FDOT), proposing a deep post-tensioned concrete cap. The lowest bidding Contractor proposed an alternative reinforced concrete cap with the same dimensions as the existing bent cap that included large (#11) GFRP bars. This innovative design solution alternative was accepted by FDOT based on earlier successful applications of GFRP reinforced pile bents for new bridge construction and supported by the positive results found by recent research on large GFRP bar applications for concrete substructures in aggressive marine environments.

The paper highlights the practical design process and challenges for the proposed new crutch bent using #11 GFRP bars based on physio-mechanical testing conducted at the University of Miami, current FDOT material and construction specifications, and AASHTO Guide Specifications for GFRP Reinforced Concrete structures. The case study also highlights the adaption of typical FDOT software for non-linear analysis of substructures (FB-MultiPier) and the use of commercial GFRP bars available in the USA.

**KEYWORDS**: GFRP Bars; Bridge Substructure; Pile Bents; Bridge Retrofit; Contractor's Proposal.

# RECYCLED AGGREGATE CONCRETE REINFORCED WITH FRP IN MARINE ENVIRONMENTS

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**ABSTRACT**
This study presents the first phase of a research project, aimed at developing durable and sustainable concrete solutions for marine infrastructures combining recycled aggregates and fiber-reinforced polymer (FRP) reinforcement, while also promoting marine biodiversity through artificial reef structures. Prior to implementing FRP systems, it is necessary to assess the mechanical and durability performance of the concrete matrix intended to support these non-metallic reinforcements under aggressive marine exposure.
An experimental program was conducted to evaluate recycled aggregate concrete (RAC) mixtures designed for marine environments. Three formulations were produced using different combinations of natural and recycled aggregates: a control concrete with natural aggregates, a mixture incorporating recycled coarse aggregates, and a fully recycled aggregate concrete. The materials were characterized through mechanical and durability tests including compressive strength, splitting tensile strength, elastic modulus, water penetration under pressure, chloride migration coefficient, ultrasonic pulse velocity and wet–dry durability cycles.
The results indicate that concrete incorporating recycled coarse aggregates can achieve mechanical properties comparable to conventional concrete while maintaining satisfactory durability indicators. In particular, chloride migration coefficients and performance under wet–dry cycles suggest that properly optimized RAC can provide adequate resistance to aggressive marine environments.
Based on these results, precast concrete elements were manufactured and installed in the Port of Bilbao (Spain), forming a three-level pyramidal artificial reef structure designed to enhance habitat complexity and support marine biodiversity. Future work will incorporate FRP reinforcement to evaluate the structural and durability performance of these marine precast elements.

**KEYWORDS**: FRP reinforcement; Recycled aggregate concrete; Marine durability; Chloride ingress; Artificial reefs.

# SS01 - FRCM composites for strengthening and repair of reinforced concrete and masonry structures

# EXPERIMENTAL INVESTIGATION ON TEXTILE REINFORCEMENT FOR MASONRY WALLS

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**ABSTRACT**

Brick masonry walls are particularly vulnerable to shear failure during earthquakes due to their low tensile strength and inherent material heterogeneity. This weakness is even more critical in unconfined configurations, such as single-story walls. To address this issue, this study reports on experimental investigations conducted at the LMDC Laboratory in Toulouse, France. Four full-scale masonry walls strengthened with Textile Reinforced Mortars (TRMs) and one unreinforced reference wall (URW) were subjected to quasi-static in-plane loading until failure. The specimens were constructed with traditional clay bricks, commonly used in Toulouse, and lime mortar. Among the reinforced walls, one was strengthened only along its diagonals, while the other three were fully covered with TRM layers. Displacements and crack propagation were monitored using displacement sensors and digital image correlation, allowing for precise analysis of failure mechanisms.

The results clearly demonstrate the effectiveness of TRM reinforcement in enhancing seismic performance. Compared to the unreinforced wall, which reached a peak load of 140 kN and dissipated 3176 J of energy, the fully reinforced wall achieved a peak load of 343 kN and an energy dissipation capacity of 13,303 J. These findings underline the potential of TRM as a robust and efficient retrofitting solution for improving the seismic resilience of masonry walls, providing valuable insights for engineers, architects, and researchers.

**KEYWORDS**: Masonry; Bricks; Earthquakes; Textile reinforced mortar (TRM); Reinforcement.

# DEVELOPMENT OF A NUMERICAL MODEL FOR FRCM RETROFITTED RC COLUMNS

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**ABSTRACT**
Fabric reinforced cementitious matrix (FRCM) composites are a relatively new strengthening technology. Many aspects of their behaviour and structural applications, such as the numerical modelling of reinforced concrete (RC) elements retrofitted with FRCM, still require further investigation. In particular, incorporating FRCM into fibre-based models, which are widely used to simulate the seismic response of RC structures, requires further refinement. This study introduces a new modelling technique that incorporates FRCM and enhances the accuracy of fibre-based simulations. The proposed numerical framework used nonlinear constitutive laws for concrete, steel reinforcement, and FRCM composites, as well as confinement effects and bond–slip interactions. The models are validated against experimental results from cyclic tests on RC columns. The columns had inadequate lateral reinforcement in the plastic hinge region, representative of structures designed under older codes. Calibration against the experimental data confirmed the ability of the developed model to capture the seismic response (load and deformation). Furthermore, the study concludes that the proposed numerical model can reliably capture the enhanced seismic performance of FRCM-strengthened RC columns. These findings contribute to the advancement of practical numerical methods for the application of FRCM systems in structural engineering, supporting their broader adoption in seismic retrofitting applications.

**KEYWORDS**: Fabric reinforced cementitious matrix (FRCM); Textile reinforced mortar (TRM); Numerical model; Fibre-based model; Concrete; Column; Seismic loading.

# BEYOND CEMENT: EXPLORING ALKALI-ACTIVATED MATRICES IN FIBRE-REINFORCED CEMENTITIOUS MATRIX STRENGTHENING OF MASONRY

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**ABSTRACT**
Extending the service life of existing masonry buildings represents a key strategy for reducing greenhouse gas emissions associated with the construction sector. Fabric-Reinforced Cementitious Matrix (FRCM) systems have become widely adopted for masonry strengthening due to their compatibility with mineral substrates and suitability for heritage applications. However, the environmental sustainability of these systems remains closely linked to the binder used in the inorganic matrix. This study investigates the structural feasibility of alkali-activated mortars as alternative matrices in polyparaphenylene benzobisoxazole (PBO)-FRCM confinement of masonry columns. An experimental programme was conducted on clay brick columns subjected to a monotonic axial compression load. Unconfined specimens were compared with columns strengthened using identical PBO mesh embedded in either a traditional lime-based mortar or an alkali-activated mortar. By maintaining constant geometry, substrate properties, and fibre architecture, the influence of matrix type on confinement behaviour was isolated. The results demonstrate that both systems significantly enhance load-bearing capacity and deformation response compared with the unconfined condition. While peak strength is primarily governed by the fibre reinforcement, matrix tensile behaviour and cracking stability play a decisive role in post-peak response and confinement activation. The findings highlight the potential of alkali-activated binders for more sustainable FRCM strengthening solutions, while also identifying key mechanical aspects that require optimisation.

**KEYWORDS**: Masonry structures; Columns; Confinement; FRCM; Alkali-activated mortar.

# IN-PLANE CYCLIC RESPONSE OF SEISMIC AND ENERGY UPGRADED MASONRY-INFILLED RC FRAMES WITH OPENINGS: EXPERIMENTAL STUDY

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## ABSTRACT

This experimental study investigates the in-plane cyclic response of masonry-infilled reinforced concrete (RC) frames with central openings, retrofitted with an integrated seismic and energy retrofitting scheme. Six tests were conducted on 1:2.5 scale single-story, single-bay specimens at the Concrete Technology and RC Structures Lab of the University of Thessaly. Two specimens were constructed without an opening, two with a central window opening and two with a central door opening. For each infill configuration (fully infilled/window/door), one specimen was tested as-built (unretrofitted), while its counterpart was tested after the application of the integrated retrofitting scheme; single-sided textile-reinforced mortar (TRM) jackets in combination with standard thermal insulation panels. The key test parameters were the presence and type of openings (window or door opening) and the effectiveness of the retrofitting scheme. The results demonstrated that the combined seismic and energy upgrading significantly enhanced the in-plane performance of substandard masonry-infilled RC frames. However, the presence of a central opening reduced the load-carrying capacity of the retrofitted frames. Nevertheless, the retrofitting scheme proved effective in all cases. It is worth mentioning that all retrofitted specimens exhibited similar lateral strength enhancement with respect to their counterparts (unretrofitted frames) regardless of the presence or type of openings, achieving an increase of approximately 38%.

**KEYWORDS**: Masonry infills; Reinforced concrete (RC); Textile-reinforced mortar (TRM); Seismic retrofitting; Energy retrofitting.

# SHEAR PERFORMANCE OF POLARIZED CFRCM-STRENGTHENED CORRODED RC CONTINUOUS BEAMS

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**ABSTRACT**

This paper investigates the shear performance of corroded reinforced concrete (RC) continuous beams strengthened with polarized carbon fabric reinforced cementitious matrix (CFRCM) plates within an innovative impressed current cathodic protection-structural strengthening (ICCP-SS) repair system. This system integrates impressed current cathodic protection (ICCP) technique to mitigate reinforcement corrosion with CFRCM-based structural strengthening (SS) to restore or enhance load-bearing capacity. Finite element analysis (FEA) incorporating the trilinear interface model was performed on five RC beams to examine critical parameters including failure mechanisms, load capacity, and shear strength. The interfacial shear stress distribution and tensile stress development in carbon fabric (CF) were analyzed. The results indicate that the layered modeling approach for CFRCM composites effectively captures the mechanical response of strengthened specimens. Anodic polarization of the first CF layer redistributes interfacial shear stress, achieving more uniform interlayer bond behavior, and partially compensating for polarization-induced material degradation. Moreover, experimental results confirm that the ACI 549.4R-20 provides conservative estimates of shear performance.

**KEYWORDS**: Carbon fabric reinforced cementitious matrix (CFRCM); Continuous beam; Finite element analysis (FEA); Layered modeling approach; Shear strength.

# THE IMPACT OF PBO-FRCM STRENGTHENING ON THE SERVICEABILITY OF RC SLABS

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**ABSTRACT**
Fabric-Reinforced Cementitious Matrix (FRCM) systems provide an alternative technique for strengthening reinforced concrete structures, particularly in cases where conventional FRP composites are unsuitable due to fire resistance requirements, environmental durability concerns, or the preservation of historic buildings. Although FRCM generally exhibits lower efficiency compared to FRP, ongoing research aims to improve its effectiveness and broaden its field applications. This paper examines the influence of PBO-FRCM strengthening on the serviceability of reinforced concrete slabs. The experimental program included seven specimens, six of which were reinforced with FRCM composites incorporating different PBO mesh anchorage solutions, and one reference specimen without strengthening. Particular attention was paid to the behavior of the specimens within the serviceability limit state, with emphasis on deflection limits and crack widths. These analyses were conducted within the typical service load range and extended to higher loading levels up to failure. Furthermore, the failure mechanisms of the specimens and their ductility were investigated. The results indicated that deflections were only slightly reduced under service loads, but the differences became more pronounced as the load increased. With respect to cracking behavior, a significant improvement in crack resistance and a reduction in crack widths were observed across the entire loading range. These findings confirm the potential of PBO-FRCM as a viable strengthening method, while also emphasizing the need for further refinement to fully exploit the material's capacity.

**KEYWORDS**: PBO-FRCM; RC slab; Serviceability; Composite; Strengthening.

# FRCM-STRENGHTENED FLANGED-RC BEAMS UNDER TORSION

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**ABSTRACT**
Torsional repair or strengthening of reinforced concrete (RC) members may be necessary due to structural degradation from aging or environmental exposure, deficiencies in original design, particularly in older structures where torsional limit states were not explicitly considered, or as a results of increased loading demands including eccentric actions. Fiber-reinforced polymer (FRP) composites have been widely utilized for this purpose; however, their effectiveness is limited by susceptibility to high temperatures, incompatibility with concrete substrates, and the potential for premature debonding. Fiber-reinforced cementitious matrix (FRCM) composites have recently emerged as a promising alternative, offering enhanced vapor permeability, superior bond with concrete, and improved fire resistance. This paper presents an experimental investigation into the torsional behavior of large-scale T-shaped RC beams externally strengthened with carbon FRCM (C-FRCM) jackets. Four beams were tested under pure torsion: (a) an unstrengthened beam, (b) a beam strengthened with an unanchored C-FRCM jacket incorporating a unidirectional CFRP grid, (c) a beam strengthened with an anchored C-FRCM jacket incorporating a unidirectional CFRP grid, and (d) a beam strengthened with an anchored C-FRCM jacket incorporating a bidirectional CFRP grid. The unidirectional grid consisted of structural fibers (SFs) aligned along a single axis oriented vertically (parallel to the beam depth), whereas the bidirectional grid included SFs along both horizontal and vertical axes. In beams (c and d), the C-FRCM jacket was mechanically anchored at the beam web–flange junction using steel angles fastened with screw anchors. It was shown that C-FRCM strengthening improved both torsional strength by 11-40% and deformability of RC T-beams by 24-71% depending on configuration and presence of anchorage, compared with the control specimen.

**KEYWORDS**: Concrete; T-beam; Torsion; FRCM; C-TRC; Cementitious mortar.

# PERFORMANCE OF STEEL REINFORCED GROUT FOR EXTERNAL STRENGTHENING OF CONCRETE MEMBERS

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## ABSTRACT

Steel-reinforced grout (SRG) is an emerging composite material used for the external bonding (EB) of concrete structural members for strengthening and retrofitting purposes. In its modern form, SRG uses sheets of uniaxial, high-strength steel cords embedded in a fine-grained cementitious matrix, in a manner similar to that of fabric-reinforced cementitious matrices (FRCMs). SRG performance is generally excellent because it capitalises on the well-established bonding capability of steel with respect to cement. However, adequate exploitation of the steel strength and prevention of early delamination depend crucially on the ingrainment of the cement paste within the mesh grid. For this reason, standard SRG composite systems use low-density steel sheets that provide enough space between the cords for the concrete matrix to penetrate in and bond. However, to meet the demands of high-end structural applications, multiple plies are needed, which in turn means that the thickness of the reinforcing laminate becomes too great to achieve good stress distribution. Consequently, the conversion rate of the steel textile appears again unsatisfactory, and the composite performance falls short of its potential. This paper presents experimental evidence on the mechanical performance of SRG with medium-density steel cords (3.14 cords/cm), in connection with the application of a micrometric epoxy coating. Despite the excellent bond quality at the steel-to-cement interface, the performance of the coupon in traction is significantly affected by the coating, paving the way for the adoption of high-density meshes, which are currently used in Steel Reinforced Polymer (SRP) systems only. Nevertheless, delamination from the concrete support still limits the potential of this technology.

**KEYWORDS**: Steel reinforced grout; High-density steel mesh; Externally bonded strengthening material; Epoxy coating.

# NONLINEAR PERFORMANCE OF FRCM-STRENGTHENED MASONRY WALLS UNDER TSUNAMI ACTION

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**ABSTRACT**

This study, part of a larger research activity, aims to analyze the out-of-plane behavior of masonry walls subjected to tsunami action, with particular focus on estimating the collapse water wave height for various geometric and constructional configurations. The walls were modeled by varying the thickness and the acting normal stress, as well as the presence and position of openings.

The research step analyzed in this work consists of quantifying the increase in resistance offered by an FRCM (Fabric-Reinforced Cementitious Matrix) reinforcement, in order to reduce the vulnerability of the walls. The analyses were conducted using SAP2000 and involved the separate modeling of the matrix and the fiber, which were subsequently assembled with the tuff masonry model. The thickness of the FRCM system was set to 3 cm, that is an upper bound of typical values.

The analyses were interrupted upon reaching matrix cracking, since, following this phenomenon, the fabric was exposed, and it was decided not to consider further post-cracking contributions. The results highlighted capacity increments varying between 20% and 60%. However, in all models, it is observed that the percentage increase tends to decrease with increasing acting normal stress.

**KEYWORDS**: FRCM; Masonry; Out-of-plane; Tsunami; Water height.

# CONFINEMENT OF REINFORCED CONCRETE COLUMNS WITH TEXTILE-REINFORCED MORTAR JACKETS

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## ABSTRACT

The confinement of reinforced concrete (RC) columns with textile-reinforced mortars (TRM) has gained increasing attention as a sustainable and fire-resistant strengthening alternative to techniques based on fiber-reinforced polymers (FRP). Research has been done on numerous aspects regarding the behavior of the TRM jacketing solutions; nonetheless, to date most of the studies have focused on small plain concrete specimens. The present study consists of an experimental program on eight short circular RC columns (200 mm in diameter and 600 mm in height) with realistic internal reinforcement detailing aimed at assessing the confinement effectiveness of the TRM jackets as a retrofitting solution. These tests aim to highlight the role of mortar composition and fiber types in correctly activating the confinement effect on the columns by means of advanced instrumentation, as well as showing the effectiveness in increasing strength and/or ductility of RC elements. To this end, two of these were tested as unconfined control elements, while the other six were retrofitted using different combinations of mortars and textiles, these being ordinary Portland cement mortar (OPC) with carbon fabric, calcium sulfoaluminate (CSA) mortar with carbon fabric and CSA mortar with basalt fabric. For each TRM system, the use of two and three textile layers was investigated. The results of the TRM jackets tests show gains in axial compressive strength of about 25-30% with respect to the control specimens, and without important differences between the types of TRM systems or number of layers employed.

**KEYWORDS**: Textile-reinforced mortar (TRM); Confinement; Structural retrofitting; Reinforced concrete; Fibres.

# EFFECT OF ACCELERATED AGING ON MECHANICAL INTERACTION BETWEEN FIBERS AND MATRIX IN PBO-FRCM

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## ABSTRACT

This study investigates the durability of PBO-FRCM systems under accelerated aging conditions, simulating potential environmental degradation. An extensive experimental campaign was conducted on PBO-FRCM coupons, subjected to two main categories of conditioning: the first is prolonged immersion in saline environments and the second is combined wet-dry cycles. For saline conditioning, specimens were immersed for 1000 h and 3000 h in three different solutions: one simulating seawater according to ASTM D1141-98 and two based on concentrations derived from literature. Results showed that matrix cracking strength generally decreased with longer exposure times and higher salt concentrations, reaching reductions up to 47% for highly concentrated solutions. Conversely, ultimate tensile strength slightly increased for some conditions, indicating a complex interaction between matrix degradation and fiber-matrix bonding.

Wet and Dry cycles, inspired by UNI EN 14066, combined 18 h of oven drying at 50°C or 70°C with 6 h immersion in either natural water or saline solutions (the same three used for the saline conditioning), for up to 50 cycles. Results revealed an initial significant decrease in cracking strength and ultimate tensile strength during the first cycles, especially for specimens in natural water, followed by partial recovery after prolonged cycling in saline environments, suggesting a possible stabilization effect.

Overall, the findings highlight the sensitivity of PBO-FRCM systems to aggressive environmental conditions and provide valuable insights into their long-term mechanical performance.

**KEYWORDS**: PBO-FRCM; Accelerated aging; Durability; Saline immersion; Wet-dry cycles.

# NUMERICAL STUDY AND COMPARISON OF CONCRETE COLUMNS STRENGTHENED WITH FRP AND TRC

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**ABSTRACT**

The use of externally bonded Fiber-Reinforced Polymer (FRP) systems has been widely adopted for strengthening reinforced concrete (RC) columns. More recently, Fabric-Reinforced Cementitious Mortar (FRCM) has emerged as an alternative technique, offering potential advantages in terms of durability, fire resistance, and compatibility with concrete substrates. Although both strengthening methods have been investigated in previous studies, systematic numerical comparisons considering multiple design parameters simultaneously remain limited. In this study, a comprehensive finite element parametric analysis of RC columns strengthened with glass FRP and AR-glass FRCM systems is conducted using ABAQUS. The numerical models are developed based on an experimentally tested column–foundation assembly and are validated against published experimental results, showing good agreement. The investigated parameters include column cross-sectional shape (square and circular) and the number of strengthening layers applied in combined vertical and wrapping configurations. Key structural performance indicators, including axial and flexural capacities, P–M interaction behavior, stress distribution, and failure modes, are evaluated and compared. The results demonstrate that both FRP and FRCM systems effectively enhance the axial and flexural performance of RC columns. However, FRCM generally provides greater capacity improvement, and with increasing numbers of layers. In contrast, FRP shows relatively higher efficiency in circular columns due to more uniform confinement. Overall, the findings highlight the significant influence of column geometry and layer configuration on strengthening efficiency and provide useful guidance for selecting appropriate strengthening techniques in practice.

**KEYWORDS**: Fibre reinforced polymer (FRP); Textile reinforced concrete (TRC); RC column strengthening; Finite element analysis; ABAQUS.

# EXPERIMENTAL CHARACTERIZATION OF TEXTILE REINFORCED MORTAR COMPOSITES UNDER CYCLIC LOADING

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## ABSTRACT

This research aims to achieve a high-fidelity mechanical characterization of Textile-Reinforced Mortars (TRM) composites subjected to low-frequency cyclic loading, with the goal of evaluating their response for seismic retrofit applications. The experimental program includes tensile and bond tests performed on three different composite systems: (i) Portland cement mortar with carbon textiles; (ii) calcium sulfoaluminate (CSA) mortar with carbon textiles; and (iii) CSA mortar with basalt textiles. Both monotonic and cyclic loading protocols are employed to capture mechanical behavior, including tensile strength and stiffness, cracking response, and bond-slip behavior. In addition to conventional instrumentation, advanced monitoring by means of digital image correlation (DIC) was employed during the test.

The results show that the cyclic loading has a limited effect on the ultimate tensile strength, but some differences were observed in the stiffness evolution and post-cracking response. In particular, cyclic loading produced no significant effects during the pre-cracking and cracking stages; however, a slightly higher post-cracking stiffness was observed under cyclic loading, likely due to a more uniform crack distribution and progressive activation of the textile reinforcement. The post-cracking stiffness increased by approximately 10% for carbon fibers and over 20% for those with basalt fibers. Similarly, the influence of cyclic loading on bond strength was negligible, as the force-slip envelopes were comparable to those of monotonic tests.

**KEYWORDS**: Textile-reinforced mortars (TRM); Fabric-reinforced cementitious matrix (FRCM); Cyclic loading; Bond behaviour; Seismic retrofit.

# ASSESSMENT OF THE BEHAVIOR BETWEEN PBO-TRC AND STEEL UNDER MIXED MODE BENDING LOADING

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**ABSTRACT**

Metallic pipelines employed in offshore environments are constantly exposed to severe conditions, making them susceptible to progressive degradation over time. Considering the need for new solutions, this study investigates the application of textile reinforced concrete (TRC) as an innovative alternative for the repair and strengthening of metallic pipelines. The proposed system consists of a PBO (polyparaphenylene benzobisoxazole) fabric embedded in an inorganic cementitious matrix, aiming to replace the organic matrices traditionally used in polymer-based composite systems. The main objective of this research is to evaluate the interfacial performance of the proposed TRC system, with emphasis on the bond behavior between the composite and the metallic substrate. To promote an effective connection between the materials, a cement paste layer was applied as an intermediate bonding agent. The interfacial behavior was characterized through mixed mode bending (MMB) fracture tests. The results indicated that the predominant failure mode was adhesive, occurring at the interface between the steel and the cement paste. For the specimens with a higher contribution of mode II, an abrupt failure was observed, without detectable crack propagation. Although the MMB test adequately represents the combined loading conditions typically observed in the field, it is noteworthy that factors inherent to real applications, such as reinforcement fabric confinement and the cylindrical geometry of the pipeline, may significantly influence the interfacial strength of the TRC system.

**KEYWORDS**: Interface; Mixed mode fracture; MMB test; Textile reinforced concrete; Steel-concrete.

# EXPERIMENTAL EVALUATION OF A PBO-TRC REPAIR SYSTEM APPLIED TO PIPELINES

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**ABSTRACT**
The application of Textile Reinforced Concrete (TRC) for the repair and strengthening of metallic pipelines subjected to severe conditions in offshore environments represents an innovative and promising approach. The proposed system emerges as an alternative to conventional Fiber Reinforced Polymer (FRP) methods, whose structural efficiency is significantly reduced when exposed to elevated temperatures, particularly above the glass transition temperature of the polymeric matrix. The developed repair system consists of an inorganic cementitious matrix based on calcium aluminate cement, combined with a PBO (polyparaphenylene benzobisoxazole) fabric. In addition, an intermediate layer of cement paste was incorporated to improve the interfacial adhesion between the cementitious composite and the metallic substrate, while also enhancing the applicability of the system under accelerated curing conditions. The system was experimentally evaluated through hydrostatic tests performed on cylindrical specimens containing machined through-thickness defects. Furthermore, the Digital Image Correlation (DIC) technique was employed to monitor the distribution and evolution of surface strains throughout the tests. The results demonstrated satisfactory performance of the system after 48 hours of curing of the cementitious matrices, evidencing good interfacial integrity after molding and highlighting the potential of TRC as an effective repair solution.

**KEYWORDS**: Textile reinforced concrete; Pipeline repair systems; Steel-concrete; Digital image correlation.

# TENSILE BEHAVIOR OF SBR-COATED GLASS FRCM UNDER ELEVATED TEMPERATURE

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## ABSTRACT

Fiber-reinforced polymers (FRPs) are nowadays effectively used as externally bonded reinforcement (EBR) for existing concrete and masonry structures thanks to their high strength- and high stiffness-to-weight ratio. In recent years, fiber-reinforced cementitious matrix (FRCM) composites have been used as an alternative to their organic-matrix counterparts, FRPs, since they overcome some of the issues related to the use of epoxy resins, such as poor compatibility with the substrate, lack of vapor permeability, and irreversibility of application. In general, FRCMs exhibit greater resistance to (relatively) high temperatures compared with FRPs, thanks to the protective role of the mortar matrix and absence of organic impregnation resin. However, limited results available in the literature show that the high temperature resistance of FRCM depends on both the effectiveness of the mortar protective layer and on the type of textile used. FRCMs with coated textile present improved textile-matrix bond behavior but may present lower resistance to high temperature with respect to corresponding dry textile FRCMs. This paper investigates the tensile behavior of a glass FRCM with a styrene butadiene rubber (SBR) coating before and after thermal preconditioning. Ten tensile tests were carried out with the clamping-grip setup on control (i.e., non-conditioned) and thermally preconditioned glass FRCM coupons. For comparison, three tensile tests were performed on bare textile control specimens and three on thermally preconditioned textiles. The same number of textile bundles was used in all tests. The results show that the thermal preconditioning had only a limited effect on the mechanical properties of the glass FRCM system investigated in this work.

**KEYWORDS**: FRCM; Tensile behavior; Elevated temperature; Clamping-grip tests.

# PRE-DAMAGED ECCENTRICALLY COMPRESSED CONCRETE CYLINDERS CONFINED WITH PBO-FRCM

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**ABSTRACT**

The paper presents a study on the behavior of pre-damaged eccentrically compressed cylindrical concrete elements strengthened with FRCM (Fabric Reinforced Cementitious Matrix) using PBO (p-Phenylene Benzobis Oxazole) mesh reinforcement – PBO-FRCM. The phenomenon of pre-damage is significant from the perspective of structural strengthening, as strengthening is typically applied to existing structures, which have already been subjected to loading. The study focused on elements made of concrete with a compressive strength of approximately 40 MPa, which is typical for present reinforced concrete structures. The pre-damage was induced through axial loading up to 80% of the average ultimate load, followed by complete unloading, after which the PBO-FRCM composite was applied. Both unstrengthened and strengthened specimens (with three layers of PBO mesh) were analyzed. The cylinders were subjected to axial or eccentric compression (at two different eccentricities). The test specimens were evaluated in terms of load-bearing capacity, deformability, and ductility. Additionally, Digital Image Correlation (DIC) measurements were used to analyze crack development in axially compressed elements, as the development of this crack is crucial from the point of view of PBO-mesh overlap delamination. The results of the study show that the pre-damage did not have a negative effect on the behavior of the tested elements.

**KEYWORDS**: Concrete; Strengthening; Composite; FRCM; Compression.

# EXPERIMENTAL ASSESSMENT OF THE DURABILITY OF CRM SYSTEMS FOR STRUCTURAL STRENGTHENING

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**ABSTRACT**

In recent decades, to overcome the poor performance of fibre-reinforced polymer (FRP) composites in the strengthening of historical masonry buildings, new composites using inorganic mortars (cement- or lime-based) instead of organic polymers have been developed, known as FRCM or CRM systems. While FRP systems are well-supported by research and guidelines, knowledge about inorganic matrix composites (IMCs), especially regarding their long-term durability, is still limited. This paper presents the experimental activity aimed at the mechanical characterization of three CRM systems, a specific type of IMC systems consisting of FRP grids embedded in lime- or cement based mortars, subjected to aggressive environmental conditions. Tensile tests, performed on individual components (glass fibres) as well as on FRP grids, were carried out before and after exposing the samples to three different conditions of temperature (23 °C, 40 °C and 60 °C), four exposure durations (1000, 2000, 3000, and 6000 hours) and three different alkaline solutions, representative of the various pH conditions generated by different types of surrounding mortar. The results show a significant reduction in tensile strength after conditioning, highlighting the detrimental effects of combined alkaline environments and severe thermo-hygrometric conditions on both fibres and composite systems.

**KEYWORDS**: Fibre-reinforced composite materials; Inorganic matrix; Durability; Alkali resistance; Experimental tests.

# BOND BEHAVIOUR OF BASALT FRCM SYSTEMS UNDER ALKALINE EXPOSURE

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**ABSTRACT**
In recent years, engineering practice has witnessed a remarkable proliferation of structural retrofit solutions aimed at strengthening and seismically upgrading existing constructions. Among these, Fiber Reinforced Cementitious Matrix (FRCM) systems have been widely applied, demonstrating excellent compatibility with masonry substrates. However, the durability of these systems remains an open and highly debated research topic. To address this gap, an experimental campaign was carried out on an FRCM system consisting of a basalt fiber mesh embedded in a lime-based mortar. Masonry wallets were reinforced with a single composite strip (300 mm bond length) and subsequently conditioned in a highly alkaline environment, obtained by immersing the specimens in a solution of Calcium Hydroxide and distilled water (target pH = 12). Two exposure durations were considered, equal to 500h and 1000h, while reference specimens were cured in air for 500h. All specimens were tested with single-lap direct shear test configuration. The results revealed a marked loss of performance under alkaline exposure: after 1000h of conditioning, the bond capacity dropped by approximately 35% compared to the air-cured specimens. This substantial reduction underscores the potential risk associated with such aggressive environments if durability issues are not properly addressed during the design stage of strengthening interventions and highlights the need for further studies on the long-term performance of FRCM systems.

**KEYWORDS**: Durability; Alkaline; Single-lap direct shear test; Basalt fibers; FRCM composite.

# BOND OF FRCM APPLIED ON CONCRETE SUBSTRATES WITH DETERIORATION

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**ABSTRACT**
Fabric Reinforced Cementitious Matrix (FRCM) composites have emerged as a promising solution for strengthening and retrofitting existing concrete structures, offering advantages such as high tensile strength, flexibility, and compatibility with cementitious substrates. While extensive research has demonstrated the effectiveness of FRCM systems in enhancing structural performance under optimal conditions, limited attention has been given to their behavior when applied to deteriorated concrete substrates commonly encountered in real-world applications. Understanding the influence of substrate condition on FRCM-concrete bond behavior is essential for developing reliable design guidelines and ensuring long-term effectiveness of these strengthening solutions. This study investigates the bond properties of carbon fabric FRCM composites applied to concrete substrates subjected to different artificial aging processes. Four substrate conditions are examined: non-deteriorated concrete (reference), high temperature exposure, saline solution immersion, and sulfate solution immersion. These conditioning processes simulate common deterioration mechanisms affecting aging infrastructure. Through single lap-shear testing, the experimental campaign investigated how substrate deterioration influences bond strength and failure mechanisms of FRCM strengthening systems. Experimental results showed that substrate aging can significantly affect the FRCM-to-concrete bond properties both positively and negatively, depending on the deterioration mechanism. The findings provide valuable insights for rehabilitating aging concrete infrastructure in harsh environmental conditions where deterioration is common.

**KEYWORDS**: Fabric reinforced cementitious matrix; Carbon textile; Bond strength; Aged concrete; Lap-shear.

# RETROFITTING RC BEAM-COLUMN JOINTS USING FRCM COMPOSITES

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## ABSTRACT

Existing reinforced concrete (RC) structures designed according to older seismic codes often exhibit inadequate detailing in beam-column joints, representing critical vulnerabilities during seismic events. These joints frequently lack sufficient transverse reinforcement and proper anchorage, making them susceptible to brittle shear failures and bond deterioration under cyclic loading. Fabric Reinforced Cementitious Matrix (FRCM) composites offer a promising retrofitting solution due to their compatibility with concrete substrates, ease of application, and high mechanical properties.

This study investigates the effectiveness of FRCM composite systems for strengthening under-designed exterior reinforced concrete beam-column joints subjected to horizontal cyclic loading simulating seismic conditions. The experimental program includes both control specimens representing typical non-seismically detailed joints and retrofitted specimens with strategically applied FRCM reinforcement. The joints were tested under quasi-static cyclic loading protocols to evaluate their hysteretic behavior, energy dissipation capacity, and failure progression.

Experimental results showed that FRCM composites can significantly improve the strength capacity and overall performance of the joints. The retrofitted specimens demonstrated enhanced load-carrying capacity, improved energy dissipation, and more favorable failure mechanisms compared to unstrengthened counterparts. The FRCM intervention effectively mitigated premature shear failures and allowed for better redistribution of internal forces within the joint region.

**KEYWORDS**: FRCM; Beam-column joints; Seismic retrofitting; Cyclic loading; Reinforced concrete.

# DURABILITY PERFORMANCE OF ULTRA-HIGH-PERFORMANCE FRCM SYSTEMS

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## ABSTRACT

Fabric-Reinforced Cementitious Matrix (FRCM) systems are increasingly used for strengthening concrete structures; however, their effectiveness is often limited by premature fabric–matrix debonding associated with weak commercial matrices. This study evaluates the durability performance of an advanced Ultra-High-Performance FRCM (UHP–FRCM) system combining a newly developed high-strength cementitious matrix with conventional polyparaphenylene benzo-bisthiazole (PBO) fabric. Concrete prisms strengthened with UHP–FRCM, and commercial systems were subjected to sustained loading (50–80% of ultimate capacity) followed by rapid chloride migration testing. The UHP–FRCM system exhibited superior crack control and significantly improved resistance to chloride ingress, achieving a 50-60% reduction in chloride diffusion coefficients compared with commercial counterparts. The results highlight the critical role of matrix design in enhancing the long-term durability of FRCM-strengthened concrete structures exposed to chloride environments.

**KEYWORDS**: FRCM; Textile; UHPC; Durability; Chloride diffusion.

# EXPERIMENTAL STUDY ON THE TEMPERATURE-DEPENDENT BOND–SLIP BEHAVIOR OF PBO AND CARBON-FRCM

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## ABSTRACT
The durability of the FRCM reinforcement system using either carbon or PBO fibers has been extensively studied. However, the effect of exposing strengthened fibers to tensile forces at the same time with exposure to high or low temperatures has not been intensively studied. The behavior of the (bond-slip) relationship under the influence of these loads and environmental conditions was studied, taking into account two types of fibers: carbon fiber and BPO. The range of temperatures that were taken into consideration represents the freezing, the normal, and the high temperature within the operational service ranges. A standard concrete masonry unit with a dimension 20x20x15 cm was considered as a substrate for this study. Standard test method ASTM 8337 (single -lab shear test) was conducted for evaluation of the bond properties of FRCM composite and masonry concrete substrate. The experimental program consisted of two phases, the first one focused on testing the specimens under the influence of 150 cycles of cooling and heating, followed by conducting a pull-out test. While the second phase involves testing the specimens under the influence of different temperatures simultaneously with the application of tensile load. As a result, the bond effectiveness of the FRCM strengthening system was not significantly affected by the change of temperature during load application.

**KEYWORDS**: FRCM; Strengthening; Masonry; PBO; Carbon FRP.

# TEXTILE REINFORCED MORTAR STRENGTHENING OF CONCRETE SLAB WITH CORRODED REINFORCEMENT

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**ABSTRACT**

Deterioration induced by corrosion of the steel reinforcement is one of the most critical factors affecting reinforced concrete structures. As many infrastructures approach advanced stages of degradation, the need for efficient restoration methods to recover their load-bearing capacity has become increasingly urgent. Textile Reinforced Mortar (TRM) has emerged as a promising external strengthening solution for deteriorated concrete elements. In this study, the flexural performance of TRM composite using carbon fibres was evaluated on a one-way concrete slab with corroded steel reinforcement and compared with a control slab with the same level of deterioration. The longitudinal steel bars on one half of the slab section were subjected to chloride accelerated corrosion until achieving an 8% mass loss, simulating non-uniform corrosion effects. One of the slabs was subsequently repaired and reinforced using TRM with two layers of carbon textile and a mortar incorporating short glass fibres in its composition. Additionally, carbon spike anchors were implemented to prevent premature debonding of the external reinforcing. The slabs were tested under flexure using a three-point bending setup. The TRM reinforced slab exhibited a 39% increase in maximum load capacity compared to the control slab, while the spike anchors demonstrated good efficiency in promoting full activation of the textile within the TRM system.

**KEYWORDS**: Textile reinforced mortar; Corrosion; Carbon textile; Flexure testing; Reinforced concrete.

# SS02 - Circular construction with FRPs: durability, sustainability, and material reuse

# THERMO-MECHANICAL PERFORMANCE OF GFRP CONFINED CONCRETE WITH GOLD MINE TAILINGS AS CEMENT REPLACEMENT

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## ABSTRACT

Growing environmental pressures on the mining and construction industries require sustainable solutions that reduce cement use and valorize mine waste by-products. This study investigates the feasibility of hybrid structures made of Concrete-Filled Fiber-reinforced Tube (HCFFT)combining glass fiber-reinforced polymer (GFRP) confinement with concrete incorporating the gold mine tailings sampled from the Canadian Malartic Mine (CMM) in Quebec were used in this study (0–50% cement replacement). The research aims to enhance the mechanical and thermal performance of concrete while promoting circular economy principles. GFRP–CMM configurations were fabricated and tested per ASTM and CSA standards for axial compression, Poisson's ratio, and thermal conductivity, benchmarked against unconfined controls. Results demonstrate that GFRP confinement significantly enhances compressive strength, achieving over 32 MPa at 10% CMM and increasing the compressive strength (f'c) by up to 127% at 50% CMM compared to unconfined reference specimens, despite CMM-induced porosity and reduced workability. In addition, GFRP's low thermal conductivity reduces effective thermal conductivity by 30%, improving thermal efficiency and stabilizing thermo-mechanical response under heating–cooling cycles by restraining dilation. These findings highlight the novel synergy of GFRP confinement and CMM-based concrete, offering a sustainable alternative to traditional materials with superior corrosion resistance and environmental benefits.

This work advances sustainable structural concrete by reducing cement consumption and repurposing mine waste.

**KEYWORDS**: Sustainable construction; Mine tailings; Thermal properties; Mechanical properties; Hybrid systems.

# DURABILITY OF FRP REINFORCING BARS EXPOSED TO AN ALKALINE ENVIRONMENT


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## ABSTRACT

The durability of fiber-reinforced polymer (FRP) reinforcing bars in alkaline environments is one of the key factors determining their long-term applicability in concrete structures. Although FRP bars are immune to corrosion, prolonged exposure to the highly alkaline pore solution of concrete may lead to degradation of their polymer matrix and the fiber–matrix interface, resulting in a reduction of mechanical performance. In this study, the resistance of glass (GFRP) and basalt (BFRP) reinforcing bars to alkaline attack was experimentally investigated. Specimens were immersed in an alkaline solution (pH ≈ 13.5) at controlled temperatures of 20°C and 60°C for a total exposure period of 1000 hours. After exposure, tensile tests were performed to evaluate the residual tensile strength and modulus of elasticity, while microscopic observations were conducted to identify possible surface degradation and fiber–matrix debonding.

The results showed that both GFRP and BFRP bars exhibited a noticeable reduction in tensile strength after exposure, with the effect being more pronounced for GFRP bars. The modulus of elasticity was only slightly affected, indicating that the degradation primarily occurred in the resin phase rather than in the fibers themselves. The study confirms that exposure to an alkaline environment significantly affects the mechanical performance and durability of FRP reinforcing bars, which should be carefully considered in the design and material selection of concrete structures exposed to high-pH and moisture conditions.



**KEYWORDS**: GFRP bars; BFRP bars; Corrosion; Damage; Mechanical properties.

# DURABILITY OF GFRP AND BFRP IN SIMULATED ALKALINE PORE SOLUTION OF CONCRETE

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## ABSTRACT

The emergence of alkali-activated concretes (AAC) requires more extensive research to assess the durability of FRP-reinforced AAC, as traditional pore solutions fail to accurately reflect the unique chemical interactions and high alkalinity characteristic of these non-conventional binders. While the resin matrix is frequently cited as the primary weak link in such aggressive environments, this study investigates the specific role of fibre type by comparing glass fibre-reinforced (GFRP) and basalt-reinforced (BFRP) rebars utilizing an identical vinyl ester matrix. Specimens were subjected to accelerated ageing in a simulated AAC pore solution at 60°C for up to 90 days. The experimental programme evaluated moisture kinetics, interlaminar and transverse shear strengths, and elemental leaching, alongside independent characterisation of the neat resin. Results indicate a fundamental disparity in performance driven by the reinforcement material. While GFRP specimens demonstrated Fickian diffusion and high mechanical retention, BFRP samples exhibited non-Fickian moisture uptake exceeding 11% and a loss of over 80% in interlaminar shear strength within the first week. Crucially, the neat vinyl ester resin retained its mechanical integrity throughout the exposure. These findings challenge the prevailing consensus that matrix hydrolysis governs degradation, suggesting instead that the rapid deterioration of BFRP in high-pH environments is dictated by the chemical instability of the basalt fibres and possibly other factors, including weak-fibre-matrix interphase and fibre sizing incompatibility.

**KEYWORDS**: Basalt FRP; Glass FRP; Vinyl ester; Durability; Alkaline concrete environment.

# PHYSICS-INFORMED MACHINE LEARNING FOR GFRP DURABILITY PREDICTION

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## ABSTRACT
Glass fiber-reinforced polymer (GFRP) bars are a promising corrosion-resistant alternative for marine reinforcement, but their broader adoption is limited by complex, product-dependent degradation and the difficulty of reliable durability assessment. To address this challenge, this study develops a physics-informed machine learning model for evaluating GFRP bar durability. Built upon an artificial neural network (ANN), the model integrates physics-guided feature engineering and an attention mechanism. A key innovation is the incorporation of a 30-day tensile strength retention metric (S30P) as a “durability gene” that captures early-age quality differences among products, enabling the model to distinguish product-specific degradation trajectories. Trained and validated on a comprehensive experimental dataset, the proposed model achieves higher predictive accuracy than conventional ANNs. Leveraging this model, a practical durability-evaluation workflow is proposed. As an illustrative application, allowable limits for one-month tensile strength reduction at 60 °C are derived to meet 20-year durability targets in marine environments. Overall, the methodology provides a practical, interpretable, and more accurate basis for GFRP material selection and durability-based design in engineering practice.

**KEYWORDS**: FRP; GFRP bar; Durability prediction; Physics-driven; Machine learning.

# A NOVEL DEGRADATION-DIFFUSION COUPLING MODEL FOR DURABILITY OF GFRP BARS

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**ABSTRACT**

The prediction of the long-term durability of glass fiber-reinforced polymer (GFRP) bars is of critical importance for structural design. Existing models often treat diffusion and material degradation independently and neglect the size effect. Since degradation initiates at the bar surface and progresses inward, the bar diameter affects its durability but is rarely considered. This study investigated the coupled effects of bar size, environment, and temperature on GFRP degradation. GFRP bars with diameters of 6, 10, and 14 mm were immersed in water and simulated seawater sea-sand concrete pore solutions at 23, 40, and 60 °C. The results show that the simulated concrete environment significantly accelerates degradation, and smaller-diameter bars exhibit more severe strength reduction, with size effects being more pronounced under alkaline and high temperature conditions. A coupled diffusion-degradation model was developed to capture the size-dependent deterioration. The model shows a good agreement with test data, and the fitted parameters follow Arrhenius relationships with clear physical meaning. The proposed framework provides a mechanistic basis for predicting the long-term performance of GFRP bars in aggressive environments.

**KEYWORDS**: FRP; GFRP bar; Durability prediction; Fick diffusion; Arrhenius.

# TENSILE PROPERTIES OF AGED CFRP STRENGTHENING PLATES AND THEIR POTENTIAL FOR REUSE AFTER DECOMMISSIONING

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## ABSTRACT

Durability of CFRP EBR systems is critical for the longevity of strengthening schemes. Many previous studies considered accelerated conditioning or real field exposure to investigate the influence of environmental degradation on materials and bond performance in outdoor (typically unprotected) applications or harsh conditions, to provide information for long-term durability design guidelines in worst-case scenarios. However, in a significant proportion of strengthened structures, CFRP systems stay protected at building interiors or are provided with additional protection measures for environmental exposure. Although the durability of protected CFRP is deemed exceptional, there is currently no information reported in the literature verifying material stability or studying the potential deterioration mechanisms after long-term ageing. This paper presents results from a mechanical characterisation study on two different prefabricated unidirectional carbon fibre/epoxy plates produced in 1986 and 1996, respectively, which have been kept at ambient indoor conditions since then. Coupon testing revealed no degradation of the fibre-dominated longitudinal tensile properties after 40 and 30 years, respectively. However, transverse tensile testing revealed potential signs of matrix degradation in the case of the 30-year-old plate, but not for the 40-year-old material. Overall, the results confirm the good long-term stability of tensile properties in prefabricated CFRP, however, further research is required regarding the influence of matrix-related deterioration on system performance. Based on these findings, the concept of circularity and potential reuse of durable CFRP strips even beyond the decommissioning stage of strengthened buildings is discussed.

**KEYWORDS**: Prefabricated CFRP plates; Durability; Ageing; Reuse; Circularity.

# CIRCULAR REUSE OF MARINE WOODEN PILES VIA CFRP-STRENGTHENED JOINTS

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**ABSTRACT**

Wooden piles have been a proven construction method for building foundations for many centuries. However, they have now been almost completely replaced by reinforced concrete and steel piles. Nevertheless, wooden piles from valuable hardwood are still used, especially for marine protective structures like dolphins and groynes. The tidal range and wood-destroying marine organisms, as well as fungi are the main causes of local degradation of the wooden piles. The conventional practice is to fully replace damaged piles with new ones, oftentimes with high-cost tropical hardwood. However, it has been found that the wooden piles remain undamaged in the large section which has been driven into the ground due to absence of oxygen. This raises the question of whether and how these intact pieces can be reconnected and reused as new piles. To answer this question in more detail, research has been conducted at Leibniz University Hannover on biaxial, flexurally rigid longitudinal wooden pile connections strengthened with carbon fiber reinforced polymer (CFRP) fabric. This study describes the small-scale tensile behaviour, as well as large-scale bending behaviour of this novel joining technique. In addition, real-scale impact pile driving tests carried out with new and 120-year-old piles are shown.

**KEYWORDS**: Wooden piles; Marine; Reuse; Timber; CFRP; Strengthening.

# MULTI-SCALE DURABILITY ASSESSMENT OF CONCRETE STRENGTHENING WITH CFRP SYSTEMS

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## ABSTRACT

Understanding the long-term performance of externally bonded strengthening systems subjected to sustained loading and environmental exposure is critical for ensuring safety and reliable design of strengthening measures for aging civil infrastructure. To this end, this study presents a comparative assessment of the long-term performance of reinforced concrete elements strengthened with unstressed and prestressed carbon fiber reinforced polymer (CFRP) strips with non-mechanical end anchors purely relying on CFRP-concrete bond, examining material performance, bond-level behavior of lap-shear specimens, and structural response of slabs. Different specimens were subjected to various accelerated or natural environmental exposures, including freeze-thaw cycling, humidity variations, and concrete carbonation. Durability data from two different institutions were used to facilitate comparative assessment and enhance the reliability of the findings. Experimental findings indicate that concrete exhibits resistance to degradation agents, whereas epoxy adhesive is highly susceptible to prolonged water exposure. Accelerated freeze-thaw (FT) cycling causes significantly greater bond deterioration than natural FT aging. CFRP prestressing via gradient anchorage presents a robust short-term performance but raises durability concerns. Overall, this study underscores the need to correlate accelerated and natural aging data to establish reliable environmental conversion factors for design, especially prestressed strengthening systems.

**KEYWORDS**: Reinforced concrete durability; CFRP strengthening; Gradient anchorage; Externally bonded reinforcement (EBR); Natural aging; Accelerated aging; Prestress.

# TOWARDS LOW-ENVIRONMENTAL-IMPACT GFRP REINFORCEMENT: CHARACTERISATION OF A RECYCLED PET-MODIFIED POLYESTER MATRIX

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## ABSTRACT

The urgent need to reduce the environmental impact of reinforced concrete structures, particularly in terms of $CO_2$ emissions and resource consumption associated with steel production, is driving the development of new sustainable reinforcement materials. This study introduces an innovative glass fiber reinforced polymer (GFRP) bar designed with a thermosetting unsaturated orthophthalic polyester resin that incorporates a minimum of 20% recycled polyethylene terephthalate (PET) from post-consumer plastic waste. The selected resin offers a significantly lower environmental footprint and reduced production cost compared with conventional vinyl ester and epoxy matrices, while ensuring adequate physical and mechanical properties for structural applications. The bar features a ribbed surface and an external epoxy coating to enhance the bond with concrete and provide resistance to environmental degradation. In this work, a preliminary experimental investigation was conducted to assess the physical, chemical, and mechanical behavior of the polyester-PET matrix, with results compared against commercial resins such as orthophthalic, isophthalic, and vinyl ester systems. Specimens were conditioned in alkaline, saline, and tap water environments to simulate aggressive exposure scenarios typical of reinforced concrete elements. The outcomes of this study provide promising indications of the feasibility of low-impact resin systems for FRP reinforcement, paving the way for the development of circular composite solutions for durable and sustainable infrastructure.

**KEYWORDS**: Sustainable glass FRP reinforcement; Recycled PET-based resin; Low-impact composite materials; Durability in aggressive environments; Circular construction technologies.

# SS03 - Advancing FRP in structural engineering: a tribute to the legacy of Dr. Sami Rizkalla

# COMPARATIVE ASSESSMENT OF PASSIVE CFRP AND ACTIVE FE-SMA CONFINEMENT SYSTEMS FOR RETROFITTING DEFICIENT RC COLUMNS

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**ABSTRACT**

Seismically deficient reinforced concrete (RC) bridge columns built to outdated design provisions are susceptible to brittle flexural-shear failures and often show inadequate ductility and premature, rapid strength degradation under cyclic loading. This study experimentally investigates and compares the effectiveness of passive Carbon Fiber-Reinforced Polymer (CFRP) jackets and active Iron-based Shape Memory Alloy (Fe-SMA) confinement systems in enhancing the seismic performance of such columns. Large-scale circular RC columns were tested under a constant axial load and quasi-static cyclic lateral loading. The unstrengthened (as-built) column failed in a brittle flexural-shear mode at low drift. In contrast, CFRP- and Fe-SMA-confined columns exhibited stable hysteretic responses, improved ductility, enhanced lateral strength, and significant post-peak strength retention.

In contrast, both confined columns exhibited pure flexural failure, emphasizing the essential role of confinement in achieving ductile performance. The CFRP jacket provided continuous, uniform passive confinement, delaying cover spalling, maintaining core integrity, stabilizing post-yield response, and increasing drift capacity. Meanwhile, when thermally activated, the Fe-SMA plates generated recovery stresses that produced active confinement pressure, further increasing displacement ductility and enhancing re-centering capacity and cumulative energy dissipation by up to 40% compared with CFRP confinement.

Overall, the results demonstrate that passive CFRP confinement offers a practical, lightweight retrofit solution, while active Fe-SMA confinement provides advanced self-stressing capability and deformation control, both of which contribute to greater seismic resilience and an extended service life for deficient RC bridge columns.

**KEYWORDS**: CFRP confinement; Ductility; Energy dissipation; Fe-SMA confinement; Seismic retrofit.

# FIRE DESIGN OF GFRP REINFORCED CONCRETE MEMBERS WITH EMPHASIS ON ACI 440.11-22 AND CSA S806

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## ABSTRACT

Canadian research on the fire performance of concrete structures containing fibre reinforced polymers (FRPs) was instigated and facilitated by Professor Sami Rizkalla's leadership in the Intelligent Sensing for Innovative Structures Research Network. Glass fibre-reinforced polymer (GFRP) reinforcement offers durability advantages over steel in corrosive environments, but its application in fire-rated concrete members has been limited by uncertainty about behaviour at elevated temperature. Recent experimental work has shown that the critical vulnerability of GFRP-reinforced concrete (GFRP-RC) members in fire is not tensile rupture of the bars but rapid degradation of bar to concrete bond and anchorage as resin temperatures approach 150–200 °C. Pull-out tests demonstrate that bond strength becomes negligible in uniformly heated regions by about 200 °C, while tensile capacity and stiffness of the bars remain partially available. Full-scale furnace tests on slabs and beams confirm that members with realistic covers and properly detailed cool anchorage zones of 200 to 300 mm can sustain two to three hours of standard fire exposure under service-level loads, whereas similar members with splices or insufficient cool length in the heated span fail much earlier by bond failure. Building on this evidence, recent codes have begun to adopt fire-design approaches focusing on bond and anchorage into cool zones. The ACI 440.11-22 Code acknowledges the sensitivity of GFRP to heat and permits its use in fire-rated assemblies only when performance is demonstrated by testing or alternative-means analysis, while the CSA S806 Standard (Annex J) provides a normative procedure that combines product-specific high-temperature tensile and bond tests with simplified relationships between cover, cool-zone length, insulation, and fire-resistance rating. Together, these developments shift fire design for GFRP reinforced concrete away from simple tensile-strength reduction factors towards a rational framework in which heat transfer, bond loss, and anchorage are treated explicitly, and in which external fire-protection systems such as cementitious spray-applied materials can be applied selectively to secure non-bond-critical behaviour where geometry alone cannot provide adequate protection.

**KEYWORDS**: GFRP reinforcement; Fire resistance; Bond degradation; CSA S806 annex j; ACI 440.11-22; Cool zone detailing.

# STATISTICAL EVALUATION OF CFRP PRESTRESSING STRANDS FOR QUALITY CONTROL IN BRIDGE APPLICATIONS

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**ABSTRACT**

The increasing use of CFRP prestressing strands in concrete bridges has outpaced the development of CFRP-oriented ASTM standards for routine quality control (QC). Consequently, current guidelines rely on research findings, GFRP-based ASTM provisions, and engineering judgment, often resulting in extensive testing requirements that are impractical for large-scale projects. This study presents a statistical evaluation of tensile test results obtained from 15.2 mm CFRP strands used in the construction of the Harkers Island Bridge, North Carolina's first all-FRP-reinforced and prestressed concrete bridge. A total of 326 CFRP strands from 73 production lots were tested as part of the project's QC program, with a filtered dataset of 290 specimens from 52 lots retained for statistical analysis. All tested lots exceeded the minimum tensile strength requirements specified in the project provisions, demonstrating consistent material performance. The experimental data were verified to follow a normal distribution and analyzed assuming a 5% margin of error at confidence levels of 90%, 95%, 99%, and 99.7%. Results indicate that the tensile modulus of elasticity is the most sensitive parameter for QC assessment and that only 2 to 5 replicate tests are required to achieve these confidence levels, compared to the 10 replicates specified in project requirements. By establishing statistically based sample-size recommendations grounded in a full-scale bridge application, this work provides a rational framework for QC of CFRP prestressing strands and informs the development of future ASTM standards specifically targeting CFRP reinforcement systems.

**KEYWORDS**: CFRP strands; Quality control; Statistical analysis; ASTM standards; Bridges.

# POST-TENSIONING OF SWISS BRIDGES WITH CFRP CABLES


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## ABSTRACT

This paper presents four bridge strengthening projects in which the structures were post-tensioned with CFRP Parallel Wire Cables (PWC) in the southern and central Swiss Alps.
The first two bridges in Verdasio and Lucerne (spanning over Kleine Emme River) were strengthened in the late 1990ies and made use of a rather complex Empa-patented gradient anchorage technology to anchor and prestress CFRP parallel-wire cables. Unidirectional CFRP wires produced via pultrusion were used, and they proved their durability over two decades under sustained prestressing forces. The long-term experience with these two bridges has been very satisfactory and monitoring data of up to 27 years are going to be presented in this paper, even though Kleine Emme bridge had to be dismantled in 2016 due to a new flooding protection scheme implemented in Lucerne.
In the past five years, Carbo-Link AG (a former Empa spin-off) and Empa have been developing novel and simpler resin grout CFRP anchorages for CFRP PWCs. This new technology has enabled Carbo-Link to prestress two bridges in the central Swiss canton of Lucerne. Ilfis-Brücke has been strengthened in 2023 installing re-used pultruded CFRP wires out of the dismantled Kleine Emme bridge, whereof monitoring data over more than 2 years are presented. End of 2024 two stronger CFRP cables could be implemented during casting of field 7 of Renggloch bridge. Project details are discussed in this paper and conclusions for future applications using CFRP post-tensioning cables will be drawn.



**KEYWORDS**: Carbon fiber reinforced polymers (CFRP); Parallel wire CFRP cables; CFRP pultrusions; Bridge post-tensioning; Bridge monitoring.

# SHOTCRETE ABRASION DAMAGE TO SAND-COATED GFRP BARS: EXPERIMENTAL TESTING AND MODELLING

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## ABSTRACT

The abrasion resistance of sand-coated glass fibre-reinforced polymer (GFRP) rebars during shotcrete placement remains uncertain, particularly under high-velocity impact from shotcrete aggregates. This study experimentally quantified shotcrete-induced abrasion damage to 15.9 mm diameter sand-coated GFRP bars exposed to wet-mix shotcrete for 5, 15, or 25 seconds using either round or angular aggregates. Angular aggregate shotcrete produced measurable cross-sectional area reductions of up to 18% after 25 s of exposure, whereas round aggregates resulted in negligible area loss within the tested spray durations. For bars that did not exhibit a measurable reduction in cross-sectional area, the removal of sand coating was frequently observed. A preliminary quadratic relationship was established between spray duration and bar cross-sectional area loss based on the limited data available. To extend these findings to structural applications, a Monte Carlo model was developed and validated to estimate the effective spray duration as a function of bar depth within a structural element. Worst-case wet- and dry-mix shotcreting conditions were incorporated to derive a simplified expression for predicting the reduced bar cross-sectional area. The proposed framework provides a practical method for estimating abrasion damage to sand-coated GFRP reinforcement in shotcrete construction. It is important to recognize that this is the first attempt to address this complex problem, based on limited data. Further experiments are underway and will most likely result in refinements to the model presented herein.

**KEYWORDS**: Shotcrete; GFRP reinforcement; Abrasion damage; Cross-sectional area loss; Monte Carlo modelling.

# DURABILITY-DRIVEN FAILURE MODE TRANSITION IN PRESTRESSED NSM-CFRP STRENGTHENED RC BEAMS SUBJECTED TO SEVERE FREEZE–THAW EXPOSURE

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**ABSTRACT**

This paper reports on an experimental investigation of the flexural response and durability performance of reinforced concrete (RC) beams strengthened with prestressed near-surface-mounted (NSM) carbon fibre reinforced polymer (CFRP) strips subjected to accelerated freeze–thaw cycling. Five full-scale simply supported beams were tested under monotonic four-point bending: one unstrengthened control specimen and four beams strengthened with NSM-CFRP strips prestressed to 0%, 20%, 40%, and 60% of the CFRP's ultimate tensile strength. After strengthening, the specimens were pre-cracked to 1.2 times the analytical cracking load and then exposed to 500 freeze–thaw cycles between +34°C and −34°C to simulate severe cold-region environmental conditions.

A comparative evaluation with identical unexposed specimens shows that freeze–thaw cycles mainly reduce the ultimate limit state by lowering concrete compressive strength and altering failure modes. At low prestressing levels (≤20%), exposure shifted the failure mode from CFRP rupture to concrete crushing, reducing the ultimate load by 2–9% and the ultimate deflection by up to 20%. Conversely, beams prestressed at ≥40% showed minimal strength loss and maintained FRP-controlled failure. Prestressing significantly increased cracking and yield loads, with increases of up to 64% compared to the control beam. An energy-based deformability assessment identified an optimal prestressing range that balances strength improvement and ductility preservation.

The findings indicate that prestressed NSM-CFRP strengthening systems sustain strong structural performance even under severe freeze–thaw conditions, particularly at moderate to high prestressing levels.

**KEYWORDS**: Prestressed NSM-CFRP strengthening; Freeze–thaw durability; Flexural behaviour; Failure mode transition; Energy-based ductility/deformability assessment.

# PERFORMANE OF CFRP STRENGTHENED RC BEAMS UNDER COMBINED ACTION OF FATIGUE LOADING AND FREEZE-THAW

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## ABSTRACT

This study investigates the performance and durability of reinforced-concrete (RC) beams strengthened in flexure with externally bonded carbon-fiber-reinforced polymer (CFRP) sheets under combined freeze–thaw exposure and fatigue loading representative of Canadian service conditions. The objective is to quantify the role of confinement and anchorage on fatigue life, stiffness retention, cracking, strain demand, and post-fatigue capacity, and to identify the governing degradation mechanism. An experimental program evaluated mechanical response, bond behavior, and damage evolution under fatigue loading applied at 3 Hz in two ranges from 37.5 to 62.5% and 30 to 70% of static capacity, and under freeze–thaw conditioning up to 300 cycles. At the lower fatigue range, specimens reached $2\times10^6$ cycles without fatigue failure, whereas the higher range produced premature failures by steel rupture (controls) or CFRP debonding (strengthened beams). U-shaped anchorages delayed or prevented premature debonding, reduced stiffness degradation by up to ~50%, and limited crack widths relative to non-anchored cases. Freeze–thaw exposure, particularly beyond 200 cycles, increased crack widths, strain demands, and stiffness loss. Post-fatigue static tests showed that several CFRP-strengthened beams retained or modestly exceeded their original static strength (up to 12%), likely due to strain hardening of the reinforcement. The novelty of this work lies in its integrated assessment of CFRP-strengthened members under simultaneous cyclic and climatic stressors with and without anchorage, and in isolating bond durability at the CFRP–concrete interface as the performance-governing limit state.

**KEYWORDS**: CFRP; Fatigue; Freeze–thaw; Reinforced-concrete beams; Bond durability.

# TORSIONAL CAPACITY PREDICTION OF FRP-STRENGTHENED CONCRETE BEAMS USING GENETIC EXPRESSION PROGRAMMING

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**ABSTRACT**

Accurate prediction of the torsional capacity of fibre-reinforced polymer (FRP) strengthened reinforced concrete (RC) beams remains a challenging task in structural design. Existing design codes, including AS 5100:2017, often adopt conservative assumptions, particularly with respect to effective FRP strain, which can lead to significant underestimation of torsional resistance. To address this limitation, this study proposes a data-driven predictive model based on Genetic Expression Programming (GEP) for estimating the torsional strength of FRP-strengthened RC beams. A comprehensive experimental database comprising 160 torsion test results collected from the literature was used to train and validate the GEP model. The predictive performance of the proposed model was evaluated using a dataset of 57 FRP-strengthened RC beams and compared against the torsional design equations of AS 5100:2017. Statistical indicators demonstrate that the GEP model significantly outperforms the code-based approach, achieving a higher coefficient of determination and substantially lower prediction errors. The findings indicate that GEP-based modelling offers a simple, efficient, and accurate tool that can be used in conjunction with existing design codes to support advanced and performance-based torsional design.

**KEYWORDS**: FRP; RC beams; PC beams; Torsion; Genetic expression programming (GEP).

# PERFORMANCE-BASED EVALUATION OF ALTERNATIVE REINFORCEMENT SYSTEMS UNDER ACCELERATED FREEZE-THAW AND CHLORIDE EXPOSURE

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**ABSTRACT**

This paper presents a comprehensive structural–durability evaluation of concrete beams reinforced with seven reinforcement systems, subjected to sustained loading and accelerated freeze–thaw cycling under chloride exposure. The reinforcement systems included steel-based reinforcement (conventional black steel–BS, stainless steel–SS, low-carbon high-chromium-alloyed steel–MM) and fiber-reinforced polymer (FRP)-based reinforcement (two types of glass FRP–GFRP, carbon FRP–CFRP, and basalt FRP–BFRP). Twenty-eight reinforced concrete beams were pre-cracked to 40% of the theoretical ultimate flexural capacity before exposure to 195 freeze–thaw cycles between −34°C and +34°C, with periodic application of a 3.5% NaCl solution. This regime simulates severe Canadian winter conditions for bridge parapets exposed to de-icing salts. The central research problem is not solely corrosion resistance but rather the performance-based evaluation of structural response, stiffness evolution, ductility, and capacity retention under realistic cracked and exposed conditions. The findings confirm that FRP-reinforced concrete beams are structurally viable alternatives to steel-reinforced systems, particularly in aggressive or durability-critical environments. While traditional ductility definitions favour steel reinforcement, energy-based and deformability assessments demonstrate that FRP systems provide reliable, stable structural performance with substantial durability benefits. Steel-based systems generally exhibited narrower, more distributed cracks, whereas FRP systems exhibited wider crack openings, consistent with lower modulus and higher curvature. Although steel-based reinforcement demonstrated superior stiffness and crack control, FRP-based reinforcement provides complete corrosion immunity, eliminating the primary deterioration mechanism in chloride-exposed bridge elements. When properly designed to meet serviceability requirements, FRP-reinforced concrete members offer highly durable, low-maintenance structural solutions, particularly suited for aggressive environments.

**KEYWORDS**: Black steel; Stainless steel; Low-carbon high-chromium-alloyed steel; CFRP; GFRP; BFRP; Freeze-thaw exposure.

# DAMAGE AND FAILURE ANALYSIS OF FRP STRENGTHENED RC BEAMS WITH OPENINGS

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## ABSTRACT

In the real world, openings are often needed in RC beams for the passage of ducts or pipes. If these openings are designed prior to construction, adequate reinforcement can be provided as a preventive measure. However, if these openings are carved after construction, these openings lead to a significant decrease in the ultimate load and stiffness due to the reduction of the cross-sectional area of the concrete and the existing steel reinforcement. In such cases, externally bonded (EB) fiber-reinforced polymer (FRP) can be used to strengthen the weakened beam. Finite element analyses of RC beams are performed in this study using ABAQUS to investigate the effect of openings on flexural behavior. The present FE approach examines the behavior of the RC beams under different structural conditions, taking into account material nonlinearity. The existing numerical models also do not consider damage in FRP. The present FE approach incorporates damage in concrete through the concrete damage plasticity model and simulates failure of FRP sheets using a progressive damage model based on Hashin damage criteria developed using a user-defined subroutine VUMAT. In this study, parametric analyses on different FRP lengths, thicknesses, and lamination schemes are carried out using the developed finite element modelling technique to find an efficient FRP strengthening system for the weakened RC beam with an opening. The study highlights that the proposed FRP strengthening system is effective when sufficient sheet length and proper fiber orientation are provided, while an increase in the thickness offers limited benefit as it suffers from premature debonding. The developed numerical modelling technique can accurately analyze RC beams with openings, and the results from the present analysis will be useful for design recommendations and practical applications.

**KEYWORDS**: RC Beams; Flexural Strengthening; Fiber Reinforced Polymer; Finite Element Modelling; Progressive Damage Model.

# FINITE ELEMENT AND ANALYTICAL ASSESSMENT OF CFRP CONFINEMENT FOR CONCRETE COLUMNS: TOWARD STIFFNESS-BASED DESIGN


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## ABSTRACT

This study presents an integrated finite element (FE) modelling and analytical investigation of concrete confinement with Carbon Fibre-Reinforced Polymer (CFRP) systems, focusing on model calibration, parametric behaviour, and design-oriented implications. Advanced FE models are developed to capture the nonlinear interaction between the CFRP jacket and the confined concrete core under uniaxial compression. The numerical framework is implemented with an extended Drucker-Prager plasticity formulation, calibrated via regression analysis of experimental data to define confinement-dependent yielding, hardening–softening behaviour, and dilation. This calibration strategy enables reliable prediction of both pre-peak and post-peak stress–strain response across a wide range of confinement levels.

In parallel, existing analytical confinement models are critically assessed and refined to improve their applicability to design. Modifications to conventional formulations are introduced via enhanced failure surfaces and confinement-sensitive constitutive relationships, addressing known deficiencies in predicting ultimate axial strength, ultimate axial strain, and post-transition behaviour of CFRP-confined concrete. Comparisons among FE predictions, refined analytical models, and experimental results show strong agreement, with lower prediction errors than those of commonly used design-oriented models.

A comprehensive parametric study is conducted using the validated FE model to quantify how CFRP jacket thickness and elastic modulus (i.e., CFRP lateral stiffness) affect confinement effectiveness and deformability. The results show that CFRP stiffness and jacket thickness govern both strength enhancement and strain capacity, directly influencing the slope and stability of the post-yield response. These findings provide practical insights for optimizing CFRP design and support the development of more reliable confinement models for structural assessment and strengthening applications.



**KEYWORDS**: CFRP confinement; Structural strengthening; Finite element modelling; Analytical modelling; Stiffness-based design.

# A RESIDUAL–EXPONENTIAL DECAY MODEL FOR POST-PEAK FLEXURAL SOFTENING IN LIGHTWEIGHT GLASS FIBER-REINFORCED CONCRETE

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## ABSTRACT

This study evaluates the flexural response of structural lightweight concrete (LWC) prisms with varying glass fiber dosages (0.5, 1.0, and 2.0% by volume), tested under four-point bending following ASTM C1609 (2012) procedures. Performance is quantified in terms of first-peak response, residual strength at specified deflections, and toughness (defined as the integrated area under the load–deflection curve). Results show that first-crack strength remains governed by the matrix, which confirms limited fiber influence prior to crack localization. In contrast, post-cracking behavior is strongly dependent on fiber volume fraction, with residual strength at 1/600 of the span length *L* increasing from 0.87 (0.5%) to 2.78 MPa (2.0%), and toughness up to *L*/150 increasing from 4.24 to 12.09 J. An analytical interpretation of the post-peak flexural softening regime is developed using a residual–exponential decay model, in which the degrading load component follows a first-order decay. The resulting decay parameters systematically decrease with increasing fiber volume fraction. The formulation further establishes a relationship between the shape of the curve and post-peak energy dissipation through a closed-form expression. Some convenient descriptors are introduced, including the characteristic softening length, half-life deflection increment, and energy retention factors. By framing the load–deflection response in terms of energy partitioning, the proposed approach distinguishes between experimental and theoretical energies, while addressing known limitations associated with truncation of the softening tail.

**KEYWORDS**: Glass fibers; Lightweight concrete; Fiber-reinforced concrete; Flexure; Toughness.

# OPTIMIZATION OF CFFT AXIAL CAPACITY: A PARAMETRIC STUDY OF GEOMETRY AND MATERIAL STRENGTH

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**ABSTRACT**

Concrete-Filled FRP Tube (CFFT) columns derive their axial capacity from the combined action of the concrete core and the confinement provided by the FRP jacket. This paper presents a comprehensive parametric study to quantify the influence of three critical design variables: concrete compressive strength ($f_c'$), GFRP tube thickness ($t_f$), and tube diameter ($D$), on the axial capacity of CFFT circular columns. The analysis utilizes a validated computational software, that was developed to predict the axial capacity over practical ranges of each parameter, considering both reinforced and unreinforced sections. Key findings show that the CFFT diameter ($D$) is the dominant factor, causing a non-linear, exponential increase in capacity. The concrete compressive strength ($f_c'$) also significantly enhances axial capacity, exhibiting a distinct bi−linear response. This behavior is interpreted as the interplay between the increasing concrete strength and the code limit on the effective confining pressure ($f_l \leq 0.33\, f_c'$). The GFRP tube thickness ($t_f$), while contributing to confinement, demonstrates a threshold beyond which further increases do not enhance axial capacity, also due to the confinement limit. The study compares the effect of reinforced and unreinforced columns, quantifying their contribution to the axial capacity. This work contributes novel design insights by explicitly mapping the non-linear relationship between key material and geometric properties and design code limits for CFFT under axial compression.

**KEYWORDS**: CFFT; Axial load capacity; Parametric study; Concrete confinement; Design optimization.

# FINITE ELEMENT MODELLING OF GFRP-REINFORCED CONCRETE BRIDGE BARRIER AND DECK OVERHANG UNDER TRANSVERSE VEHICLE IMPACT LOADING

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**ABSTRACT**

This paper presents a finite element (FE) investigation of a glass fiber-reinforced polymer (GFRP) reinforced concrete bridge barrier and deck overhang subjected to transverse vehicle impact loading, using the nonlinear dynamic software LS-DYNA. The study focuses on accurately modeling the material behavior of concrete and GFRP reinforcement under dynamic impact conditions. Model verification was conducted using experimental results from a recently performed full-scale TL-5 vehicle crash test. A detailed mesh sensitivity study was performed to evaluate the influence of different element sizes (50 mm and 100 mm) on the accuracy and computational efficiency of the model. The verified LS-DYNA model demonstrated excellent correlation with experimental observations, successfully replicating key performance parameters such as barrier deflection, crack initiation, and strain distribution. The findings validate the robustness of LS-DYNA for simulating complex impact behavior in GFRP-reinforced concrete systems and provide valuable guidance for optimizing reinforcement layouts and mesh strategies. The research outcomes support future design and safety assessments of bridge-deck overhangs and barriers in accordance with evolving highway bridge design standards.

**KEYWORDS**: Bridge barrier; Deck overhang; GFRP bars; Finite element modelling; LS-DYNA; Vehicle impact; Mesh sensitivity; Crash test verification.

# FINITE ELEMENT MODELING OF CONTINUOUS CONCRETE BEAMS PRESTRESSED WITH CFRP TENDONS

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## ABSTRACT

This study introduces and validates a comprehensive finite-element (FE) framework designed to simulate the structural behavior of continuous concrete beams prestressed with a hybrid configuration of bonded and unbonded steel and/or CFRP tendons. The formulation integrates a "trussed-beam" analogy within the FE model to capture global compatibility and tendon force recovery in unbonded layouts. Concrete is modeled with nonlinear tension-softening and compression damage models for concrete; while CFRP tendons are treated as linear elastic until rupture; and steel reinforcement as elastoplastic. Prestressing is introduced via equivalent initial strain/shortening, enabling direct tracking of the tendon stress increase, as well as secondary reactions across continuous spans. The framework is validated against full-scale experimental tests conducted by the authors, and other test data from the literature. Analytical results including load–deflection behavior, load– stress increment (Δfp) relationships, crack patterns, failure modes, and moment redistribution are compared to the experimental ones. The model idealizes tendons using embedded truss/cable elements and accounts for anchor compliance and deviator interactions. Finally, a parametric study quantifying the influence of tendon ratio and profile, prestress level, bond condition, and span continuity on strength, deformability, crack control, and service deflection is included. The results show close agreement between predictions and tests for stresses, deflections, cracking moment, and ultimate strength, and demonstrate that the proposed FE approach reliably estimates service deflections and Δfp for continuous members hybrid tendon configurations.

**KEYWORDS**: CFRP tendons; Unbonded prestressing; Finite-element analysis; Tendon stress increase; Continuous beams.

# RECENT DEVELOPMENTS RELATED TO FRP REINFORCEMENT FOR CONCRETE STRUCTURES, DESIGN CODES, AND APPLICATIONS IN CANADA

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**ABSTRACT**
The design principle of fiber-reinforced polymer (FRP) reinforcing bars for concrete structures has been well established through extensive research and field practices. Provisions governing certification testing and evaluation as well as quality control/assessment and FRP design provisions, are now in place to regulate materials specifications and design aspects and guide FRP manufacturers and end-users. The Canadian Standards Association (CSA) group addressing the state-of-the-art FRP material specifications and design requirement recently issued two updated provisions. The new editions of CSA S807, ASTM D7957, and ASTM D8505 include several additions and modifications in terms of quality and qualification requirements, material properties, testing procedures, and material mechanical and durability limitations. Additionally, the updated Section 16 of the Canadian Highway Bridge Design Code (CHBDC, CSA S6) for the design of fiber reinforced structures and highway bridges, the new edition of CSA S806 for the design and construction of building structures with Fibre-Reinforced Polymers (2026), the ACI 440.11 and AASHTO aimed at providing more rational design algorithms and allowing practitioners to take full advantage of the efficiency and economic appeal of FRP bars. This keynote presents a summary of these recent modifications in Canadian codes and standards, introducing the underlying rationale. Additionally, the keynote highlights the recent field applications of FRP bars in different types of concrete civil engineering infrastructure as well as the developments and advances in FRP reinforcements for sustainable and resilient concrete including straight and bent rebars using innovative techniques and materials.

**KEYWORDS**: Fiber-reinforced polymer (FRP); FRP-reinforced concrete structures; Design codes.

# FLEXURAL BEHAVIOUR OF HYBRID UTILITY POLES: NEW DESIGN OPTIMIZATION USING LIGHT-WEIGHT-MORTAR AND HOLLOW STEEL/CFFT CONFIGURATION

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## ABSTRACT

Utility poles are a crucial component of modern society, forming the backbone of infrastructure that supports electric lines, communication cables, traffic lights, and signals. In this study, three configurations of hybrid utility poles were investigated, and the results of full-scale testing are presented and compared. All poles were 12 ft in length, and bending tests were performed in accordance with ANSI Standard C136.20-2012 (R2021). Two configurations consisted of light-weight mortar filling sandwiched between an outer GFRP composite layer and an inner steel layer. The experimental program was conducted in two phases: the first phase served as a baseline for the initial design, and the second phase incorporated significant improvements over the initial configuration. Several parameters were considered during the design optimization phase, including the winding angles and number of layers in the GFRP shell. Improvements of up to 400 % in bending strength were achieved, resulting in more ductile and resilient utility poles using lightweight concrete filling. This paper presents the results of this design optimization and experimental study. The research aims to develop utility poles that are lighter, stronger, and more durable, contributing to a more sustainable future.

**KEYWORDS**: Utility poles; Composite structures; Flexural performance; Hybrid structures; Hollow steel/CFFT.

# ADVANCING PERFORMANCE-BASED DESIGN OF FRP RETROFITS FOR RC STRUCTURES

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## ABSTRACT

Pre-1970s reinforced concrete (RC) buildings are highly vulnerable to earthquakes due to poor reinforcement detailing in plastic hinge regions (e.g. poor confinement and the existence of lap splices) and insufficient transverse reinforcement in the beam-column joint on frame buildings. Methodologies for seismic performance evaluation of existing RC buildings have received global attention over the last few decades, yet the advancement of fiber-reinforced polymer (FRP) seismic retrofit design has not kept pace. Although sophisticated performance-based evaluation frameworks are now available, current FRP retrofit provisions re-main predominantly strength-based and are not explicitly linked to performance objectives. A primary limitation is the lack of validated nonlinear modeling parameters for FRP-retrofitted components, which constrains their integration into performance-based engineering practice. This study examines how performance-based engineering principles can be ex-tended to the design of FRP seismic retrofits. For deformation-controlled actions, FRP strengthening can be designed using a displacement-based approach, supported by ASCE 41-type nonlinear modeling parameters and acceptance criteria. Conversely, force-controlled actions (e.g., FRP retrofit of beam-column joints) can continue to follow a strength-based de-sign approach. Accordingly, the study presents nonlinear modeling parameters and acceptance criteria for FRP-jacketed RC columns, as well as a shear strength equation for FRP-retrofitted beam-column joints calibrated against experimental databases. The proposed formulations collectively advance on the performance-based design of FRP seismic retrofits by enabling consistent evaluation of the seismic performance of as-built and retrofitted RC structures.

**KEYWORDS**: Retrofit; Seismic; FRP; Performance-based; Reinforced concrete.

# SS04 - Applied artificial intelligence and reliability assessment methods in structural concrete members reinforced with FRP

# SURROGATE-ASSISTED RELIABILITY-BASED DESIGN OPTIMIZATION OF NOVEL FRP-RC SANDWICH PANELS

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**ABSTRACT**

The increasing use of Fiber-Reinforced Polymer (FRP) reinforcement in concrete structures, prized for its corrosion resistance, demands advanced design methodologies that account for its unique linear-elastic and brittle behavior. This paper proposes a comprehensive methodology for the surrogate-assisted Reliability-Based Design Optimization (RBDO) of an innovative Expanded Polystyrene-Reinforced Concrete (EPSB-RC) sandwich panel system, considering both Glass FRP (GFRP) and conventional steel reinforcement. The core of the proposed framework addresses the prohibitive computational expense of running high-fidelity nonlinear Finite Element (FE) simulations directly within an optimization loop. To overcome this, an efficient surrogate model (e.g., Kriging or Polynomial Chaos Expansions) is trained on a limited set of high-fidelity FE model evaluations. This metamodel is constructed in an augmented space, which combines both deterministic design variables (e.g., geometry) and random variables (e.g., material properties, loads) to accurately approximate the system's limit-state function across the entire design domain. This surrogate then replaces the computationally expensive FE analysis within a double-loop optimization process. The outer loop employs a Multi-Objective Genetic Algorithm (MOGA) to explore the design space and identify a Pareto-optimal front, balancing conflicting objectives such as maximizing structural capacity while minimizing cost and environmental impact. The inner loop performs a reliability analysis (e.g., First-Order Reliability Method or Monte Carlo Simulation) to evaluate the probabilistic constraints for each candidate design. This ensures that the resulting Pareto-optimal designs satisfy a pre-defined target reliability level (β-target). By integrating these techniques, the adopted framework provides a computationally efficient pathway for developing safe, optimized, and reliable design guidelines for novel FRP-composite structures.

**KEYWORDS**: Fiber-reinforced polymer (FRP); Sandwich panel; Composite structures; Multi-objective optimization; Structural reliability analysis.

# PHYSICS-INFORMED ML PREDICTION MODEL FOR THE FLEXURAL CAPACITY OF FRP-RC BEAMS

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## ABSTRACT

Fiber-reinforced polymer (FRP) bars are increasingly adopted as an alternative to steel reinforcement in reinforced concrete (RC) structures due to their high tensile strength and excellent resistance to corrosion. However, the structural design of FRP-RC members remains challenging because FRP reinforcement exhibits linear-elastic behaviour up to brittle failure, leading to flexural mechanisms fundamentally different from those of conventional steel-RC beams. Although several analytical and empirical models have been proposed, their limited predictive accuracy restricts the broader application of FRP-RC systems. This study proposes a physics-informed machine learning (PIML) framework for predicting the flexural capacity of FRP-reinforced concrete beams. A comprehensive database comprising 299 experimental flexural test results, covering a wide range of geometrical configurations of beams, concrete strengths, and FRP material properties, is compiled for model development and validation. The proposed approach embeds section-level mechanics directly into the learning process of a multilayer perceptron, such that predictions are not only data-driven but also consistent with governing structural principles. The imposed mechanics-based constraints considered in this study include strain compatibility, internal force equilibrium, FRP rupture and concrete crushing limits, complemented by guidance from ACI 440 design provisions. Key relationships are enforced as hard constraints through the mechanics-based section formulation, while remaining requirements are incorporated as soft penalties via residual terms in the loss function. The results demonstrate that the proposed PIML model consistently outperforms conventional design equations and purely data-driven machine learning models on the compiled database, reduces non-physical predictions, and generalizes better across different FRP types and parameter ranges. The findings confirm the potential of PIML as a reliable and robust tool for structural design, offering improved predictive accuracy while maintaining consistency with established structural mechanics, and supporting the wider adoption of sustainable FRP reinforcement in concrete structures.

**KEYWORDS**: Fiber-reinforced polymer (FRP); Reinforced concrete (RC); Flexural strength; Physics-informed machine learning (PIML); Design codes.

# THE IMPACT OF FEATURE ENGINEERING AND DATA ON ML/AI PERFORMANCE FOR CONCRETE STRUCTURES

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**ABSTRACT**

Disturbed regions (D-regions) in reinforced concrete structural elements have non-linear strain and stress distribution across the cross-section that cannot be adequately described using classical sectional design approaches based on linear strain distribution. The Strut-and-Tie Method (STM) provides a rational mechanical framework for modeling these regions, yet its application relies heavily on engineering judgment and iterative equilibrium solutions, limiting its automation and scalability in large parametric studies. This paper presents a comprehensive data-driven framework for predicting tie tensile forces in Strut-and-Tie models of fiber-reinforced polymer (FRP) reinforced concrete D-regions using Artificial Neural Networks (ANNs) and Deep Neural Networks (DNNs). A large synthetic dataset of approximately 100,000 STM equilibrium solutions was generated algorithmically, covering a wide range of geometries, material properties, reinforcement ratios, and load configurations representative of FRP reinforced concrete deep beams which are considered a classical D-region elements due to their low span-to-depth ratio (<~2). Three levels of feature representation were examined: raw inputs (FE0), square interaction features (FE2), and higher-order physics-informed nonlinear features (FE3). Systematic comparisons between ANN models and progressively deeper DNN architectures were conducted using consistent training protocols. The findings indicate that accurate prediction of STM tie forces in FRP D-regions can be improved in ANN models through feature engineering, whereas in deeper models (DNN) feature engineering has a negligible effect on model accuracy. The proposed framework offers a robust basis for integrating machine learning into automated STM-based structural design workflows.

**KEYWORDS**: Artificial neural network; Deep neural network; Strut-and-tie model; D-regions; Reinforced concrete; FRP reinforcement; Machine learning; Structural engineering.

# RELIABILITY-BASED DESIGN OF FRP STRENGTHENING FOR EXISTING STRUCTURES: REAL-LIFE PROJECT EXPERINCE AND NEEDS

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**ABSTRACT**
Reliability analysis offers a rational framework for addressing uncertainties in the evaluation and strengthening of existing structures, and its use is recognized in specialized codes such as ACI 562 code (Assessment, Repair, and Rehabilitation of Existing Concrete Structures). Nevertheless, its application by practicing engineers remains limited. The primary barriers are the inherent complexity of probabilistic methods, which hinders the development of straightforward design aids that can be applied by structural design engineers, and the difficulty of standardizing project-specific information and conditions within current design codes/standards. The objective of this paper is to bridge the gap between research, codes, and practice by examining reliability analysis through the lens of real-life projects in Canada and Dubai, which the author has participated in, focusing on the role of reliability analysis in the evaluation and fiber-reinforced polymer (FRP) design of existing structures. The methodology synthesizes insights gained from buildings and structural systems where deficiencies ranged from under-designed members to deterioration in both gravity systems and lateral systems. From these experiences, the paper highlights how incomplete documentation, variable material properties, and site-specific deterioration mechanisms influence probabilistic modelling and design decisions. Based on these lessons, practitioner-oriented recommendations are presented, including simplified reliability-based procedures, strategies for integrating limited project data, and guidance for applying reliability outcomes to FRP design.

**KEYWORDS**: Reliability analysis; Existing structure; FRP design; Evaluation; Concrete structures.

# FLEXURAL DESIGN OF HYBRID GFRP-STEEL REINFORCED BEAMS USING PARTICLE SWARM OPTIMIZATION AND MOMENT-CURVATURE ANALYSIS

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**ABSTRACT**
Hybrid glass fiber reinforced polymer (GFRP)-steel reinforced steel fiber reinforced concrete (SFRC) beams offer significant advantages in corrosive environments. Steel reinforcement enhances ductility, while SFRC fibers reduce the formation of cracks, improve shear resistance and effectively minimize the need for traditional steel stirrups. However, designing these hybrid beams poses challenges, as existing code-based methodologies often fail to address the complexities of combined prestressed reinforcement. This study introduces an innovative approach to optimize the flexural design of hybrid GFRP-steel SFRC beams using metaheuristic optimization, specifically Particle Swarm Optimization (PSO). By integrating moment-curvature analysis, the proposed method accurately determines flexural capacity while achieving an optimal balance between strength, and ductility efficiency. Unlike data-intensive modern AI techniques, which are often limited to specific cross-sectional shapes, the PSO-based approach provides a statistically robust and versatile alternative. This ensures both adequate ductility and structural performance, filling a critical gap in the design of hybrid SFRC beams.

**KEYWORDS**: Hybrid reinforcement; GFRP-steel; SFRC; PSO; Moment-curvature analysis.

# DAMAGE IDENTIFICATION IN FRP-STRENGHENED RC BEAMS BASED ON VAE AND DISENTANGLED LATENT REPRESENTATION

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## ABSTRACT

Local monitoring of reinforced concrete (RC) structures strengthened with fibre reinforced polymers (FRPs) in civil construction applications allows to detect the possible premature debonding by identifying minor local damages. Different procedures based on the electromechanical impedance (EMI) method, formulated from measurements obtained from PZT patches, have been implemented in the recent years for this purpose.

Variational autoencoders (VAEs) are a probabilistic machine learning framework for posterior inference that projects an input set of high-dimensional data, such as the impedance spectra, to a lower-dimensional, latent space. The latent space learned with a VAE offers an low dimension attractive framework to develop damage and anomaly detection approaches from EMI spectra. However, the learned latent space is typically disorganized and entangled: Disentangled representation learning in variational autoencoders has emerged as a strategy to identify and disentangle underlying factors from observable data to improve identification capabilities such as EMl signals. Disentangled representation provides a representation where a change in one dimension corresponds to a change in one factor of variation, while being relatively invariant to changes in other factors. In this work, the performance of three different alternatives, standard VAE, β-VAE and Factor VAE ,to disentangle the latent space learned by a VAE is addressed.

**KEYWORDS**: FRP-strengthening; Structural health monitoring; EMI method; Variational autoencoders; Disentanglement.

# SS05 - IIFC TG3. FRP in extreme settings

# FIRE PERFORMANCE OF GFRP COMPOSITE SANDWICH PANELS: INFLUENCE OF CORE FOAMS AND WEB ARCHITECTURE

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**ABSTRACT**
This paper presents an experimental investigation about the fire resistance behaviour of vacuum infused sandwich panels composed of glass fibre-reinforced polymer (GFRP) face sheets and a polymeric core material. The main objectives of the study were to evaluate the influence of various parameters, such as (i) different panel's geometry (homogeneous-core vs. web-core panels), (ii) core materials (PET and PUR foams) and (iii) passive fire protection systems. To this end, simply supported GFRP panels were simultaneously subjected to a service load and the ISO 834 fire curve. The results obtained showed: (i) the better fire performance of sandwich panels with PET core compared to PUR; (ii) the longer fire resistance of web-core sandwich panels compared to homogenous-core ones, essentially due to the higher shear stiffness and strength provided by the longitudinal webs; and (iii) the effectiveness of passive fire protection systems in extending the fire endurance of the sandwich panels, as they delay the thermal degradation of their constituent materials.

**KEYWORDS**: Sandwich panels; GFRP; Fire behaviour; Fire protection systems; Polymeric core foams.

# DURABILITY OF POLYESTER-BASED GFRP-RC BEAMS UNDER HYDROTHERMAL AGING

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## ABSTRACT

Fiber-reinforced polymer (FRP) bars are suitable reinforcement materials for reinforced concrete (RC) elements, as they exhibit good mechanical performance, low weight, electromagnetic transparency, and, especially, a non-corrosive nature. Nevertheless, its durability decreases when exposed to humidity and alkaline ions. The durability of epoxy-and vinyl ester-based FRP bars is well documented, showing greater chemical resistance than that of polyester-based FRP bars. Recent studies have also shown that polyester-based FRP bars can exhibit tensile behavior similar to that of epoxy-and vinyl ester-based bars after alkaline aging. However, there is still a gap regarding the durability of polyester-based GFRP bars considering different conditioning times and temperatures, as well as the degradation rate of these bars when used in RC elements. This study aims to examine the hydrothermal effect of direct immersion of bare polyester-based GFRP in an alkaline solution at 30, 40, and 60°C for up to 6 months, and simultaneously age GFRP-RC beams in distilled water at 60°C for up to 6 months. After each aging time, the bare GFRP bars were subjected to tensile tests, and the GFRP-RC beams were subjected to three-point bending. Using the tensile data of bare GFRP bars, a predictive degradation model based on the Arrhenius Law was developed, allowing the definition of a long-term tensile strength retention rate. From the flexural data of the GFRP-RC beams, it was possible to compare the results with those from direct immersion and understand the effect of the degradation of the polyester-based GFRP bars on the flexural behavior of beams.

**KEYWORDS**: GFRP bars; RC beams; Long-term aging; Accelerated conditioning.

# DESIGN BOND STRENGTH REDUCTION CURVE FOR GFRP-REINFORCED CONCRETE AT ELAVATED TEMPERATURES

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**ABSTRACT**

The article focuses on the current area of designing concrete structures reinforced by modern composite materials and their application in extreme conditions. Drawing on a comprehensive database of experimental results on the bond strength of fibre-reinforced polymers (FRP) at elevated temperatures, the study aims to establish a design bond strength reduction curve in accordance with relevant standard regulations. The article also briefly summarises the existing state of knowledge in this field. The database combines previously published international experimental data with laboratory results obtained by the authors. Based on the created database, design quantiles were determined in accordance with the Eurocodes, from which the proposed reduction curve for FRP bond strength at elevated temperatures was derived. The proposed reduction curve considers the safety margins for the design of structures exposed to the effects of fire and is meant as a basis for new generations of European technical standards and their practical applications.  In contrast to most published curves, which are based solely on the mean values of the measurements, this proposed model adopts a more conservative approach, making it suitable for practical use. The article also reacts to the gap in the current design regulation, which allows the usage of FRP reinforcement; however, it does not consider its behaviour under fire load.

**KEYWORDS**: Glass fiber reinforced polymer (GFRP); Bond strength; Elevated temperature.

# CREEP BEHAVIOR OF CONCRETE BEAMS REINFORCED WITH MODIFIED GFRP BARS

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**ABSTRACT**

Reinforced concrete is a fundamental material in structural applications; however, the corrosion of steel reinforcement continues to pose significant durability challenges. Glass fiber reinforced polymer (GFRP) bars provide a promising corrosion-resistant substitute, especially for structures exposed to aggressive environments. Nevertheless, the long-term creep performance of GFRP bars remains a concern, motivating the development of modified GFRP materials to overcome this limitation and enhance their leverage. This study explores the creep behavior of concrete beams reinforced with modified GFRP bars under varying sustained stress for 75 days. Results showed that the creep ratio reached approximately 30% after 75 days of loading. In comparison with existing similar studies, the beam with modified GFRP bars showed superior creep performance. Furthermore, it was found that the creep ratio trend changed over time, as the creep ratio tended to be larger for specimens under higher loads during the early period but shifted to those under lower loads in the later period. The creep performance was also observed to exhibit two distinct stages, the primary stage and the secondary stage, with the primary stage showing a much more rapid increase in creep. These two stages were separated by an inflection point that clearly marked the transition between the phases. The results provided valuable insights for understanding the behavior of GFRP-reinforced concrete in general, as well as for improving their properties in particular.

**KEYWORDS**: Creep; Modified GFRP bars; Reinforced concrete beam.

# SS06 - IIFC TG1. Decarbonizing structures: FRP and FRCM strategies for concrete and masonry

# OPTIMAL FRP-REINFORCED CONCRETE SHELLS FOR CONSTRUCTION DECARBONIZATION: A PARAMETRIC ANALYSIS

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**ABSTRACT**

Although shell structures are an efficient solution for large-span buildings, their use is increasingly limited by the high embodied carbon associated with reinforced concrete and traditional construction methods. To address this issue, this paper presents a numerical procedure aimed at minimising the embodied carbon of concrete shells reinforced with fibre-reinforced polymer (FRP) bars. Developed in a Python–Grasshopper environment, the procedure combines shape and sizing optimisation, automated reinforcement design, and genetic algorithms.

A parametric study was conducted on square shells with spans ranging from 5 to 20 metres, focusing on the influence of key design variables such as shell thickness, support footprint and force density. The results show that total embodied carbon increases significantly with span, from around 3300 $kgCO_2e$ for L = 5 m to over 50000 $kgCO_2e$ for L = 20 m, with the contribution of FRP reinforcement remaining relatively limited at around 5%. The largest share is accounted for by the shell and columns. Optimal solutions are consistently obtained with a minimum shell thickness of 0.10 m and a balanced relationship between shell curvature and column size. When expressed per unit area, the embodied carbon ranges from 130 to 190 $kgCO_2e/m^2$, with improved efficiency observed for larger spans.

**KEYWORDS**: Concrete shells; Structural optimisation; Embodied carbon; Parametric analysis; FEM.

# MECHANICAL AND BOND PERFORMANCE OF FLAX-BASED NATURAL COMPOSITES FOR SUSTAINABLE RETROFITTING

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**ABSTRACT**

The construction sector is a major contributor to global emissions, with building materials accounting for nearly 40% of total emissions. Sustainable urban regeneration, achieved by rehabilitating rather than replacing existing structures, is therefore essential. In seismic regions such as Italy, however, structural safety must also be addressed by reducing the vulnerability of the built environment. Recently developed retrofitting solutions include fibre-reinforced composites with inorganic matrices (Textile Reinforced Mortars - TRMs). Compared to epoxy-based composite systems, TRMs exhibit superior chemical compatibility with masonry, reversibility for heritage applications, higher fire resistance, and lower environmental impact. Moreover, structural properties of plant-based fibres, such as flax, hemp, sisal, and jute, are increasingly investigated. Their use with inorganic matrices enabled the development of Natural Textile Reinforced Mortars (NTRMs), a green strengthening system. However, current knowledge of NTRMs remains limited, as their mechanical behaviour strongly depends on fibre properties, textile architecture, and bond performance with matrices and masonry substrates. The study aims to address some of these gaps by presenting the first results of a comprehensive experimental program on flax-based NTRM (F-NTRM) systems for masonry strengthening. Direct tensile tests on dry textiles were performed to assess the mechanical response, whereas single-lap shear tests on strengthened masonry blocks were then conducted to evaluate bond behaviour. It is highlighted that this work is part of the REHARZE project, funded under the PRIN 2022 program.

**KEYWORDS**: Sustainable composite materials; Masonry; External strengthening; Tensile tests; Direct single-lap shear tests.

# EXPERIMENTAL ASSESSMENT OF THE SHEAR BEHAVIOR IN MASONRY WALLS EXTERNALLY STRENGTHENED BY NATURAL TEXTILE-REINFORCED MORTARS

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## ABSTRACT

In recent years, growing attention to energy and environmental sustainability has prompted the construction industry to explore the use of environmentally friendly materials in structural reinforcement. In this context, inorganic matrix composites reinforced with natural fibres (natural textile-reinforced mortar, or NTRM) offer a promising solution for reducing environmental impact by providing an alternative to traditional synthetic material reinforcements. This study experimentally analysed the mechanical behaviour of masonry panels strengthened with NTRM systems in terms of shear strength and ductility, using diagonal compression tests. The reinforcement system was made using an innovative hybrid vegetal textile: flax textile impregnated with a biopolymer. Prior to testing the masonry walls, the mechanical properties of all elements constituting the reinforcement systems were characterised, including the mortars, meshes and other components. The results showed that panels strengthened with hybrid plant fibres performed significantly better, exhibiting a more uniform distribution of cracks and greater deformability. The experimental results were also analysed in light of existing regulations for these systems. The proposed analysis showed that the shear strength of the externally strengthened wall is more than 40% higher than that of the unreinforced wall when natural textiles are used. In fact, while the experimental evidence confirmed the potential of NTRM systems as a masonry wall strengthening solution, it also emphasised the need for further research into possible durability issues in the bio-based textiles and the overall reliability of the strengthening solution.

**KEYWORDS**: Textile reinforced mortars; Natural fibers; Masonry; Diagonal compression test.

# MECHANICAL BEHAVIOR OF CFRP-CONFINED LC3 CONCRETE INCORPORATING $CO_2$-TREATED RECYCLED AGGREGATE


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## ABSTRACT

With the growing urgency to decarbonize the construction industry, developing low-carbon materials with comparable mechanical performance to conventional systems has become a key challenge. This study investigates the mechanical behavior of Carbon Fiber-Reinforced Polymer (CFRP)-confined low-carbon concretes, including Limestone Calcined Clay Cement (LC3) and $CO_2$-treated Recycled Coarse Aggregate (CO2-RCA) based concretes, under different confinement levels. The experimental program examined the effects of water-to-cement (w/c) ratio, cement type, aggregate type, and number of FRP layers on strength and deformation characteristics. Results indicate that LC3 concrete exhibits approximately 5% lower compressive strength than Ordinary Portland Cement (OPC) in low-strength mixes, but about 6% higher in high-strength groups. $CO_2$ treatment improves the microstructure of recycled aggregates without a corresponding and effective increase in crushing value, which leads to about a 13% reduction in peak stress compared to natural aggregate concrete at high strength. CFRP confinement significantly enhances both strength and ductility in low-strength concretes; however, its confinement effectiveness factor decreases by roughly 12% for high-strength LC3 systems. Both LC3 and $CO_2$-RCA reduce confinement effectiveness factor under the same confinement ratio. Overall, CFRP confinement offers a promising reinforcement strategy for sustainable concretes, though design optimization is necessary to account for binder and coarse aggregate interactions to ensure reliable structural and environmental performance.



**KEYWORDS**: Carbon fiber-reinforced polymer (CFRP); Limestone calcined clay cement (LC3); $CO_2$-treated recycled coarse aggregate ($CO_2$-RCA); Confinement.

# SHEAR STRENGTHENING OF RC BEAMS WITH LOW-CARBON FOOTPRINT TEXTILE-REINFORCED MORTAR JACKETS

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## ABSTRACT

Textile-reinforced matrix (TRM) is an advanced technique for strengthening substandard reinforced concrete (RC) members. However, ordinary portland cement (OPC) production accounts for almost 7% of total global $CO_2$ emissions. Geopolymer and belite calcium sulphoaluminate (BCSA) cement are gaining interest as low carbon alternatives for TRM matrices. In this study, the effectiveness of U-shaped TRM jackets for the shear strengthening of RC beams is experimental-ly investigated, focusing on the use of low-carbon footprint mortars as an alternative to OPC-based mortars. Seven simply supported rectangular RC beams with dimensions of 120 × 200 × 1600 mm were subjected to monotonic four-point bending tests. The shear spans of the beams were both equal to 480 mm, yielding a shear-span to depth ratio (a/d) of 2.5. The parameters examined in this study include: i) the matrix of the TRM overlays (geopolymer, BCSA-based, or OPC-based mortar), and ii) the age of the TRM strengthening layer (3 days or 5 months). One beam remained unstrengthened as reference. The experimental results are discussed in terms of failure mechanisms and shear strength enhancement due to strengthening. It is concluded that both innovative strengthening systems (geopolymer- and BCSA-based) are suitable for retrofitting applications, leading to similar mechanical or even better response compared to conventional OPC-based TRM.

**KEYWORDS**: Shear Strengthening; Textile-reinforced mortar (TRM); Reinforced concrete (RC); Geopolymer; Belite calcium sulphoaluminate (BCSA) cement.

# TENSILE BEHAVIOUR OF FLAX FRCM SYSTEMS WITH SINGLE AND DOUBLE LAYER CONFIGURATION

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**ABSTRACT**
The growing demand for sustainable construction materials and the need to preserve existing masonry heritage have led to the development of eco-friendly structural strengthening solutions. Being Fiber Reinforced Cementitious Matrix (FRCM) systems an effective technique for enhancing the mechanical performance of masonry elements, recent research has focused on the substitution of traditional fibers (e.g., carbon, glass, basalt, steel, aramid, etc.) with natural fibers. Natural FRCM systems are characterized by lower mechanical properties compared to traditional FRCMs, therefore, when a significant strength increase is needed for the structural elements, multi-layer configurations could be adopted. This study investigates the tensile behaviour of FRCM composites reinforced with flax fibers, emphasizing their potential as sustainable alternatives for structural retrofitting applications. In more details, tensile tests are performed on a flax grid and on FRCM coupons, the latter constituted by one or two layers of flax fibers embedded within an inorganic lime-based mortar matrix. The experimental tests are presented in the paper and comparisons between single- and double- layer configurations are discussed, in terms of capacity, deformability and crack propagation, with the objective of assessing the cracking process and the effectiveness of the double-layer applications. The results demonstrate that the studied flax FRCM system exhibits promising tensile properties and effective interlayer collaboration, supporting its viability as an environmentally sustainable solution for masonry retrofitting.

**KEYWORDS**: Strengthening; Sustainable materials; Natural FRCM; Flax fibers; Tensile behaviour.

# CYCLIC BEHAVIOR OF A FLAX-TEXTILE FRCM SUBJECTED TO TENSILE TESTS

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**ABSTRACT**

Fiber-reinforced cementitious matrix (FRCM) composites including textiles made with natural fibers have been attracting the interest of the construction industry in the last few years. They represent a promising solution as externally bonded reinforcement (EBR) of masonry members, since they combine sustainability and compatibility with the substrate. Masonry structures are often strengthened and retrofitted to improve their behavior with respect to horizontal loadings, e.g., those induced by seismic events. In this case, the FRCM would be subjected to a cyclic loading that might cause progressive damage of the matrix, textile, and matrix-textile interface. To assess this behavior, the European assessment document EAD 340275-00-0104 requires tensile tests with an applied cyclic loading on FRCM coupons.

In this paper, the cyclic behavior of a flax-textile FRCM composite is assessed using clamping-grip tensile tests performed according to EAD 340275-00-0104. Different numbers of cycles were applied. The variations of cycle slope and area within each cycle are studied with respect to the total number of cycles applied. After the application of cycles, quasi-static tensile tests were performed on the specimens to study their post-cycle behavior and assess the peak stress and slope of the cracked branch of the applied stress – axial strain response. The results obtained provide an insight into the cyclic behavior of the flax-textile FRCM studied with respect to different numbers of cycles.

**KEYWORDS**: Flax textile; Natural FRCM; Cyclic behavior; Tensile tests.

# TOWARDS ECO-FRIENDLY FRCM SYSTEMS: LONG-TERM MECHANICAL BEHAVIOUR OF VEGETAL FIBER REINFORCED COMPOSITES

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**ABSTRACT**

Fabric Reinforced Cementitious Matrix (FRCM) systems have gained increasing attention in structural strengthening applications due to their compatibility with masonry substrates and improved behaviour under high temperatures compared to polymer-based composites. In this context, the use of bio-based fibers represents a sustainable alternative aligned with current environmental and circular economy principles. This study presents an experimental investigation on FRCM systems reinforced with vegetal fibers. The research program includes direct tensile tests on dry fabrics to characterize the mechanical properties of the reinforcement and tensile tests on FRCM coupons to evaluate the composite stress–strain response. In addition, the effect of accelerated alkaline ageing on both textiles and bio-FRCM specimens is examined to evaluate their residual mechanical performance. Preliminary results indicate that flax-based FRCM systems exhibit a typical pseudo-ductile behavior, governed by progressive matrix cracking and subsequent stress transfer to the textile reinforcement. A reduction in tensile strength and stiffness is observed after ageing, although this effect appears more pronounced in the bare fibers than in the composite system. These findings suggest a certain sensitivity of vegetal fibers to alkaline environments and elevated temperatures. Overall, the study provides valuable insights into the mechanical behaviour and durability of eco-friendly FRCM systems, supporting their potential use in sustainable structural strengthening applications.

**KEYWORDS**: Bio-FRCM; Direct tensile tests; Sustainability.

# MUSSEL-INSPIRED EPOXY ADHESIVES WITH IMPROVED ADHESION IN WET CONDITIONS


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## ABSTRACT

Durability of the externally bonded FRP–concrete bond in wet and humid environments remains a key limitation for strengthening and repair applications. This is largely attributed to the sensitivity of conventional epoxy adhesives to interfacial degradation when water disrupts hydrogen bonding between the adhesive and substrate, reducing bond performance. Nature solved this challenge through millions of years of evolution: mussels remain firmly anchored to wet mineral and organic surfaces in turbulent marine environments by secreting adhesive proteins rich in 3,4-dihydroxyphenylalanine (DOPA). The catechol functionality enables robust wet adhesion via bi-dentate hydrogen bonding, coordination bonding, and π–cation interactions not accessible to conventional synthetic adhesives. Inspired by this mechanism, a novel amine-functionalized catechol monomer (CPA) was synthesized and incorporated into epoxy formulations at concentrations up to 25 times higher than previously reported (7.48 vs. 0.28 wt%). CPA-modified adhesives cured un-der ambient conditions achieved extents of cure comparable to the control (72–74%), with glass transition temperatures of 42.7–45.1 °C, increasing to 85.8–92.6 °C following post-cure. Addition of 3.8 wt% CPA reduced gel time by ~50% (11.5 vs. 24.9 h), indicating accelerated curing kinetics. Pull-off adhesion strength of the EBFRP system was evaluated per ASTM C1583 on high-strength concrete substrates under dry and saturated surface-dry (SSD) conditions. Under SSD conditions, the CPA-modified primer achieved 2.3 times higher bond strength than the control, retained 73% of dry strength (vs. 42%), and doubled cohesive substrate failure, demonstrating the effectiveness of catechol-mediated wet adhesion for EBFRP applications.



**KEYWORDS**: Epoxy; Catechol; CFRP; Biomimetic; Adhesion.

# SS07 - Experimental tests on FRP bars: mechanical, physical and bond properties

# ASSESSMENT OF ANCHORAGE LENGTH FOR FRP BARS IN RC STRUCTURES

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**ABSTRACT**
Use of FRP bars as internal reinforcement for concrete elements has become in the last years a topic of great interest to the scientific community and manufacturers. Specific rules need to design new structures made by reinforced concrete (RC) elements with FRP bars, under both serviceability and ultimate loading conditions, and, thus, several national and internationals codes are updating. Within the design rules, a central aspect is the evaluation of the 'anchorage length' of the bars. To this aim, several bond tests carried out on different types of FRP bars embedded in concrete elements were collected from the literature to assess, firstly, an expression for the maximum tensile stress in the bars in function of some meaningful mechanical and geometrical parameters (concrete compressive strength, bar diameter, concrete cover, bonded length, quality of bond) according to the 'design by testing' procedure. Then, by reversing such an expression, a formulation for the 'anchorage length' was obtained having the same format suggested in the recent version of Eurocode 2 for steel and FRP bars embedded in concrete elements. The proposed expression, which may provide average, characteristic and design values for the anchorage length, is compared with other formulations available in literature for FRP and steel bars.

**KEYWORDS**: FRP bars; Bond behavior; Anchorage length; Pull-out tests; Design by testing.

# BONDS TESTS ON FRP BARS IN CONCRETE ELEMENTS: A CRITICAL REVIEW OF EXPERIMENTAL RESULTS


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## ABSTRACT

Bond behaviour of FRP (fibre-reinforced polymer) bars embedded in concrete elements is a critical issue that may strongly influence the overall performance of Reinforce Concrete (RC) structures both at serviceability (i.e., verifications regarding cracking and deflections control) and ultimate limit states (i.e., assessment of anchorage length). Various parameters influence bond behavior, including fiber types, surface treatments, embedment length, concrete cover and compressive strength; these parameters may play a different role in the bond behavior of FRP bars in comparison with steel bars and, thus, it is necessary to investigate their effect to provide reliable predictive models.

This paper focuses attention on the assessment of bond strength, and, to this aim, an experimental database was compiled by the authors, including more than 1100 test samples coming from about 60 different experimental programs concerning bond tests of FRP bars embedded in concrete elements available in literature and characterized by a wide range of parameters investigated. The paper firstly discusses the variability of the parameters in the database and their influence on bond strength and then presents several comparisons with theoretical formulations.

Then, for a subset of experimental data concerning the only specimens with glass FRP bars, the theoretical predictions of bond strength provided by ACI 440.1R-15 formulation are compared with the experimental values.



**KEYWORDS**: FRP bars; Concrete elements; Bond behaviour; Bond tests; Shear strength.

# EFFECT OF GEOMETRICAL AND MECHANICAL PARAMETERS ON THE BOND STRENGTH OF FRP BARS EMBEDDED IN CONCRETE ELEMENTS


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## ABSTRACT

Bond behavior of FRP (fiber reinforced polymer) bars embedded in concrete elements depends on several parameters, including surface treatments, diameter and embedment length of the bars, concrete cover and compressive strength. Because of the evolution of production technologies and of the wide variety of FRP bars typologies and surface treatments available on the market, interpretation and modelling of bond behavior is still an open issue. This paper presents the results of a wide experimental program made of bond tests on glass FRP bars embedded in concrete elements where several parameters are investigated: concrete compressive strength (class C20/25 and C50/60), bar diameter (7, 10, 16 mm), bonded length (5, 10, 23 times the bar diameter), bar surface treatment (with or without lacquering), and eccentricity of the bar in the test configuration. The tests were carried out according to a pull-out set-up following the recommendations provided by EAD 260023-00-0301, specific for qualification of FRP bars. The experimental results are presented in terms of failure mode, maximum load and bond strength. A critical comparison of these results is presented to highlight the influence of the parameters under investigation on the bond strength of the FRP bars.



**KEYWORDS**: FRP bars; Concrete; Bond behaviour; Pull-out tests; Bond strength.

# EVALUATING BOND STRENGTH OF GFRP BARS WITH CONCRETE USING HINGED BEAM TEST

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## ABSTRACT

The use of glass fibre-reinforced polymer (GFRP) bars is a viable solution to the corrosion issue in reinforced concrete infrastructure because of their non-corrosive properties. GFRP's distinct properties and surface patterns lead to a different force transfer mechanism with concrete compared to steel. In the last decade, several researchers looked into the phenomena, predominantly employing pull-out tests. There are discrepancies in the results due to unrealistic stress conditions; therefore, this study is focusing on evaluating bond-slip behaviour of GFRP bars with concrete using hinged beam tests, which represent the bond behaviour between the bar and concrete in a more realistic way. The study evaluated thread wrapped GFRP bars with fine sand coating and coarse sand coating in comparison to steel bars. It is found that the bond of thread-wrapped GFRP bars exhibits 25.6% bond strength in comparison to its steel counterpart; however, bond strength is found to be increased substantially by fine and coarse sand coating to 59.3% and 54.9% in comparison to its steel counterpart. In addition to bond strength, it is observed that the corresponding slip shows a substantial reduction in slippage when the bars are coated with either fine or coarse sand. When the bond strength is compared to analytical bond equations, test results are found to be considerably in better agreement with CSA S806-12 than ACI 440.1 R15. Furthermore, both modified Bertero-Popov-Eligehausen (mBPE) and Cosenza-Manfredi-Realfonzo (CMR) models are found to be effective in capturing the bond-slip behaviour of the test specimens.

**KEYWORDS**: Bond Strength; GFRP bars; Bond-slip behaviour; Beam-end Test; Surface coating.

# DEVELOPMENT OF A SUSTAINABLE UNIDIRECTIONAL INTERLAYER GLASS-FLAX HYBRID LAMINATE

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**ABSTRACT**

In this study, a novel fibre combination for an interlayer hybrid fibre-reinforced polymer laminate was investigated to achieve pseudo-ductile behaviour under uniaxial tensile loading. For this purpose, unidirectional (UD) S-glass fibres were selected as high strain material and UD flax fibres as low strain material. In addition to their suitable mechanical properties, these materials have a considerably reduced environmental impact in comparison to carbon/carbon and carbon/glass hybrids. An available analytical model was used to select optimal configurations of the two materials for a hybrid laminate to achieve the desired failure modes. The modelling was based on preliminary tensile tests of the two basic components investigated in this research: UD laminates reinforced with either flax fibres or S-glass fibres. Hybrid specimens were then designed, manufactured using heat-assisted pressing, and eleven specimens were evaluated using tensile tests. The strain measurement was performed using embedded distributed fibre optic sensing which were integrated between the composite plies. Ultimately, a repeatable pseudo-ductile behaviour was obtained for hybrid laminates under quasi-static uniaxial tension along the fibre direction. The two different damage modes 'catastrophic delamination' and 'fragmentation and delamination' were demonstrated during the tensile tests, for two different hybrid-laminate layups. The different damage modes were validated using the local strain measurement, offered by the integrated optical fibre.

**KEYWORDS**: Interlayer S-glass-Flax hybrid laminates; Tensile pseudo-ductile behaviour; Distributed fibre optic strain sensing.

# BOND BEHAVIOR OF FRP BARS IN LIGHTWEIGHT CONCRETE

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**ABSTRACT**
Since the introduction of fibre-reinforced polymer (FRP) bars as an alternative reinforcement material for conventional steel reinforcement in reinforced concrete (RC), efforts have been made to understand the bond behaviour between these composite materials and concrete. Nonetheless, no efforts have been made to investigate the bond performance of FRP bars embedded in lightweight concrete (LWC). Lightweight concrete is low-density concrete composed of lightweight aggregates, cement, water, and admixtures. It is an excellent alternative to reduce the overall weight of a structure, which reduces the dead load demands on different elements. This study aims at filling this gap by conducting hinged-beams test on LWC specimens reinforced with FRP bars. The tested parameters are the type of FRP bars (i.e., GFRP and BFRP) and the embedment length (i.e., 4, 9, and 14 times the bar diameter). The beams are 720 mm in length, and have a cross-sectional area of 150 mm by 180 mm; the notch is 64 mm long and 44 mm deep, and the gap between the beam halves is 20 mm. The bar-end slips and ultimate failure loads are captured. Increasing the embedment length was found to have a significant influence on the maximum failure load and bar-end slip. Regarding the different surface conditions, a substantial difference in the performance was observed between the GFRP and BFRP bars. The predominant failure mode was bond-splitting failure on the bottom face of the beam for all specimens.

**KEYWORDS**: BFRP; Bond strength; GFRP; Lightweight concrete; Hinged-beam test.

# DURABILITY OF GFRP BARS IN MARINE EXPOSURE: EXPERIMENTAL, EMPIRICAL AND ANN-BASED BOND STRENGTH MODELING

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**ABSTRACT**

This study investigated the durability of glass fiber-reinforced polymer (GFRP) bars embedded in concrete under marine exposure. Concrete specimens reinforced with two bar types—ribbed-type and sand-coated—were exposed to tidal wet–dry cycles at KFUPM Beach. After one year of exposure, specimens were retrieved and tested for tensile and bond strength, with unexposed controls serving as references. Experimental results indicate that ribbed-type bars retained an average tensile strength of approximately 864 MPa and bond strength of 14.3 MPa, while sand-coated bars exhibited higher values, with tensile strength of approximately 958 MPa and bond strength of 20.8 MPa. The elastic modulus remained largely unchanged, suggesting negligible stiffness degradation during the first year of exposure. To broaden predictive capability, an empirical model for bond strength was formulated by combining the present findings with 119 data points from the literature and the current study. The model incorporates exposure duration, surface configuration, and environmental parameters to estimate residual bond capacity of GFRP bars subjected to aggressive marine environments. In addition, an artificial neural network (ANN) model trained using Bayesian regularization provided accurate bond predictions with near-unity bias and strong agreement with measured values ($R^2 \approx 0.86$). Comparison between field measurements and literature-based predictions confirmed the proposed models' consistency in capturing early-stage performance and projected long-term trends.

**KEYWORDS**: Glass fiber-reinforced polymer (GFRP); Marine exposure; Bond strength degradation; Empirical model; Artificial neural networks.

# EXPERIMENTAL INVESTIGATION ON THE EFFECT OF RIB GROOVE DEPTH ON BOND PULL-OUT BEHAVIOR OF LARGE DIAMETER GFRP BARS

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## ABSTRACT

The bond performance of GFRP bars in concrete is strongly influenced by surface geometry, particularly for large-diameter bars where anchorage is critical. This study investigates the effect of rib groove depth on bond behavior of 24.7 mm M25 ribbed GFRP bars using pull-out tests on ten transversely confined concrete bond specimens. Two groove depths 0.3 mm and 0.7 mm, were investigated with five specimens tested for each group. The results showed that increasing the groove depth improved the average peak bond stress from 12.7 MPa to 15.8 MPa, corresponding to an increase of about 24%, and increased the peak failure load by about 19%, while also reducing slip at comparable load levels. The deeper grooves enhance mechanical interlock and stress transfer, resulting in reduced slip at similar load levels. Supporting tensile tests conducted on small M10 bars with similar groove depths and interlaminar shear stress tests on M25 bars are also discussed. These results demonstrate that groove depth as an important geometric parameter affecting the bond and anchorage performance of large diameter ribbed GFRP bars and provide a basis for empirical models that relate rib geometry to bond capacity, enabling more reliable design of GFRP-reinforced concrete members.

**KEYWORDS**: GFRP bars; Bond strength; Pull-out test; Groove depth.

# HINGED-BEAM TESTS FOR BOND STRENGTH OF HOOKED GFRP BARS

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**ABSTRACT**

The bond strength of hooked glass fiber-reinforced polymer (GFRP) bars is a topic not directly studied for over 30 years. With the development of 'modern' GFRP bars, tensile strength and manufacturing quality has considerably improved, prompting a demand to revisit bond strength design equations. This research program includes nine hinged-beam specimens which investigate the effect of bar size, straight embedment length, and surface configuration on bond strength. Three embedment lengths based on ratios of the bar diameter ($d_b$) including, $10d_b$, $19d_b$, and $28d_b$ were considered. No.4 and No.6 bar sizes and both sand-coated and deformed bar surfaces were also studied. Tensile load was applied to the bars through a four-point bending configuration until failure, and the resulting tensile stress in the bar was determined. Typical failure modes include hook rupture, hook pull-out, or concrete splitting bond failure. For a No.4 sized hooked bar, an embedment length of $19d_b$ achieves approximately 87% of the nominal straight part tensile strength. As bar diameter increases, bond strength decreases. For a No.6 size bar, an embedment length of $28d_b$ achieved approximately 60% of the straight part tensile capacity. Additionally, the effect of surface configuration appears to vary between the bent and straight part of the bar. The bent part of a hooked bar appears to achieve greater bond with the deformed surface coating. In contrast, the straight embedment length of the hooked bar achieves greater bond with sand coating.

**KEYWORDS**: GFRP rebar; Hook; Bent; Bond; Development length.

# INFLUENCE OF ALKALINE ENVIRONMENT ON THE MECHANICAL PERFORMANCE OF FRP REBARS

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**ABSTRACT**

The high strength, good durability and excellent corrosion resistance of fibre reinforced polymer (FRP) rebars have made them a suitable alternative of steel rebars in harsh environments. However, they are not completely immune to environmental effects, and the presence of highly alkaline conditions may detriment their mechanical performances, especially when coupled to sustained loading. For this reason, recent years have been characterised by a renewed interest in investigating and assessing the performance of FRP rebars in harsh conditions which has in turn favoured the evolution of codes and qualification procedures.

At the European level, a European Assessment Document (EAD) has been recently published, which defines the essential characteristics and test methods for the qualification and CE marking of FRP bars, including testing after ageing in alkali solutions with different exposure durations.

Results of tensile and interlaminar shear tests after alkali exposure on various glass FRP bars by different manufacturers, qualified according to the procedures included in the above-mentioned EAD, have been collected and analysed. The paper will illustrate the influence of different exposure and loading conditions on the performance of GFRP rebars, and the results will be analysed in comparison to the environmental factors currently recommended by structural design codes.

**KEYWORDS**: FRP rebars; Durability; Alkali environment; Experimental test; Qualification.

# EXPERIMENTAL INVESTIGATION ON THE BOND BEHAVIOUR OF GLASS FIBRES REINFORCED POLYMERS IN FIBRE REINFORCED CONCRETE


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## ABSTRACT

Fibre-reinforced polymer (FRP) bars have emerged as a viable alternative to conventional steel reinforcement in harsh or corrosive environments. However, the use of glass FRP (GFRP) bars in structural elements is limited by their relatively poor bond performance compared with steel-reinforced concrete. This study experimentally investigated the influence of synthetic and glass fibres on the bond behaviour of concrete reinforced with GFRP bars. The experimental programme included pull-out tests on GFRP bars embedded in fibre-reinforced concrete cubes, considering key parameters such as fibre type, bar diameter, and fibre content. A total of 45 cubic specimens were tested. The effects of these parameters on the bond behaviour were analysed in terms of bond strength, bond stress–slip response, and failure mode. The results demonstrated that the inclusion of synthetic fibres enhanced the ductility of the specimens under pull-out loading, with synthetic fibres exhibiting superior performance compared to glass fibres.



**KEYWORDS**: Pull-out; Synthetic fibre; Bond strength; GFRP; Stress-slip.

# DATA-DRIVEN TENSILE PROPERTY PREDICTION OF STRAIGHT FRP BARS USING MACHINE LEARNING MODELS

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## ABSTRACT

Laboratory experience at the University of Miami has resulted in the generation of a large dataset on fiber-reinforced polymer (FRP) reinforcing bars of varying diameters, fiber types, surface deformations, and pultrusion techniques offered by several manufacturers. The dataset includes the results of over 1100 tensile strength tests performed under standardized ASTM International and Florida Department of Transportation procedures. In this study, the dataset was trained using multiple machine learning (ML) techniques and predictive models were generated for tensile strength and modulus of straight FRP bars. Input features included fiber type, diameter, surface deformation, and pultrusion method prescribed by different manufacturers, while targets corresponded to measured test values. Models such as Linear Regression, Support Vector Machine (SVM), Random Forest (RF), Gradient Boosting Machines (GBM), and Artificial Neural Networks (ANN) were trained and validated to evaluate predictive accuracy and generalization. The results demonstrate that ensemble models such as RF and GBM along with ANN outperform traditional regression approaches by achieving the coefficient of determination of over 0.96 that contribute to strong correlations with experimental results. The integration of ML with experimental testing provides a framework for rapidly estimating the tensile properties of FRP bars and reduces the need for exhaustive laboratory testing. This study highlights the potential of data-driven modeling to complement experimental characterization.

**KEYWORDS**: Fiber-reinforced polymer (FRP); Tensile properties; Data-driven property prediction; Machine learning; Artificial neural networks (ANN).

# CRITICAL ISSUES IN THE ASSESSMENT OF THE REACTION TO FIRE PERFORMANCE OF FRP REBARS

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**ABSTRACT**

The increasing interest in fibre reinforced polymer (FRP) rebars as internal or external reinforcement of concrete elements has favoured the worldwide evolution of qualification and design rules in the civil engineering sector. The use of FRP bars is strongly influenced by their physical and mechanical properties, therefore the correct design of structures with FRP reinforcement strongly relies upon an adequate assessment of the composite material's properties. At the European level, the recently published European Assessment Document (EAD) for the CE marking of the FRP bars includes the essential characteristics and the relative methods for their assessment, among which the reaction to fire tests represent the only assessment foreseen for the fire safety requirement of construction works. The document includes the reference to the methods foreseen by EN 13501-1, which generally applies to all construction products, in order to classify the FRP bars for reaction to fire, together with indication of the preparation of specimen and mounting and fixing provisions for the specific case of FRP bars.

The SBI (Single Burning Item) test method is one of the procedures used to determine the fire reaction classification; however, the standardized threshold values that discriminate between classes were originally established on the basis of analyses of results from an earlier experimental campaign focused on internal coatings. Considering these aspects and the differences with the product at hand, the results obtained on the FRP bars were critically analysed to ensure an interpretation of the data consistent with the intended use of the tested product.

**KEYWORDS**: FRP bars; Reaction to fire; Experimental test; Standards; Qualification.

# MECHANICAL CHARACTERIZATION AND STIFFNESS MATRIX OF CFRP RODS

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## ABSTRACT

CFRP rods are increasingly used in civil engineering due to their excellent properties such as lightweight, high strength, and corrosion resistance. As a transversely isotropic material, the fiber direction tensile mechanical properties of CFRP rods are significantly higher than those of the other direction. Studying the mechanical properties of CFRP rods helps predict their behavior under complex loads. Through a series of mechanical tests, including tensile, transverse split, transverse shear, and interlaminar shear, the mechanical parameters of CFRP rods were obtained, and their failure mechanisms were analyzed. The strength and stiffness matrices of different types of rods were calculated, followed by a comprehensive analysis of the stiffness matrices. The analysis of the stiffness matrix of CFRP rods reveals that rods with different resin matrices exhibit distinct mechanical properties.

**KEYWORDS**: CFRP rods; Transversely isotropic materials; Mechanical properties; Stiffness matrix.

# EXPERIMENTAL INVESTIGATION ON THE BOND BEHAVIOR OF CFRP BARS EMBEDDED IN HIGH-STRENGTH MORTAR

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## ABSTRACT

In recent years, fiber-reinforced polymer (FRP) bars have been increasingly used as an alternative to traditional steel reinforcement in concrete structures exposed to aggressive environments. Different types of FRPs are available on the market. The most used are made of glass (GFRP), carbon (CFRP), and aramid (AFRP) fibers. Among them, CFRPs exhibit the highest tensile strength, lowest deformability, and highest fatigue resistance. CFRP bars can be used as internal reinforcement of new reinforced concrete (RC) structures and as reinforcement of mor-tar jackets used to strengthen existing RC members. The high tensile strength of CFRP bars may require long bonded lengths to provide proper stress-transfer with the surrounding concrete and/or mortar. Furthermore, the bond behavior between mortar and CFRP bar is governed by several parameters, including the bar surface treatment and diameter, bonded length, and mortar compressive strength.

In this study, a preliminary experimental campaign is performed to investigate the bond behaviour between sand-coated CFRP bars and a high-performance mortar. After an initial characterization of the CFRP bars and the mortar used, four pull-out tests are carried out to study the bar-mortar stress-transfer mechanism considering a bonded length equal to five times the bar diameter. The failure mode, peak load, and average bond stress are analyzed to obtain information on the mechanisms governing the load transfer at the joint interface. These findings contribute to a better understanding of the bond behavior of CFRP reinforcements.

**KEYWORDS**: CFRP; High-performance mortar; Bond behavior; Pull-out test.

# REDISTRIBUTION CAPACITY OF EMBEDDED RIBBED AND SANDED GFRP REBAR REINFORCED CONCRETE BEAMS

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## ABSTRACT

It was already shown that concrete with sanded glass fiber reinforced polymer (GFRP) rebars exhibits a redistribution capacity due to (partly irreversible) slip of the reinforcement. A behavior that can be expected of ductile materials, and in that way, it is a counterintuitive finding, as GFRP-RC can be seen as a combination of two brittle materials. In ordinary reinforced concrete (RC), ribbed steel rebars are known to perform better and more reliably than smooth ones. In this work, four identical double-span beams (2×1.3 m, 0.24×0.30 m²) with two different configurations of upper reinforcement (2×1Ø16 mm and 2×1Ø20 mm) and ribbed GFRP rebars were tested. Results are compared to the outcomes of a recently developed analytical model and previously executed tests, where sanded GFRP rebars have been used. As with the sanded rebars, the behavior of all specimens during the test was found to be independent of diameter, which was in line with expectations based on the analytical model. A slightly higher load level was observed for the ribbed rebar beams at the moment when slip began, as well as at the ultimate bearing capacity. They also showed a better redistribution capacity, thanks to the stiffer adhesion of ribbed GFRP rebars, a very good redistribution can be achieved if reinforcement is designed to be slip-tolerant (in ULS). In addition, no clear difference in behavior and capacity could be found as a function of the upper rebar diameter.

**KEYWORDS**: Redistribution; GFRP-reinforcement; Sanded and ribbed rebars; Reinforced concrete beams; Experimental comparative study.

# SS08 - Recent trends and advances on seismic retrofit of RC structures with externally bonded FRP

# A NUMERICAL STUDY ON THE SEISMIC RESPONSE OF RETROFITTED RC BEAM-COLUMN JOINTS UNDER MONOTONIC STATIC LOAD

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## ABSTRACT

This paper presents nonlinear 3D finite element (FE) models developed in ABAQUS to simulate reinforced concrete (RC) beam-column joint (BCJ) behaviour under monotonic loading, validated against the authors' experimental results. In developing countries, prevalent structural deficiencies in concrete quality and reinforcement detailing significantly increase seismic vulnerability, particularly in BCJs, which represent critical failure points. This necessitates effective retrofitting strategies. The study builds upon large-scale experimental work, which included three retrofitting techniques: near-surface mounted (NSM) steel bars, externally bonded (EB) GFRP sheets, and a hybrid EBNSM method. The results showed a significant performance increase of 15.3%, 21.8% and 37% in the maximum load capacity in the pulling direction and 12.9%, 26.4% and 28.1% in the pushing direction, respectively, compared to the control specimen. Three full-scale exterior BCJs were numerically investigated in this article: an unretrofitted control specimen (S1-Control), an NSM-strengthened joint (S2-NSM), and a hybrid specimen (S4-Hybrid). The Finite Element Analysis (FEA) serves dual purposes: providing a deeper understanding of experimental outcomes and establishing a predictive framework for future connection designs. Numerical results showed strong correlation with experimental data, validating the model's accuracy in capturing joint behaviour. The research highlights the superior performance of the hybrid EBNSM technique while demonstrating the effectiveness of finite element modelling as an analytical tool for retrofitted joints. These findings contribute to improved seismic design methodologies, particularly for vulnerable building stocks in developing regions. The validated models offer practical value for engineers seeking to evaluate and design retrofitted connections, potentially reducing seismic risks in existing structures.

**KEYWORDS**: Finite element; Reinforced concrete; Seismic retrofit; Near-surface mounted; Externally bonded .

# STRENGTHENING DEFICIENT CAST-IN-PLACE RC FOUNDATION–COLUMN JOINTS USING CFRP

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**ABSTRACT**
Field observations from recent seismic events have shown that exterior or corner cast-in-place reinforced concrete (RC) foundation–column joints (FCJs) lacking transverse reinforcement are highly prone to damage, which compromises the seismic performance of the entire structural system. The damage typically occurs beneath exterior or corner columns, where the column longitudinal reinforcement within the foundation is not laterally restrained. The predominant failure mode is axial, characterized by concrete crushing and buckling of the column longitudinal reinforcement within the foundation panel. This experimental study investigated the cyclic response of a deficient, code-compliant exterior RC FCJ, along with the strengthening of FCJ using carbon fiber-reinforced polymer (CFRP). The deficient FCJ failed due to concrete crushing and longitudinal bar buckling within the foundation panel—consistent with post-earthquake field evidence. A code-compliant FCJ with adequate transverse reinforcement in foundation panel was also tested as a reference, primarily exhibited a ductile response by the development of flexural hinge at the column base above the FCJ panel. The CFRP strengthening scheme effectively mitigated panel deterioration and significantly enhanced both the strength and displacement capacities of the deficient FCJ, outperforming even the code-compliant specimen. The results confirm that CFRP application to the FCJ panel is a highly effective method for improving the cyclic performance of exterior FCJs lacking transverse reinforcement.

**KEYWORDS**: Foundation column joint; Recovery; Confinement; Strengthening; Axial failure.

# TITANIUM NSM BARS FOR RETROFITTING LIMITED-DUCTILITY CONCRETE BUILDINGS

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**ABSTRACT**
A limited-ductility concrete (LDC) building in Southern California, constructed in the 1960s, is being assessed for compliance with current seismic codes. The building's column splicing system, designed according to outdated seismic provisions is tension-deficient, creating a structural vulnerability. As part of the retrofit strategy, near-surface mounted (NSM) titanium alloy bars were evaluated as an alternative to using linear-elastic fiber reinforced polymers (FRP). The effectiveness of this system was confirmed through large-scale experimental testing at UCLA, where retrofitted columns were subjected to axial load and bending moments. The titanium alloy bars provide a high yield strength (130 ksi), significant elongation capacity (10%), corrosion resistance, fatigue resistance, and are about half the weight of steel, making them a unique solution for seismic strengthening. Test results from columns under axial compression show that the proposed retrofit technique increases the moment capacity by approximately 50% and enhances the deformation capacity by 100%, demonstrating a substantial improvement in structural performance. This presentation addresses the challenges of tension-deficient column splicing and introduces a novel solution that will be adopted for the retrofit.

**KEYWORDS**: Titanium alloy; Tension-deficient splicing; Near-surface mounted; G-loc device.

# EXPERIMENTAL STUDY OF RC STRUCTURAL WALLS WITH FRP OVERLAYS DESIGNED WITH CURRENT ACI 440 PROVISIONS

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## ABSTRACT

Reinforced concrete (RC) structural walls are a common lateral force-resisting system in regions of high seismicity. Fiber-reinforced polymer (FRP) overlays have gained prominence as a seismic retrofit technique for non-compliant RC walls. The design of FRP-based retrofit overlays is governed by the provisions of the ACI PRC 440.2-23 document. The equations of the specific document have been primarily developed from tests on column or beam components. An experimental study, focused on RC walls with a barbell section, was undertaken to evaluate the efficacy of current ACI-440 provisions for (1) shear-strengthening, (2) flexural bar buckling prevention, and (3) lap-splice slip prevention. The retrofit strategies employed horizontal FRP, including a web overlay and/or wraps for the pilaster (end) regions of the section. The specimens were tested under a constant axial load and quasi-static lateral load with increasing displacement. The shear-strengthening retrofit was able to effectively delay diagonal tensile failure, validating the design with current ACI-440 shear-strengthening equations. The bar buckling retrofit was also effective, but resulted in unexpectedly high vertical reinforcement strains due to vertical strengthening through the FRP epoxy matrix and the vertical FRP anchor patches. The specimen with FRP over-lays wrapped around a lap-splice region experienced strength degradation through bar rupture, eliminating the occurrence of lap-splice slip failure.

**KEYWORDS**: FRP retrofit; Code assessment; Shear strengthening; Bar buckling; Lap-splice.

# GUIDELINES FOR SEISMIC DESIGN AND NONLINEAR MODELING OF FRP JACKETED CONCRETE COLUMNS

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## ABSTRACT

The damage susceptibility of existing reinforced concrete buildings designed prior to development of modern seismic provisions has been repeatedly demonstrated after past earthquakes. In the United States, documents focusing on evaluation and seismic retrofit of existing buildings have evolved significantly since the publication of *FEMA 273* in 1997. The basic framework for evaluation and retrofit was laid out in these early guideline documents and subsequently evolved into the current Seismic Evaluation and Retrofit of Existing Buildings Standard (*ASCE/SEI 41-23*) over approximately 25 years. Design of retrofitting techniques has been lacking in *ASCE/SEI 41-23*, so engineers resort to a few available guides that might not be compatible with the intended framework.

To address this gap, guidelines for the seismic design and modeling of FRP jackets applied to RC columns were recently developed. The primary goals were to achieve consistency in application and ensure compatibility with *ASCE/SEI 41-23*. This paper presents an overview of the Guidelines for Seismic Design and Evaluation of Concrete Members Retrofitted using Externally Applied FRP (*NIST SP 1333*). Emphasis is placed on the design philosophy, which affects the design procedures and modeling parameters in the *Guidelines*. The fundamental philosophy in *NIST SP 1333* was to eliminate shear failures in retrofitted concrete columns and promote flexural behavior. Anchorage of FRP materials for enhanced confinement and force transfer is treated explicitly in the proposed design and evaluation procedures.

**KEYWORDS**: Fiber reinforced polymer (FRP); Modeling parameters; Performance-based design; Retrofit; Reinforced concrete structures; Seismic design.

# DUCTILITY ENHANCEMENT WITH EXTERNAL FRP CONFINEMENT FOR SEISMIC PERFORMANCE: COMPARISON WITH TSDC-2018

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**ABSTRACT**
In the existing building stock in Türkiye, many reinforced concrete (RC) buildings have limited ductility under seismic loading due to inadequate transverse reinforcement, poor detailing, or outdated design assumptions that do not meet current seismic demands. Confinement with fiber-reinforced polymer (FRP) composites is widely employed to improve the deformation capacity and ductile behavior of RC members, supported by extensive experimental studies and design guidelines. However, the extent to which code-based evaluation procedures realistically represent the ductility enhancement provided by FRP confinement remains uncertain. This study investigates how ductility improvement achieved through FRP confinement is represented in code-based analytical procedures through comparison with experimental responses. A database of rectangular RC columns strengthened with FRP and tested under constant axial load and cyclic lateral displacement is compiled from the literature. Displacement-based ductility values derived from experimental load-displacement responses are compared with analytically obtained ductility estimates calculated in accordance with the Turkish Seismic Design Code (TSDC-2018). The results show that TSDC-2018 predicts remarkably lower ductility values than those observed experimentally. The ratio of code-based to experimental ductility has an average value of approximately 0.30, indicating that experimental ductility is typically 3-4 times higher than analytical estimates. No clear systematic variation was identified with respect to cross-sectional dimensions or volumetric confinement ratio, and no distinct monotonic relationship with axial load ratio was observed. These findings highlight the conservative nature of the strain-limit-based formulation and provide insight into the adequacy of current displacement-based seismic evaluation procedures for FRP-confined RC columns.

**KEYWORDS**: FRP confinement; Ductility; Reinforced concrete; Seismic strengthening.

# SS09 - Smart FRP and TRM composites for self-monitoring applications

# INSIGHTS ON GFRP-REINFORCED CONCRETE SHEAR BEHAVIOR USING DISTRIBUTED FIBER OPTIC SENSORS

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## ABSTRACT

Glass fiber-reinforced polymer (GFRP) bars are increasingly used as reinforcement for concrete structures because of their light weight, high tensile strength, corrosion resistance, and environmental sustainability. Unlike steel, GFRP bars do not yield and therefore the structural response of a GFRP-reinforced concrete member is highly dependent on the distribution of strain under the effects of applied loads. For instance, calculating the contribution of GFRP stirrups to shear resistance first requires an estimate of the maximum strain of the transverse reinforcement across a shear crack. Distributed fiber optic sensors (DFOS) enable high resolution real-time strain measurements along their entire length, making them well-suited for structural health monitoring and laboratory investigations. Unlike discrete strain sensors, DFOS systems do not require a priori knowledge of crack locations and have a negligible effect on GFRP-concrete bond. Six GFRP-RC beams with different stirrup sizes, stirrup spacing, and shear span to depth ratio were tested in four-point bending. DFOS cables were attached to GFRP longitudinal and transverse reinforcement to obtain a comprehensive understanding of the effect of key design parameters on strain distribution and GFRP efficiency. The test results from one beam are presented in this paper and compared with the assumptions of relevant design codes and standards.

**KEYWORDS**: Distributed fiber optic sensors; Glass fiber reinforced polymers; Reinforced concrete; Shear; Strain distribution.

# SMART MONITORING OF RC BEAMS UNDER ENVIRONMENTAL AND FATIGUE LOADING

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**ABSTRACT**

This study aimed to investigate the cracking behaviour of RC beams strengthened by external bonded smart FRP. A large scale beam is strengthened by FRP and loaded under fatigue for more than one million cycles. The beam is exposed to natural exposure for two years in the same time. Reinforced concrete (RC) beams is strengthened using two layers of externally bonded carbon fibre-reinforced polymer (CFRP), and tested under for 4-point bending. A smart CFRP was described and implemented in the tested beams and was used to measure the bond stress at the interface and cracks location. Based on the experimental results, a semi-empirical model, capable of providing the stress value at the interface around a crack using its width as the only input, was proposed and validated. Strain and shear bond stress profiles have been reconstructed for a reference beam showing consistent results.

This proposed model constitutes a monitoring process for CFRP-reinforced beams. In order to improve it, further tests should be considered to introduce for example the loading conditions, the type of reinforcement and the reinforcement ratio, as well as the ageing of the materials.

During the test, the sensor measured the mechanical strain distribution of the composite with a millimetric spatial resolution. The recorded strains were used to deduce the evolution of bond shear stresses at the CFRP/concrete interface.

**KEYWORDS**: RC beams; FRP strengthening; Fatigue; Monitoring; Durability .

# ELECTRO-MECHANICAL TESTING FOR CHARACTERISATION OF SMART TRM SYSTEMS

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## ABSTRACT

Textile-Reinforced Mortars (TRM) are ideal candidates to be transformed into self-sensing composites, as both textile and mortar can be used as sensitive elements, thus acting both as reinforcement and monitoring systems. However, research on the topic is still in its infancy and is further hindered by the lack of testing characterization methods to assess the self-sensing characteristics. This paper examines the self-sensing potential of TRM systems using different functional approaches and employing different testing protocols. Two groups of TRM composites were produced, comprising either bi-directional glass textiles or unidirectional steel cords, embedded into lime- and cement-based mortars, respectively. These composites were tested in quasi-static tension, with concurrent monitoring of their electrical resistance change. Electrical impedance measurements were obtained using the four-wire method, with the electrodes either embedded within the composite or externally bonded using copper tapes in different configurations. Both alternate and direct current excitation was also investigated to assess its effect on the crack formation. Digital image correlation was employed to correlate the electrical data with crack evolution. The results demonstrate the suitability of multi-electrode configurations in capturing the formation and localization of individual cracks due to the more distributed location of the electrodes. They also highlight the critical role of the electrical connection at the electrode/composite interface on the overall self-sensing sensitivity.

**KEYWORDS**: Self-sensing; Smart; TRM; Composite; Electrical resistivity.

# AN ANALYTICAL STUDY OF THE INFLUENCE OF TEMPERATURE VARIATIONS ON THE PERFORMANCE OF SELF-SENSING FRCM COMPOSITES

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## ABSTRACT

Efforts toward smart, all-in-one structural and sensing systems have recently focused on self-sensing Fiber-Reinforced Cementitious Matrix (FRCM) composites for combined Structural Health Monitoring (SHM) and strengthening of existing structures. Although thermal effects on conventional FRCM have been examined, the influence of temperature variations on self-sensing FRCM remains largely unexplored. This is a critical issue as temperature variations, such as thermal gradients, freeze–thaw cycling, accidental fire exposures, and longer-term climatic warming, affect the performance of mortars and concrete through combined moisture migration, thermal mismatch, and microcracking, promoting changes in both mechanical and electrical properties. This paper presents an analytical framework for the development and analysis of self-sensing FRCM under realistic thermal exposures, with emphasis on durability and long-term reliability. The framework considers how temperature variations affect the electrical properties used to evaluate self-sensing ability in cementitious composites and, consequently, the interpretation of SHM measurements. It also addresses material selection, focusing on fibers and mortars that are less susceptible to degradation under extreme temperatures and that maintain stable electrical properties for self-sensing applications. By collecting available information on this issue, the study formulates how to address existing challenges and highlights the importance of future research aimed at improving the performance of multifunctional FRCM under different environmental conditions.

**KEYWORDS**: Self-sensing; FRCM; SHM; Temperature variations; Durability.

# INVESTIGATION INTO THE OPTIMUM DISTRIBUTION OF RFID TAGS FOR MONITORING COMPOSITE INTERFACES

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**ABSTRACT**

Strengthening of existing structures has become increasingly important in civil engineering to extend the service life, improve load-carrying capacity, and maintain the safe operation of ageing infrastructure. Externally bonded strengthening systems, particularly Fibre-Reinforced Polymer (FRP) and Fabric-Reinforced Cementitious Matrix (FRCM), offer effective solutions for strengthening existing reinforced concrete (RC) structures without being invasive. These externally bonded strengthening systems significantly depend on the bond performance at the interface between the substrate and the strengthening material for their structural efficiency. Assuring long-term operation and detecting any possible defects or damage at the interface, which could evolve into debonding, requires periodic monitoring of these strengthened structures. Radio Frequency Identification (RFID) technology offers explicit benefits, including passive operation, wireless data collection, and cost-effectiveness for large-scale implementations, unlike conventional non-destructive monitoring techniques. Notwithstanding these advantages, electromagnetic coupling effects can cause considerable difficulties regarding the deployment of multiple RFID tags, possibly jeopardising reading precision and reliability. This study experimentally investigates the optimal inter-tag spacing of RFID tags attached to acrylic, concrete, and composite (basalt-strengthened mortar) substrates to minimise mutual coupling and maximise monitoring efficiency. The acrylic substrate represents air-like environments due to its similar dielectric characteristics, while concrete and composite substrates simulate realistic structural conditions, especially for the FRCM-strengthened concrete structures. The outcomes provide substrate-dependent optimum spacing limits crucial for establishing reliable monitoring systems that could potentially detect micro-cracks, delamination, and deterioration in composite interfaces for FRCM-strengthened concrete structures. Understanding this knowledge allows engineers to develop effective tag layouts that provide trustworthy long-term monitoring over larger surfaces of both standard and strengthened reinforced concrete structures.

**KEYWORDS**: RFID technology; Structural health monitoring; Coupling effect; Strengthening; Composite interfaces.

# DEVELOPMENT OF A RAPID-CURING CNT-EPOXY COMPOSITE WITH RECYCLED CONCRETE AGGREGATE FOR STRUCTURAL REPAIR

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## ABSTRACT

This study proposes a sustainable multifunctional carbon nanotube (CNT)-Epoxy composite incorporating recycled concrete aggregate (RCA) for rapid structural recovery and integrated self sensing in damaged concrete structures. RCAs with particle sizes of 0.6 to 1.2 mm obtained from disaster generated concrete debris were incorporated at a 1:1 mass ratio with the CNT-Epoxy matrix. A Joule heating based curing approach was applied to enable rapid repair under emergency conditions. Electrical current flowing through the conductive CNT network generated internal heat within the composite, allowing curing to be completed within two hours. During this process, electrical resistance gradually decreased and converged as curing progressed, indicating that the curing state can be tracked through real time electrical monitoring. Electrical conductivity increased markedly beyond the percolation threshold, confirming the formation of a stable conductive network. Based on the conductivity evolution, CNT concentrations of 1.5 wt.%, 3.0 wt.%, and 5.0 wt.% were selected for further evaluation. For each composition, voltage levels generated during Joule heating and subsequent early stage loading were quantified, demonstrating that the composite can provide measurable electrical signals shortly after rapid curing. Compression tests were conducted using the CNT 3.0 wt.% composite as a mixture to evaluate load sensing performance. The repaired zone exhibited consistent voltage variations in response to applied compressive stress, confirming stable piezoresistive behavior. The results demonstrate that the proposed RCA based CNT-Epoxy composite can restore structural functionality while simultaneously ena-bling real time stress monitoring, providing a sustainable and practical solution for post disaster concrete infrastructure recovery.

**KEYWORDS**: Carbon nanotube-epoxy composite; Recycled concrete aggregate; Rapid curing; Structural health monitoring; Concrete repair.

# SS12 - FRC composites for strengthening RC buildings and infrastructure

# FLEXURAL STRENGTHENING OF SEVERELY CORRODED RC BEAM WITH NSM-CFRP STRIPS AND HIGH-STRENGTH SHCC

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**ABSTRACT**
Corrosion-induced deterioration significantly reduces the steel reinforcement area in reinforced concrete (RC) structures, compromising their structural integrity and safety. Traditional repair methods often require extensive removal of sound concrete, making them economically and practically inefficient. This study introduces a hybrid repair approach utilizing high-strength Strain-Hardening Cementitious Composites (SHCC) combined with Carbon Fiber Reinforced Polymer (CFRP) strips to rehabilitate severely corroded RC structures efficiently. Four-point bending tests were conducted on beam specimens designed with a 50% reduction in steel reinforcement area to evaluate the efficacy of this technique. Results demonstrated that repaired beams effectively recovered more than 90% of their original load-carrying capacities compared to undamaged control specimens. Specifically, repaired beams exhibited improved crack distribution and reduced deflection. Analysis highlighted the critical importance of optimal bonding at SHCC–CFRP and SHCC–concrete interfaces. The dimensions and bond lengths of the CFRP strips significantly influenced structural performance, emphasizing the need for meticulous design considerations. The findings confirm the practicality and effectiveness of the SHCC–CFRP hybrid repair method, offering a robust and economical solution for extending the service life of corroded RC structures.

**KEYWORDS**: Structural repair; Reinforced concrete; Strain-hardening cementitious composites (SHCC); Fiber reinforced polymer (FRP); Corrosion.

# COMPARATIVE STUDY OF CONCRETE WITH P POLYPROPYLENE MACROFIBERS AND RECYCLED TIRE STEEL FIBERS

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## ABSTRACT

This study presents a material characterization of high-workability concrete reinforced with polypropylene macrofibers and recycled tire steel fibers. The experimental program evaluated fresh-state workability, compressive strength, tensile splitting strength, and post-cracking flexural behavior to compare both reinforcement strategies.

Results show that polypropylene macrofibers enhance flexural strength while maintaining good flowability, whereas recycled steel fibers provide superior toughness and residual strength, despite presenting dispersion challenges due to their irregular geometry. Both fiber types demonstrate technical feasibility, and their selection should be guided by mechanical performance requirements and sustainability criteria. Recycled steel fibers are advantageous when toughness and environmental impact are priorities, while polypropylene macrofibers are preferable for applications requiring homogeneous dispersion and ease of placement.

**KEYWORDS**: Concrete; Polypropylene macrofibers; Recycled steel fibers.

# STRUCTURAL ENHANCEMENT OF NON-CIRCULAR RC COLUMNS USING HPFRC JACKETING


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## ABSTRACT

The construction industry consumes large amounts of raw materials, leading to high costs and a significant carbon footprint. In this context, materials with enhanced performance are being studied, such as High-Performance Fiber-Reinforced Concrete (HPFRC), which can be used as a thin jacketing system for RC columns. The present research includes an experimental program of pure axial compression tests, together with a review of the limited available studies on RC columns strengthened with HPFRC jackets.

The experimental program involved eight non-circular RC columns, 1200 mm in height, with square and rectangular cross-sections. Thin HPFRC jackets were applied using a commercial two-component mortar reinforced with straight metallic fibers (aspect ratio 62, 2% by volume) to enhance mechanical performance. The tests showed that both square and rectangular strengthened columns exhibited substantial increases in axial load capacity, ranging from 77% to 105% compared to unstrengthened specimens of the same concrete strength, with an average gain of 88%. The mechanical behavior of the strengthened columns appeared independent of cross-sectional shape, showing increased stiffness and a linear response up to slightly over 50% of the maximum load. Notably, failure occurred progressively through cracking rather than explosively.

Analysis of the experimental results and the data from available previous studies indicates that non-circular RC columns benefit from HPFRC jacketing regardless of section shape. Load enhancements seem to be primarily governed by the jacket mechanical ratio. These preliminary results suggest that cross-sectional geometry has little effect on jacket performance, highlighting its efficiency and advantages over other confinement systems.



**KEYWORDS**: Structural strengthening; High-performance materials; HPFRC; Jacketing; RC columns; Experimental program.

# TENSILE PERFORMANCE OF LOW-CARBON TEXTILE-REINFORCED 'JUST-ADD-WATER' GEOPOLYMER MORTAR

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## ABSTRACT

The increasing demand for sustainable and durable materials for structural strengthening has driven the development of low-carbon alternatives to conventional textile-reinforced mortar (TRM) systems. The reliance of TRMs on ordinary Portland cement (OPC) results in significant embodied carbon emissions. Textile-reinforced geopolymer mortar (TRGM) has therefore emerged as a low-carbon alternative by the complete replacement of OPC with geopolymer derived from aluminosilicate precursors and alkaline activators. However, most existing TRGMs are based on 'two-part' geopolymer formulations using liquid activators and conventional precursors such as fly ash and GGBS. However, the use of corrosive and often viscous liquid activators presents practical challenges for large-scale applications, while the availability of fly ash and GGBS in the UK is declining. To address these limitations, this study investigates the tensile performance of a TRGM based on a 'one-part' calcined clay geopolymer incorporating a small amount of solid activator, enabling a dry-mix "just-add-water" formulation and enhancing large-scale applications and commercial viability. The effects of two basalt textile reinforcement densities and different curing regimes were evaluated. The developed TRGM exhibited the typical tri-linear stress–strain response of conventional TRMs. Heat curing produced a stiffer initial response with lower cracking strains, whereas ambient temperature curing enhanced ductility. Ultimate tensile stresses approaching 1.0 GPa and tensile strains up to approximately 2.2% were achieved, depending on curing regime and reinforcement ratio, with textile exploitation ratios between 62% and 66%.

**KEYWORDS**: Calcined clay; One-part geopolymer; Textile-reinforced mortar; Tensile behavior; Sustainability.

# FATIGUE BEHAVIOUR OF SRG STRENGTHENED SHEAR CRITICAL RC BEAMS WITH VARYING TEXTILE DENSITY

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**ABSTRACT**

Reinforced concrete (RC) bridges subjected to increasing traffic loads are prone to fatigue-induced deterioration, in which progressive cracking and stiffness degradation may culminate in brittle shear failure. Such degradation poses a critical threat to the safety and serviceability of ageing infrastructure. Externally bonded mortar-based composites, particularly steel-reinforced grout (SRG) systems, have been shown to enhance shear resistance under monotonic loading; however, their performance under fatigue loading has received limited investigation, despite the urgent need for reliable retrofitting strategies.

This study examines the fatigue behaviour of three full-scale shear-deficient RC beams tested in asymmetric three-point bending. One specimen served as a control (unstrengthened), while two were retrofitted with U-shaped SRG jackets employing ultra-high-tensile-strength steel (UHTSS) textiles at nominal densities of 1.57 and 3.14 cords/cm. Cyclic loading was applied at 4 Hz between 30% and 70% of the static peak shear capacity. The control beam failed after only 75 cycles, whereas the low-density SRG configuration extended the fatigue life to 227 cycles and exhibited mitigated stiffness degradation and moderated displacement growth compared with the control. In contrast, the high-density system failed prematurely after 29 cycles due to inadequate grout adhesion and early debonding. Considering that the strengthened beams carried substantially higher loads, and that the low-density configuration achieved approximately three times the fatigue life of the control, SRG can be regarded as beneficial in improving the fatigue response of shear-deficient RC beams. All strengthened specimens ultimately failed in shear due to premature detachment of the SRG jacket. The observations highlight that, under the present configuration, fatigue performance is primarily governed by the bond behaviour at the mortar–textile interface. Consequently, further research is required to optimise interface preparation, textile density selection, and anchorage detailing, and to establish reliable design guidance for SRG-strengthened RC members under repeated loading.

**KEYWORDS**: SRG; Fatigue; Beam; Strengthening; Reinforced concrete.

# COMPRESSIVE BEHAVIOUR OF CONCRETE COLUMNS CONFINED WITH STEEL WIRE-REINFORCED HIGH TENSILE STRENGTH SHCC JACKETS


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## ABSTRACT

The deficiencies in existing concrete columns caused by non-compliant seismic detailing and material deterioration can be addressed via jacketing retrofitting. Among the available systems, Strain-Hardening Cementitious Composites (SHCC) have gained attention in retrofitting of existing concrete structures due to their compatibility with concrete, improved ductility, and superior energy absorption. SHCC have been reinforced with Fiber-Reinforced Polymer (FRP) grids to increase the stiffness of the jacket. However, the relatively high cost could limit the widespread adoption of such a system. The present study introduces a novel inorganic confinement system which consists of spirally running High Tensile Strength Steel Wires (HTS-SWs) combined with greener High Tensile Strength SHCC (HTS-SHCC). The HTS-SHCC was produced by replacing 40% of the cement with Limestone Calcined Clay (LC2), hence reducing environmental impact while enhancing the mechanical performance. This study experimentally investigates the axial compressive behaviour of concrete columns confined with the proposed jackets under uniaxial compression loading. The main test variable was the pitch spacing of the Steel Wire (SW) spiral reinforcement (i.e., 7 mm and 9 mm c/c). The results showed a notable increase in the load-bearing capacity of confined columns compared with unconfined columns. Furthermore, a significant enhancement in axial ductility was observed. Both bearing capacity and ductility improved with the steel wire reinforcement ratio. These findings demonstrate the potential of SW-reinforced HTS-SHCC jackets as an efficient concrete confinement system.



**KEYWORDS**: SHCC; ECC; Jacket; High tensile strength mortars; Steel wires; Limestone calcined clay; Confinement; Uniaxial compression.

# FLEXURAL STRENGTHENING OF RC BEAMS WITH GREEN FRCC LIGHT JACKETING

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## ABSTRACT

Existing reinforced concrete (RC) beams may become unable to carry vertical loads during service life due to changes in use of the structure, variation in design loads or exceptional loading conditions. Furthermore, degradation phenomena, such as corrosion, may affect the durability of RC structures and reduce the capacity of members. In this context, light jacketing with Fibre Reinforced Cementitious Composites (FRCC) has been proven to be an effective solution for enhancing the durability of RC members and improving the structural capacity. In this study, a green FRCC is considered, in which recycled steel fibres from tyre waste are used (S-FRCC). Moreover, to reduce the steel content, a part of the recycled fibres is replaced with short PE fibres (S-PE-FRCC). The green FRCCs are herein adopted for the flexural strengthening of RC beams. Four-point bending tests are performed on five small-scale beams. One specimen is used as the control reference specimen. Two additional specimens are reinforced with S-FRCC U-shaped jacketing, each using different fibre ratios. The final two specimens are strengthened with S-PE-FRCC, using two configurations: U-shaped jacketing and an S-PE-FRCC layer at the bottom of the beam. This report presents and discusses the results of the tests, highlighting the effectiveness of these solutions for enhancing the flexural capacity of existing beams.

**KEYWORDS**: Fibre reinforced cementitious composites; FRCC; Recycled fibres; Light jacketing; Flexural strengthening.

# UNIAXIAL TENSILE BEHAVIOUR AND CRACK DEVELOPMENT OF CFRP GRID REINFORCED UHPFRC

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**ABSTRACT**

This study investigates the uniaxial tensile behaviour of carbon fibre reinforced polymer (CFRP) textile grid reinforced ultra-high performance fibre reinforced concrete (TR-UHPFRC). Direct tensile tests were carried out on dog-bone specimens to evaluate the influence of textile reinforcement and steel fibre content on tensile strength, strain-hardening response, crack development, crack width control, and failure mechanisms. Specimens were reinforced with up to three layers of CFRP textile grid and randomly distributed micro steel fibres at volume fractions ranging from 0% to 2%. Digital Image Correlation (DIC) was used to assess crack propagation, crack spacing, and crack width evolution throughout the loading process.

The results show that the addition of CFRP textile reinforcement significantly enhances the post-cracking tensile response, while having only a limited influence on cracking strength. The average ultimate tensile strength increased by approximately 444%, from 13.61 MPa for the reference UHPFRC specimens to 74.08 MPa for specimens with three textile layers, both containing 2% steel fibres. Increasing the reinforcement ratio also resulted in denser crack patterns, reduced crack spacing, and substantially improved crack width control. At a tensile strain of 0.8%, the average crack width decreased from 115.8 µm to 45.5 µm for specimens with two CFRP textile layers and 2% steel fibres, compared with specimens with one textile layer and 0.5% steel fibres. Steel fibres contributed to stress redistribution and delayed crack localisation during tensile loading, thereby enabling more effective engagement of the CFRP textile reinforcement throughout the strain-hardening stage. The findings demonstrate a strong potential of TR-UHPFRC for structural applications requiring high tensile resistance together with controlled cracking behaviour.

**KEYWORDS**: TR-UHPFRC; CFRP grid reinforcement; Direct tensile behaviour; Strain-hardening behaviour; Crack width control.

# SS13 - Strengthening floor diaphragms with FRP: experimental advances and design integration

# TENSION STRENGTHENING OF REINFORCED CONCRETE USING LARGE-SCALE EB-FRP WITH AND WITHOUT FIBER ANCHORS

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**ABSTRACT**

Externally bonded fiber-reinforced polymer (EB-FRP) systems are widely used to strengthen reinforced concrete (RC) members, but debonding at the FRP–concrete interface often limits structural strengthening performance. This study summarizes the results from 131 large-scale axial tension tests on unanchored (59 tests), isolated anchored (24 tests), and single- and dual-anchored EB-FRP systems (48 tests), covering wide parameter ranges, including FRP thickness (0.5–6 mm), bond length (305–1524 mm), anchor dowel diameter (7–25 mm), embedment depth (51–102 mm), fan length (205–410 mm), and concrete strength (19.2–41.4 MPa). Failure modes were classified, revealing bond–anchor interactions for short upstream bond lengths and independent anchor contribution when bonded regions were sufficiently long. A unified empirical strength model was developed integrating bond-controlled debonding and anchor-controlled capacity. Predictions were validated against an independent database of 2,501 tests, including all configurations examined in this study. Results demonstrate robust ultimate strength predictions across all configurations, with reduced scatter and improved accuracy compared with existing models. The findings provide a practical framework for designing fiber-anchored EB-FRP axial tension strengthening systems.

**KEYWORDS**: Externally bonded; FRP; FRP anchors; Strengthening; Reinforced concrete.

# THREE-DIMENSIONAL NUMERICAL SIMULATION OF FRP-TO-CONCRETE INTERFACE DEBONDING CONSIDERING WIDTH EFFECT

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## ABSTRACT

The width effect is a critical factor in understanding the bond behaviour between concrete and externally bonded fibre-reinforced polymer (EB-FRP) systems, typically manifested as the nonuniform distribution of strain across the FRP width. Existing simplified models often fail to capture the complex width effect in large-scale specimens. This study develops a three-dimensional (3D) finite element (FE) model incorporating the Cohesive Zone Model (CZM) and the Concrete Damaged Plasticity (CDP) model, systematically validated against large-scale single-lap shear tests with bonded lengths up to 900 mm. The simulations accurately replicate the 3D characteristics of the width effect: while the central FRP region transfers loads through the concrete directly beneath it, the edge regions mobilize the surrounding concrete to participate in resistance, resulting in an effective load-resisting width that exceeds the actual FRP width. Furthermore, both FRP stiffness and concrete strength are found to influence lateral stress diffusion. Current CNR-DT 200 and fib Bulletin 90 guidelines are evaluated against the joint numerical and experimental analysis, revealing a significant tendency for non-conservative predictions when applied to large-scale specimens. To address this problem, a global correction coefficient ($\lambda$= 0.855) is proposed using nonlinear regression. The resulting capacity calculation framework effectively mitigates the systematic overestimation bias and agrees well with experimental results, providing a safer theoretical basis for the design of large-scale FRP-strengthened structures.

**KEYWORDS**: FRP; Reinforced concrete; Width effect; Nonuniformity; Effective width.

# CYCLIC SHEAR TESTING OF CONCRETE DIAPHRAGMS STRENGTHEN WITH CFRP AND A NEW INNOVATIVE ANCHORAGE SYSTEM

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**ABSTRACT**

Externally bonded fiber reinforced polymers (FRP) are widely employed for seismic retrofitting of non-ductile concrete buildings, particularly for strengthening concrete diaphragms with shear deficiencies. A recent collaborative research program between industry and academia was initiated to refine detailing methods and establish best practices for seismic applications of externally bonded FRP. This paper presents results and partial analysis of two specimens referred to as CD13 and CD14. Unlike earlier test specimens in this program that used FRP-only solutions, these panels evaluated a hybrid anchoring method integrating steel and FRP. The system consisted of the Duktil FRP Anchor plate, bonded with the LOCTITE Tyfo SCH-41 FRP system and mechanically anchored into the substrate using HILTI EZ-C countersunk screws. The objective was to enhance displacement ductility, increase shear strength, and improve energy dissipation through combined anchorage and optimized FRP detailing. Both retrofit schemes demonstrated significant gains in strength, ductility, and energy dissipation capacity. Notably, the retrofitted diaphragms exceeded the maximum nominal shear strength prescribed by ACI 318-19. Previous investigations on similar cantilever diaphragm specimens have provided design recommendations for practice. The current results extend this body of work, demonstrating the potential advantages of hybrid anchoring systems in conjunction with externally bonded FRP. The findings support the development of improved design strategies for seismic retrofitting, particularly in achieving higher ductility and reliability in diaphragm strengthening applications.

**KEYWORDS**: Hybrid plate; Mechanical anchors; FRP anchors; Diaphragm strengthening.

# SEISMIC PERFORMANCE OF EB-FRP IN RC DIAPHRAGMS: EXPERIMENTAL EVALUATION

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**ABSTRACT**
Concrete floor diaphragms in existing reinforced concrete (RC) buildings often lack adequate tensile capacity to transfer seismic forces between lateral force-resisting elements, primarily due to insufficient reinforcement as prescribed by outdated design. Externally Bonded Fiber Reinforced Polymer (EB-FRP) systems provide a cost-efficient retrofit solution, combining high tensile performance with relatively easy installation. However, current design guidelines such as ACI 440.2R offer limited provisions because large-scale experimental data for FRP application in diaphragm strengthening and the behaviour of FRP anchorage systems subjected to seismic loading remains insufficiently understood. This paper presents an experimental investigation into the tensile performance of wide, thick, and long FRP collectors bonded onto RC diaphragms, considering multiple end and intermediate anchorage configurations. The specimens were subjected to cyclic tension-compression loading simulating realistic earthquake demands. The study focuses on three aspects: (I) the force-elongation response of FRP-strengthened diaphragms, (II) the progression of FRP debonding and associated failure mechanisms, and (III) the effectiveness of anchor systems. The results provide new insights into the tensile behaviour of FRP collectors subjected to seismic loading and inform the development of a practical design methodology. By bridging the gaps between actual structural behaviour of FRP-strengthened diaphragms and existing design approaches not originally intended for diaphragm applications, this work aims to improve the understanding of RC diaphragm retrofit performance and enhance the structural resilience of RC buildings.

**KEYWORDS**: EB-FRP; FRP anchors; Floor diaphragm; Seismic strengthening; Large-scale tests.

# SESIMIC STRENGTHENING OF THE PRECAST DIAPHRAGMS USING FRP TIES SUBJECTED TO DEFORMATION INCOMPATIBILITY

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## ABSTRACT

FRP ties are increasingly used to retrofit hollow-core floor diaphragms in New Zealand buildings; however, deformation incompatibility induced by support beam rotation can generate additional force demand and cause damage to FRP ties and anchors. This study experimentally investigates the behaviour of FRP ties subjected to simulated support beam rotation using a sub-assembly test setup. Four specimens were tested with varying tie width, thickness, and anchor configuration, including one specimen with an intentionally unbonded interface region. The results show that tie width and thickness significantly influence the force demand at the beam–unit interface. When anchor dowel and breakout capacities exceeded the tie demand, controlled debonding governed the response without beam damage; however, insufficient breakout capacity led to concrete cracking and anchorage-related damage. Introducing an unbonded interface region reduced the debonding strain and force demand, mitigated beam damage, and promoted a more desirable debonding mechanism. These findings provide insight into anchorage design requirements and support the development of practical design recommendations for FRP tie retrofits in hollow-core diaphragm systems.

**KEYWORDS**: FRP strengthening; Hollow-core floor diaphragm; Deformation incompatibility; Progressive; Debonding; FRP anchor design; Seismic retrofit.

# NONLINEAR ANALYSIS OF FRP STRENGTHENED DIAPHRAGMS USING THE STRINGER-PANEL METHOD

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**ABSTRACT**

This paper evaluates a nonlinear implementation of the Stringer–Panel Method (SPM) for analysis of reinforced concrete diaphragms, including diaphragms strengthened with externally bonded fiber reinforced polymer (FRP). The method discretizes the diaphragm into axial force stringers and shear-carrying panels, with nonlinear panel response modeled using the Modified Compression Field Theory and FRP incorporated through effective reinforcement contributions. The formulation is validated against six large-scale cantilever diaphragm tests representing one-sided diaphragm end regions adjacent to a shear wall, including one control specimen and five FRP-retrofitted specimens with varying strengthening layouts, fiber orientations, and anchorage details. Comparisons are made in terms of backbone load-shear angle response, peak load, peak deformation, FRP strain demand, crack patterns, and failure characteristics. The simulations show good agreement with the experiments, with mean predicted-to-experimental ratios of 1.01 for peak load and 1.10 for shear angle at peak, and they capture key features of the observed behavior, including diagonal cracking, strut action, and the influence of FRP. Although additional refinement is needed to better represent localized post-peak mechanisms such as debonding and anchorage distress, the results demonstrate that SPM is a practical and computationally efficient tool for predicting diaphragm force flow and peak response in cantilever-like diaphragm regions. Broader application to other diaphragm configurations, boundary conditions, and loading scenarios will require additional validation.

**KEYWORDS**: Diaphragms; FRP retrofitting; Nonlinear analysis; Shear.

# CURRENT DESIGN GUIDELINES FOR FRP REINFORCED CONCRETE BASED ON FULL-SCALE TESTS IN UNITED STATES

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## ABSTRACT

Current design practice for the seismic retrofit of reinforced concrete (RC) structures with externally bonded fiber-reinforced polymers (FRP) remains fragmented and inconsistently applied. Existing United States standards, such as ASCE/SEI 41, ACI 440.2R, ICC AC125, and IAPMO EC 038, provide valuable background but do not offer a unified, performance-based framework specific to seismic demands. To address this gap, the West Hollywood Guideline for FRP Seismic Retrofit, developed collaboratively by practicing engineers in Southern California in conjunction with SEAOSC, represents the first comprehensive attempt to consolidate available design provisions and supplement them with emerging experimental evidence.

This presentation will first summarize the state of knowledge captured in the West Hollywood guideline, with emphasis on its treatment of FRP design strain, anchorage, and diaphragm load paths. It will then present results from more recent large-scale testing programs that further inform best practice. Key findings to be discussed include: (1) shear-controlled concrete wall (2) diaphragm shear performance from reverse-cyclic tests, and (3) collector tension and anchorage behavior studied through full-scale diaphragm collector tests. Together, these results provide new insights into FRP bond mechanics, anchor group behavior, and post-elastic deformation capacity that extend beyond the assumptions embedded in current guidelines.

By connecting codified provisions, engineering practice, and experimental evidence, the session aims to outline a rational and practical design roadmap for seismic FRP retrofit of RC diaphragms and walls, improving both reliability and constructability in future applications.

**KEYWORDS**: FRP; Strengthening; Concrete; CFRP; Seismic.

# SS14 - Thermoplastic composite rebar for concrete reinforcement

# DURABILITY OF THERMOPLASTIC GFRP REBARS AND THEIR BOND WITH CONCRETE UNDER ALKALINE EXPOSURE

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**ABSTRACT**
Glass fiber-reinforced polymer (GFRP) reinforcing bars (rebars) are a well-established alternative to steel for reinforcing concrete structures, particularly in aggressive environments where corrosion resistance is essential. Thermoplastic-based GFRP (TP-GFRP) rebars are currently under development and offer additional advantages over their thermoset counterparts, including bendability at elevated temperature and potential end-of-life recyclability. However, limited research has investigated the long-term durability of these novel rebars and their interfacial behavior with concrete, especially in alkaline environments. In this study, TP-GFRP rebars were conditioned in alkaline solutions and exposed to elevated temperatures to accelerate degradation processes. Comprehensive physicochemical and mechanical characterizations were performed before and after conditioning. In addition, pull-out tests were conducted to assess the evolution of the rebar–concrete bond behavior under alkaline aging. The results were compared to the initial properties of the rebars, and the observed changes were interpreted in light of the underlying microstructural degradation mechanisms. Mechanical performance was also evaluated against the requirements of existing standards. Overall, the findings provide deeper insights into the long-term behavior of TP-GFRP rebars in alkaline environments.

**KEYWORDS**: GFRPs; Thermoplastic matrix; Alkaline solution; Microstructure and mechanical properties; Bond behavior.

# THERMOPLASTIC GFRP BARS: ENGINEERING THE FUTURE OF REINFORCEMENT

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**ABSTRACT**
Historically, the industry has relied on thermoset resin matrices for GFRP bars, which, while providing high mechanical strength and chemical resistance, inherently lack the ability to be re-shaped after curing.
This paper presents the development and evaluation of a new generation of thermoplastic GFRP bars. Utilizing a liquid acrylic resin, these bars, unlike their thermoset counterparts, can be heated and reformed on-site, enabling tailored bending and customization to suit specific project geometries and late-stage design modifications.
Comprehensive experimental testing, conducted at the University of Sherbrooke, assessed the mechanical and durability performance of these thermoplastic GFRP bars. The results demonstrate compliance with, and in several cases surpass, the technical requirements set by ASTM D7957 and CSA S807 specification for tensile strength, modulus of elasticity, and long-term durability. Furthermore, creep-rupture testing projects a strength retention of 68% over a 100-year service life, underscoring their suitability for demanding structural applications.
Following these initial results, additional testing focusing on the performance of bent thermoplastic GFRP bars were performed. These investigations provided valuable feedback on the pro-duction process and helped orient research efforts toward optimizing the bending capabilities and ensuring viability for real-world construction applications.

**KEYWORDS**: Thermoplastic; GFRP bars; Durability; Creep-rupture; Bent bar performance.

# BEND CAPACITY OF THERMOPLASTIC GFRP REBARS: AN EXPERIMENTAL INVESTIGATION

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**ABSTRACT**

This study investigates the bend capacity of glass fiber-reinforced polymer (GFRP) rebars with a thermoplastic matrix, a material gaining attention for its recyclability and its unique ability to be bent after curing, which is a potential advantage on construction sites. The bend capacity is a critical property in reinforced concrete resisting mechanisms, as it strongly influences the design and detailing of shear reinforcement, anchorage, and bond. An experimental program with 30 specimens was conducted to evaluate the influence of bend radius, bar diameter, tail length, and bend angle on bend performance. Unexpectedly, a larger bend radius did not consistently yield higher capacity; in some cases, tighter bends performed similarly. The bend angle also showed a significant influence on bend capacity. These findings suggest that post-curing bending may induce local damage not considered in existing models, highlighting the need for refining both manufacturing techniques and predictive approaches for thermoplastic GFRP rebars. The paper also briefly discusses some aspects related with the test setup – namely the use of two hydraulic jacks and instrumentation, and compares the obtained results against predictions from empirical models developed for thermoset GFRP reinforcement.

**KEYWORDS**: Thermoplastic GFPR rebars; Bend capacity; Tail length; Bend radius; Anchorage.

# FLEXURAL BEHAVIOR OF CONCRETE BEAMS REINFORCED WITH THERMOPLASTIC GFRP BARS

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## ABSTRACT

Most of the glass fiber-reinforced polymer (GFRP) bars currently available in the market are manufactured with thermoset resins, which hinder recyclability and limit sustainability. In this context, GFRP bars with an Ellium® thermoplastic matrix (TP GFRP) emerge as an innovative alternative, offering not only the inherent durability of GFRP but also enhance recyclability while reducing logistical costs due to their bendability. However, limited research has addressed their structural performance under flexural loading.

This study presents the results of four full-scale simply supported concrete beams reinforced with GFRP bars and tested under a four-point bending configuration up to failure. The main experimental parameters include the longitudinal reinforcement and transverse reinforcement ratio. The experiments employed detailed instrumentation and digital image correlation (DIC), enabling the assessment of the the GFRP-reinforced beams in terms of stiffness, cracking, and ultimate capacity. Despite the beams being reinforced with FRP transverse reinforcement, a shear failure was obtained in some of the cases due to the rupture of the stirrups in the bent area.

**KEYWORDS**: Thermoplastic GFRP; Flexural behavior; Anchorage; Sustainable reinforcement.

# DURABILITY OF THERMOPLASTIC GLASS-FIBER REINFORCED REBARS UNDER ACCELERATED ALKALI IMMERSION

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## ABSTRACT

Recent advancements in manufacturing technologies have enabled the commercial-scale production of thermoplastic glass fiber-reinforced polymer (GFRP) rebars. Before these rebars can be adopted for structural applications, their long-term durability must be assessed. Current qualification practices, including those outlined by AASHTO and ACI, refer to ASTM standards for evaluating the FRP rebar performance, with one key criterion being durability of the rebars under accelerated alkali immersion. This study investigates the durability of glass fiber-reinforced polybutylene terephthalate (GF-PBT) rebars subjected to accelerated alkaline ageing. Baseline mechanical properties of tensile strength, apparent horizontal shear strength, and transverse shear strength were evaluated in accordance with relevant ASTM standards. Commercially available GF-vinyl ester rebars were included for comparison. Specimens were immersed in a pH 12.9 solution at 23°C, 60°C, and 80°C for 30, 60, and 90 days. GF-PBT was the thermoplastic rebar used. Results indicate that the baseline properties of GF-PBT rebars are comparable to those of the commercially available thermoset rebars. However, significant degradation in mechanical properties was observed for GF-PBT rebars after accelerated alkali immersion, highlighting the need for further research on improving the alkali resistance of thermoplastic rebars.

**KEYWORDS**: Thermoplastic rebar; Durability; Alkali; Accelerated ageing.

# ALKALI RESISTANCE OF THERMOPLASTIC FRP REBARS: EXPERIMENTAL EVALUATION

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## ABSTRACT

This paper presents an experimental study on the alkali resistance of thermoplastic fiber-reinforced polymer (TP FRP) rebars intended for use in reinforced concrete structures. Thermoplastic FRP composites are gaining attention due to their potential for improved durability, recyclability, and ease of processing compared to traditional thermoset-based systems. To assess their performance in alkaline environments typical of concrete pore solutions, thermoplastic FRP rebars were immersed in a simulated alkali solution for durations ranging from 1000 hours, up to 365 days. The exposure conditions in accordance with ISO 10406-1 were designed to accelerate chemical aging and simulate long-term service environments. Mechanical properties, including tensile strength and modulus of elasticity, were measured at each interval to evaluate retention and degradation trends over time. The experimental protocol also included visual inspection and dimensional stability assessments to detect any signs of swelling, discoloration, or surface deterioration. The results provide insight into the durability of thermoplastic FRP rebars under sustained alkali exposure and contribute to the broader understanding of their suitability for structural applications. This study supports ongoing efforts to qualify thermoplastic FRP materials for use in civil infrastructure, particularly in environments where long-term chemical resistance is critical.

**KEYWORDS**: Thermoplastic FRP; Alkali resistance; Durability; Experimental investigation; Tensile properties.

# EXPERIMENTAL INVESTIGATION OF BOND BEHAVIOR OF THERMOPLASTIC GFRP BARS EMBEDDED IN CONCRETE

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## ABSTRACT

Glass fiber-reinforced polymer (GFRP) reinforcing bars represent a valid solution to improve the durability of reinforced concrete (RC) members exposed to aggressive conditions. GFRP bars do not corrode and have a high strength-to-weight ratio. The role of fibers is to resist the applied load, whereas the organic resin is responsible for the stress transfer among fiber filaments and for protecting them from the external aggressive environments. In general, thermoset resins are used in GFRP bars. Thermoplastic resins, which allow for heating and reshaping the bars after resin polymerization, have been increasingly used. However, the body of research on the use of thermo-plastic resin GFRP bars is still limited. In this paper, the bond behavior of slightly grooved thermoplastic-resin GFRP bars embedded in concrete is studied using pull-out tests. Tests are carried out according to the European assessment document 260023-00-0301 considering a bonded length equal to five times the bar nominal diameter. Bars with nominal diameter equal to 6 and 12 mm are tested. The results obtained are discussed in terms of failure modes and applied load – free end slip responses. The results reported in this work shed light on the bond behavior of newly developed thermoplastic GFRP bars when increasing the bar nominal diameter from 6 mm to 12 mm.

**KEYWORDS**: GFRP bars; Bond; Pull-out; Thermoplastic resin.

# SS15 - IIFC TG2. Challenges and opportunities for end-of-life fibre reinforced polymers in civil engineering

# DEVELOPMENT OF THE CONNECTIONS OF DECK SLAB AND DECOMMISSIONED WIND TURBINE BLADE GIRDER

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**ABSTRACT**

The typical lifespan of a wind turbine is about 20–25 years. One of the major challenges in wind energy is the recycling of rotor blades, which are manufactured from FRP composites. In the earliest wind farms, blade replacements have already been necessary, and in the coming years, the number of blades requiring disposal will continue to increase. Currently, the primary recycling methods involve energy-intensive processes such as cement co-processing, mechanical treatment, solvolysis, and pyrolysis. However, the most promising approaches focus on reusing entire wind turbine blades. Thanks to their shape and mechanical properties, these blades can be repurposed in the construction industry, for example as bridge girders. The paper presents the results of research project focused on development the connections between FRP reinforced bridge deck and the girder made of decommissioned wind turbine blade Vestas V66. Conceptual design, numerical analysis and the results of experimental shear test including both static and fatigue investigations, conducted on a total of six test models are presented.

The study discusses slip curves, load-bearing capacity, failure modes, and fatigue durability. Developed connections exhibited higher load bearing capacity than calculated for road bridge using Eurocode standards and fulfilled all assumed requirements. Therefore, they were qualified to use for prototype road bridge.

**KEYWORDS**: Connection; Deck slab; Decommissioned wind turbine blade; FRP reinforcement; Girder.

# STATIC AND DYNAMIC TESTING OF A 15M BRIDGE CONSTRUCTED FROM A DECOMMISSIONED WIND BLADE

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**ABSTRACT**

Static load and dynamic vibration testing of a15-meter long pedestrian bridge (known as a BladeBridge) made from a segment of a decommissioned 49-meter Siemens Gamesa Renewable Energy (SGRE) wind turbine blade is described in this paper. The bridge has a single central blade girder and two timber decks, 1 meter wide on each side, and was constructed in Beaver Brook Park in Atlanta, Georgia, USA. The bridge was completed in May 2025, testing was completed in June and July 2025 after which it was opened to the public. Details of the bridge design and analysis have been reported elsewhere. Results of the testing and of FEM analysis are reported. The dynamic (modal) testing, using accelerometers, was performed to measure vertical, lateral and torsional vibration frequencies. The pseudo-static load was applied using water-filled plastic barriers. A uniformly distributed load of 40.2 psf (1.93 kN/m$^2$) was applied to both decks and to one side deck only to measure deflection and twist. Data for the static load test was collected using strain gages, dial gages, tilt gages and digital image correlation (DIC). The first natural frequencies measured were greater than code stipulated limits and load test results for deflections and strains showed small maximum values relative to span and ultimate strains relative to limit strains. Good correlation for deflections, strains and natural frequencies was obtained with FEM results.

**KEYWORDS**: FRP recycling; FRP material reuse; Wind energy; FRP bridges.

# CLOSING THE LOOP: RECYCLING END-OF-LIFE THERMOPLASTIC GFRP REBARS FROM CONCRETE

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**ABSTRACT**

The adoption of Fibre Reinforced Polymers (FRPs) in civil engineering faces a significant sustainability challenge: managing end-of-life (EoL) waste. While thermoplastic (TP)-based FRPs offer inherent recyclability, a viable pathway for recovering and valorising rebars from demolished concrete structures has been a major barrier. This paper presents a complete and successfully demonstrated recycling loop for TP Glass Fibre Reinforced Polymer (GFRP) rebars, developed within the TOP-Crete project. The critical first step—separation of the reinforcement from the concrete—was achieved by processing EoL reinforced concrete elements through a standard industrial recycling plant, without any washing step. The liberated TP GFRP rebar fragments underwent mechanical shredding and grinding, followed by twin-screw extrusion compounding with recycled acrylonitrile butadiene styrene (r-ABS) to produce a fully recycled composite granulate (80% r-ABS + 20% EoL rebars). Characterisation of injection-moulded specimens confirmed density, melt flow index, and mechanical properties comparable to commercial virgin ABS/glass-fibre grades, with scanning electron microscopy verifying excellent fibre-matrix adhesion. The process was validated at industrial scale by manufacturing a real-world pipe coupling sleeve, achieving Technology Readiness Level (TRL) 6–7 and successfully passing full-scale pull-out tests. This research demonstrates, for the first time, a tangible, scalable and cost-effective EoL solution for thermoplastic composites in construction, transforming demolition waste into a valuable resource for new industrial applications and closing the loop towards a truly circular economy in the FRP sector.

**KEYWORDS**: Thermoplastic GFRP; End-of-life (EoL); Concrete recycling; Mechanical recycling; Circular economy.

# CHEMICAL ACTIVATION OF RECYCLED POWDER FROM WASTE WIND TURBINE BLADES FOR ITS USE AS SUPPLEMENTARY CEMENTITIOUS MATERIAL

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**ABSTRACT**

The reactivity of waste wind turbine blade (WTB) powder as a precursor for alkali-activated materials remains insufficiently quantified. This study investigates the dissolution behaviour of WTB powder and resin-free glass fibre powder (GFP) under different alkaline environments. The dissolution of Si, Al, and Ca was evaluated using dissolution extent and BET-surface-area-normalised forward dissolution rates r+. The results show that the dissolution reactivity of Si and Al in both WTB and GFP is of the same order of magnitude as that of low-calcium fly ash. Al dissolution concentration, extent, and r^+are consistently lower in WTB than in GFP under medium-to-high alkalinity, indicating a selective kinetic suppression beyond simple dilution induced by the epoxy resin. Ca dissolution exhibits non-monotonic behaviour and is more strongly suppressed in WTB. The results demonstrate that the WTB possesses dissolution reactivity comparable to low-calcium fly ash, supporting its potential as an aluminosilicate precursor for alkali-activated materials.

**KEYWORDS**: Waste wind turbine blade; Alkali activation; Ion dissolution; Epoxy resin.

# REPURPOSING CARBON FIBRE REINFORCED POLYMER (CFRP) COMPOSITE WASTE IN SUSTAINABLE CEMENTITIOUS COMPOSITES


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## ABSTRACT

Fibre-reinforced polymer (FRP) waste from the aerospace and utility industries is increasing rapidly and poses serious environmental concerns because of its non-biodegradable nature. This study proposes sustainable strategies to repurpose carbon-FRP (CFRP) manufacturing waste into sustainable cementitious composites. Scrap CFRP components were mechanically processed into micron-sized recyclates (<600 µm) consisting of short fibres and resin fragments, which were incorporated into mortar at 1–10 wt% as partial cement replacements. In parallel, short carbon-fibre (CF) offcuts generated during cutting and trimming operations were added at 0.1 vol% as discrete reinforcement, with and without a bio-based tannic acid (TA) surface treatment to enhance interfacial bonding. Mechanical performance, water absorption and microstructural behaviour were evaluated. The CFRP recyclate mixtures demonstrated substantial performance improvements, with compressive strength increasing by up to 67.4%, flexural strength by 61.0%, and water absorption reduced by 20.5% compared with the control. Mortars containing 0.1 vol% TA-treated CFs also exhibited enhanced behaviour, achieving 29.7% higher compressive strength, 15.7% higher flexural strength, and 2.4% lower water absorption than the control. SEM analysis confirmed that the recyclates acted as micro-fillers that improved matrix packing and densified the ITZ, while TA-treated fibres promoted hydration-product deposition and formed stronger fibre–matrix interfaces, enabling more efficient stress transfer. These findings demonstrate a low-energy, scalable approach for diverting CFRP manufacturing waste into high-performance cementitious composites, supporting circular-material strategies and contributing to more sustainable construction practices.



**KEYWORDS**: Fibre-reinforced polymer (FRP) waste; Cementitious composites; Mechanical properties; Micro-structural analysis; Surface modification.

# FRACTURE ENERGY OF CONCRETE REINFORCED WITH RECYCLED FRP MACROFIBRES

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## ABSTRACT

While the wind energy sector is recognised for its positive environmental impact through zero-carbon electricity production, it faces challenges associated with recycling wind turbine blades made of glass-fibre-reinforced polymers (GFRPs). Mechanical recycling of GFRPs, including their incorporation into concrete, represents one of the most promising solutions. In this study, we evaluate the fracture energy performance of concrete reinforced with recycled GFRP macrofibres derived from reclaimed wind turbine blades. Previous research has primarily focused on the compressive and split tensile strength of normal concrete with recycled FRPs. However, split tensile tests are limited in their ability to capture the crack-bridging behaviour of concrete with recycled FRP materials. To address this, the wedge splitting (WS) test is employed to measure the fracture energy of concrete specimens with 5% GFRP macrofibres by volume of the aggregate, alongside control samples. Three different measurement techniques, LVDTS, clip gauge, and video gauge, were adopted for assessing the crack mouth opening displacement (CMOD). The mechanical performance of the concrete mixes was also evaluated via concrete compressive and split tensile tests. The results showed that incorporating 5% recycled GFRP macrofibres reduced compressive and splitting tensile strengths by approximately 11.0% and 5.8%, respectively, while improving fracture energy by approximately 7–41% compared with the control specimens. The GFRP-reinforced concrete also exhibited a more gradual post-peak response and enhanced crack-bridging behaviour, indicating improved energy absorption capacity.

**KEYWORDS**: Recycled FRP; Concrete fracture energy; FRP mechanical recycling.

# SS16 - fib-ACI joint session on specification and design of concrete structures with internal FRP reinforcement

# THE NEW ITALIAN GUIDELINES FOR DESIGN CONCRETE ELEMENTS WITH FRP BARS: AN OVERVIEW

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## ABSTRACT

In the last years the renewed interest for fiber reinforced plastic (FRP) bars as internal reinforcement for concrete elements has prompted the updating of existing guidelines or the development of new ones in order to comply with the new generation of FRP bars available on the market. In Italy a guideline for design new concrete elements with FRP bars was firstly published in 2006, i.e. the document CNR DT 203/2006, and in 2024 a review process was started: the updated version is available on CNR website from 2026 (https://www.cnr.it/en/technical-instructions-construction). The guideline provides design indications for concrete elements strengthened with FRP bars both at ultimate and serviceability limit states (ULS and SLS) under bending, shear, torsion, and normal stresses. In particular, the following issues were introduced in the reviewed version: classification of FRP bars based on fibres typology (glass or carbon), tensile strength and Young's modulus, definition of bond quality classes based on results of bond tests, design formulations for anchorage length depending on bond quality, new formulations for cracking and deflections control at SLS taking into account the bond quality, possibility of using FRP and steel bars in the same section (hybrid reinforcements), effect of sustained loads on the tensile strength of FRP bars at ULS (creep rupture), design criteria for structures in seismic areas, annex with design examples under bending and shear stresses. In general, the guideline is strongly correlated with the existing Italian and European qualification documents for determining the essential mechanical and physical characteristics of the FRP bars to be used in the design formulations. The paper focusses on the presentation of some of these issues.

**KEYWORDS**: Concrete elements; FRP bars, Design; Ultimate limit state; Serviceability limit state.

# EVALUATION OF SHEAR DESIGN PROVISIONS FOR FRP-REINFORCED CONCRETE BEAMS

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## ABSTRACT

FRP-reinforced concrete (FRP-RC) beams exhibit reduced shear strength compared with members reinforced with an equivalent steel reinforcement ratio. This is mainly attributed to the lower elastic modulus of FRP bars and their linear elastic behaviour up to failure, which can affect the development of shear resisting mechanisms. Existing standards and guidelines adopt different models for predicting the shear resistance of beams without transverse reinforcement and rely on different strain limits to estimate the contribution of FRP shear reinforcement. This paper presents a comparative study of shear design provisions for FRP-RC beams, including ACI 440.11-22, CSA S806-12, EN 1992-1-1:2023, and fib Model Code 2020, and assesses their performance and sensitivity to key design parameters. A literature-based database of slender beams reinforced with FRP longitudinal and transverse reinforcement was collected and analysed. Sensitivity analysis is conducted to examine the influence of key parameters on predictive accuracy, including reinforcement ratio and elastic modulus of FRP bars, shear span-to-depth ratio, compressive strength of concrete and effective depth of beams. Overall, existing provisions were found to be conservative and inconsistent, resulting in different safety levels. The inclusion of FRP stirrups reduces variability in shear strength predictions for all design models compared to the predictions for beams without stirrups. The sensitivity analysis indicates that for most design models, shear span-to-depth ratio is the dominant factor influencing predictive accuracy for beams without stirrups, while for beams with FRP stirrups, the stiffness of FRP reinforcement becomes a key parameter.

**KEYWORDS**: FRP-reinforced concrete (FRP-RC) beams; Shear strength; Predictive models; Safety level; Sensitivity analysis.

# SHEAR PERFORMANCE OF GFRP-REINFORCED CONCRETE BEAMS: EXPERIMENTS VS DESIGN CODE ASSESSMENT

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**ABSTRACT**
Shear behaviour in concrete beams is inherently complex, and it remains less well understood in members reinforced with GFRP bars than in conventional steel-reinforced elements. This is mainly due to the distinct mechanical properties of GFRP reinforcement, such as anisotropy, lower transverse stiffness, and limited dowel action compared to steel. The total shear capacity of a beam is generally considered as the combined contribution of concrete and shear reinforcement, while several interacting mechanisms participate in shear transfer, including aggregate interlock, dowel action of longitudinal bars, compression zone action, and the contribution of transverse reinforcement. Owing to the complexity of these mechanisms, a number of design standards and analytical models have been developed to estimate the shear resistance of GFRP-reinforced concrete beams, often leading to different predictions and levels of conservatism. This paper presents an analytical assessment of the shear capacity of T-section beams reinforced with GFRP bars, tested as part of a broader research programme at Lodz University of Technology, including beams without shear reinforcement. Experimental shear forces ($V_{test}$) were compared with calculated shear capacities ($V_{cal}$) obtained according to selected international design standards. The comparative study included the American ACI 440.1R-15 and ACI 440.11-22, Canadian CSA-S806-12 2021R, Italian CNR-DT 203/2006, and EN 1992-1-1:2023. The results revealed significant discrepancies in predicted shear capacities among the standards and provided valuable insights into the applicability and limitations of current design provisions for GFRP-RC beams.

**KEYWORDS**: GFRP reinforcement; Shear capacity; T-beam; Design standards.

# ANALYTICAL FORMULATIONS FOR CRACK CONTROL FOR FRP-REINFORCED CONCRETE ELEMENTS

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**ABSTRACT**

To overcome the problems related to the durability of reinforced concrete structures, in recent years, the use of fiber reinforced polymer (FRP) rebars in substitution for steel reinforcements has become widespread, given that FRP rebars are not subject to corrosion. To promote the use of these reinforcing systems in the engineering practice, several Codes and Guidelines for the design of FRP-reinforced concrete structures have been published in the last decades. With reference to serviceability limit state conditions, the objective of the present research is to analyze existing analytical formulations for crack control, starting from the approaches reported in Italian CNR Guidelines, which have been recently updated. For this reason, an extensive literature review is conducted and a collection of data is performed about flexural tests carried out on concrete beams reinforced with different type of FRP rebars. The results of 76 tests are analyzed, and different analytical formulations are taken into account to evaluate which one can better capture the experimental results. For a more consistent analysis, subsets of data are considered, depending on the concrete class and on the surface treatment of the FRP rebars. Correlations between the theoretical and experimental values of the crack opening are discussed in the paper, together with the calibration of alternative formulations, which may better describe the experimental results. The outcomes of the research may support an update of existing guidelines for the design and verification of FRP-reinforced concrete elements.

**KEYWORDS**: Concrete elements; FRP pultruded bars; Serviceability limit state; Crack control.

# REGULATORY PATHWAYS FOR GFRP BARS IN CONCRETE STRUCTURES: COMPARATIVE ANALYSIS OF CE MARKING AND ASTM SPECIFICATIONS

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**ABSTRACT**
Glass Fiber Reinforced Polymer (GFRP) reinforcing bars are increasingly used in concrete structures due to their corrosion resistance and favorable mechanical properties. Their structural application, however, depends on qualification frameworks capable of ensuring reliable and reproducible performance. This paper compares the European CE marking route based on the European Technical Assessment (ETA) issued under EAD 260023-00-0301 with the ASTM specification standards D7957 and D8505 used predominantly in North America. The comparison focuses on qualification philosophy, scope of tested properties, durability assessment, and approaches to conformity and quality control. The analysis highlights methodological differences that reflect distinct regulatory and design traditions rather than differences in technical rigor, and discusses their implications for international acceptance and dual compliance.

**KEYWORDS**: CE marking; EAD; ETA; ASTM; GFRP rebars.

# EFFECT OF THE MECHANICAL PROPERTIES OF GFRP BARS ON THE DESIGN OF REINFORCED CONCRETE BEAMS


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**ABSTRACT**

The recent updates of international guidelines and codes for the design of reinforced concrete (RC) elements with FRP bars reflect the growing scientific, technical, and commercial interest in this topic. As part of a broader parametric analysis of international standards, this study focuses on how the mechanical properties of concrete and GFRP bars may affect design outcomes. More specifically, some current codes and guidelines related to the design of RC elements with FRP bars commonly refer to test methods and minimum property requirements for the qualification, quality control, and certification of FRP bars. Thus, the effects of mechanical properties of FRP bars in compliance with minimum standard specifications given by ASTM standards and CNR DT 200 R1/2026 are herein investigated in terms of their impact on design outcomes obtained by applying the American ACI code and the recent version of the Italian CNR guidelines. A set of parametric analyses has been performed on a reference case consisting of a simply supported beam under a uniformly distributed load. The resulting design was examined in terms of the governing limit state, either serviceability or ultimate, which determines the required amount of reinforcement.

The outcomes show how differences in design approaches as well as material classes may influence or not design strategies, material selection, and elements construction costs. In general, it is observed that in the case under investigation, the serviceability limit state deflection check is the governing one and that the design result is basically dependent on the elastic modulus of GFRP, while a negligible impact is associated with tensile strength of material.



**KEYWORDS**: GFRP bar; Reinforced concrete; Design; Elastic modulus; Tensile strength.

# CONCRETE SHEAR STRENGTH IN FRP RC: PERSPECTIVE ON ADVANCING ACI 440 PROVISIONS

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**ABSTRACT**

The ACI CODE-440.11-22 provisions represent an advancement of the 2015 ACI 440 guide provisions to estimate the nominal shear strength, $V_c$, of glass fiber-reinforced polymer (FRP) reinforced concrete (RC) beams and one-way slabs without shear reinforcement. First, a size effect factor, $\lambda s$, has been introduced to account for the decrease in shear strength at increasing effective depth. Second, a lower bound for $V_c$ is specified for lightly reinforced members without shear reinforcement. The resulting provisions are simple to apply, and explicitly account for both strain effect and size effect. This presentation discusses how these provisions pave the way for further improvement that is significant and—in the author's opinion—necessary to facilitate the adoption of FRP reinforcement when corrosion is of concern. An up-to-date database of test results from 120 slender FRP-RC beam and slab specimens was assembled. For this database, when transitioning from the ACI 440 2015 guide to the 2022 code, it was found that: (i) the mean ratio of experimental to nominal shear strength remains essentially unchanged at ~1.8; and (ii) for this ratio, the maximum-minimum range narrows from 3.7-1.1 to a less desirable 3.1-0.7. In addition, a formula error analysis indicated that: (i) accounting for both overt and covert understrength factors, the effective strength reduction factor remains essentially unchanged at ~0.35; and (ii) the code provisions offer ample margins of improvement in accuracy irrespective of size and reinforcement ratio. The presentation closes by demonstrating a practical approach to updating the code provisions for $V_c$ to enhance accuracy and maintain safety, in a manner that is consistent with the current format.

**KEYWORDS**: Concrete; Design; FRP reinforcement; Shear; Safety.

# SS17 - Shear behavior of concrete members reinforced with organic- and inorganic-matrix composites

# SHEAR PERFORMANCE OF PRESTRESSED CONCRETE GIRDERS REINFORCED WITH GFRP STIRRUPS

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**ABSTRACT**
It is well known that the corrosion of steel reinforcement is a major factor in the deterioration of concrete structures. Almost four decades ago, researchers found FRP to be a viable alternative to steel reinforcement that can extend the service life and reduce maintenance. Most of the FRP research has focused on reinforced concrete (RC) flexural members, so experimental and analytical data on prestressed concrete (PSC) girders with FRP auxiliary reinforcement are limited. This study aims to investigate the shear behavior, and capacity of one large-scale prestressed concrete bridge girder. The tested girder is a part of the experimental program of NCHRP 12-121 project, funded by the National Cooperative Highway Research Program (NCHRP). This project aims to develop guidelines for the application of FRP as auxiliary reinforcement in bridge elements. The girder was designed as AASHTO Type I bridge girder with a 10.4 m length and a cast-in-place composite deck. Test results were analyzed in terms of ultimate shear stress, failure mode, reinforcement strain, and crack patterns. The shear reinforcement strain recorded in the tests exceeded the design strain limits of the current design provisions as CAN/CSA S6-19 (2019), ACI 440.11-22 (2022), and AASHTO LRFD GFRP-2 (2018a). These results suggest that with appropriate adjustments to current design provisions, GFRP can be effectively used as shear reinforcement in prestressed concrete girders, offering a lightweight, corrosion-resistant alternative to traditional materials.

**KEYWORDS**: Glass fiber-reinforced polymer (GFRP); Shear capacity; Pre-stressed concrete (PSC) girders; Full-scale girders.

# EXPERIMENTAL TESTS ON THE SHEAR BEHAVIOUR OF R.C. BEAMS STRENGTHENED WITH STEEL REINFORCED POLYMERS

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**ABSTRACT**

Current knowledge on the shear performance of reinforced concrete (RC) beams strengthened with Steel Reinforced Polymer (SRP) composites remains limited when compared to the large body of evidence available for Fibre Reinforced Polymers (FRP) with carbon and glass fibres. To address this gap, an experimental investigation was conducted on full-scale T-shaped RC beams strengthened with SRP systems. The specimens were designed to replicate realistic structural configurations in which a complete U-wrap application of the strengthening material is not feasible, a common situation in existing buildings where beams emerge below slabs.

The test program comprised both unstrengthened reference and strengthened beams, including different textile surface mass density as well as layouts with and without anchorage devices, aimed at preventing premature end debonding of the SRP strips. Cyclic displacement-controlled loading was applied to simulate demanding service and seismic conditions.

The investigation is intended to clarify the structural effectiveness of SRP strengthening in shear, to quantify the contribution of anchorage systems, and to examine the extent to which current design models developed for FRP can be extended to SRP. The results are also expected to provide experimental evidence useful for the calibration of future design guidelines and for the wider implementation of SRP composites in structural strengthening practice.

**KEYWORDS**: Steel reinforced polymer (SRP); Shear strengthening; Reinforced concrete beams; Anchorage systems**;** Cyclic loading.

# STUDY OF SHEAR BEHAVIOR IN AN RC BEAM WITH EB-FRP STRENGTHEN-ING CONSIDERING SIZE AND REINFORCEMENT INTERACTION EFFECT

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**ABSTRACT**
Use of structural reinforcements made of fiber-reinforced polymers (FRP) is now fully established in the aerospace and automotive industries. While in civil engineering it has long ceased to be a novelty, it is still approached with caution and even distrust, particularly when structural dimensions are scaled up. This cautiousness is clearly reflected in design codes, where direct and indirect safety factors are introduced, leading to an overdesign when applying these technologies. Moreover, the high cost of both fibers and resins has often led civil engineering applications to prioritize alternative solutions that, although less efficient, are also less expensive.
The ageing of the structural stock in Spain and across Europe today demands a thorough reassessment of these technologies, with the aim of extending service life and ensuring adequate structural performance in the face of increasing demands on our bridges. At the same time, the downward trend in the cost provides an additional incentive to deepen their study.
This project therefore aims to investigate the behaviour of structural strengthening, specifically through the use of carbon fiber, applied to beams with depths commonly found in our bridges. The study will focus on strengthening a beam 1 m in depth and 6 m in length. The beam is designed to collapse in shear, making this the reinforcement of greatest interest in our study. Prior to this, a smaller-scale flat beam will be used to refine the testing procedure. Finally, a comparison will be made between the experimental results and the calculations according to current design codes.

**KEYWORDS**: FRP; Concrete; Composites; Strengthening; Shear.

# DATABASE OF TESTED SHEAR-STRENGTHENED RC BEAMS WITH NSM FRP AND ANALYSIS OF RELEVANT PARAMETERS

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## ABSTRACT

Over the last 25 years a large amount of literature has been published regarding shear strengthening of reinforced concrete (RC) beams with Near-Surface Mounted (NSM) Fiber Reinforced Polymers (FRP). To leverage all this information, a database known as the Overall NSM Database (ONDB) has been created, which evaluated all epoxy-based, non-prestressed, RC beams strengthened in shear using NSM FRP published in open literature. The ONDB consists of 226 specimens from 23 publications, 22.6% (51) of which are non-FRP strengthened control specimens and 77.4% (175) of which are NSM FRP strengthened specimens. This database was compiled and cross-validated by separate research groups from two universities to ensure the independence and accuracy of the database. After establishing the ONDB, a set of criteria was established that was used to further refine the database to what is known as the Evaluation NSM Database (ENDB), which consists of 98 NSM FRP specimens. Examples of criteria include having a shear span to effective depth ratio above 2.4 and providing a minimum 10% gain in shear strength. Using the ENDB a wide range of parameters related to NSM FRP shear strengthening were investigated to confirm known existing relationships and to find gaps in current understanding which would serve as the basis for justifying future experimental work. The ONDB and ENDB can serve as a reliable database with an established framework which future NSM researchers can consult and expand with additional specimens.

**KEYWORDS**: Fiber reinforced polymer (FRP); Near-surface mounted (NSM); Shear strengthening; Reinforced concrete; Database.

# USE OF ANCHORS IN FRCM SHEAR STRENGTHENING OF RC BEAMS

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**ABSTRACT**

Fiber-reinforced cementitious matrix (FRCM) composites are nowadays used as externally bonded (EB) reinforcement of existing concrete and masonry structures. They were proven effective as flexural, shear, and torsional reinforcement of reinforced concrete (RC) elements. Shear strengthening of existing RC beams can be performed using three different configurations, namely side bonding, U-wrapping, and full-wrapping. While the first configuration is not recommended by international guidelines on FRCM composites, the fully wrapped configuration can be performed only when the top surface of the element is accessible or as shear strengthening of RC columns. The most common configuration is the U-wrapping, where the EB FRCM is applied on the beam lateral sides and bottom surface. A major limitation of the shear strengthening with U-wrapped EB FRCM is premature debonding of the FRCM layer. In order to delay or prevent FRCM debonding, mechanical or textile-based anchors can be used to increase the shear strength contribution provided by the U-wrapped FRCMs. This paper presents a state-of-the-art review on the role of anchors in the shear strengthening of existing RC beams with U-wrapped EB FRCM. Several parameters are analyzed, including the type of anchor, spacing, and FRCM layout. Comparison between RC beams shear-strengthened with FRCM systems with and without anchors reported in the literature allows for better understanding the key parameters influencing the anchor contribution to the beam shear strength. This review provides some insights into the anchors role and offers preliminary guidance for optimizing the design of U-wrapped FRCM shear strengthening of existing RC structures.

**KEYWORDS**: Anchors; Shear strength; FRCM; RC beams.

# PRESTRESSED CFRP STRAPS FOR SHEAR STRENGTHENING OF EXISTING CONCRETE STRUCTURES: FROM RESEARCH TO PRACTICE

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**ABSTRACT**
Prestressed, non-laminated carbon fibre reinforced polymer (CFRP) straps have been investigated for more than two decades as an alternative solution for the shear strengthening of reinforced concrete (RC) structures. Unlike bonded FRP systems, CFRP straps act as mechanically anchored, unbonded transverse reinforcement that can be actively prestressed. The development of this strengthening approach followed a progressive research path addressing material behaviour, mechanical anchorage, and structural feasibility. This paper reviews the conceptual and experimental evolution of prestressed CFRP straps, tracing their development from early material research through structural beam testing and numerical modelling to full-scale on-site applications. Particular emphasis is placed on how insights gained from successive experimental programs enabled the transition from academic research to engineering practice, culminating in the development of the CL-RESTRAP system. Laboratory and on-site evidence demonstrates that prestressed CFRP straps can significantly increase shear capacity, reduce crack widths, and transform brittle shear failure into ductile flexural behaviour. The successful application of the system in the heritage renovation of the Leuenhof building in Zurich provides clear proof of its practicality and robustness.

**KEYWORDS**: CFRP straps; Shear strengthening; Prestressing; Literature review; CL-RESTRAP.

# NUMERICAL MODELING OF REINFORCED CONCRETE BEAMS STRENGTHENED WITH CFRP FLEXURAL REINFORCEMENT AND U-WRAPS

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**ABSTRACT**

While externally bonded carbon fiber-reinforced polymers (CFRP) reinforcements are effective for strengthening reinforced concrete (RC) structural elements, their efficiency is often limited by debonding. CFRP U-wraps—commonly used as supplemental shear reinforcement—are also employed as anchorage for flexural CFRP sheets in RC beams to delay or prevent debonding. However, the dual use of U-wraps for both shear strengthening and anchorage of flexural CFRP in RC beams was not extensively explored in the literature and the design guidance is lacking. To investigate this problem, nonlinear 3D finite element (FE) models of RC T-beams strengthened with U-wraps and flexural CFRP were developed using the commercial FE software ATENA and verified against experimental results. In addition to the fracture-plasticity-based model used to simulate concrete cracking and crushing, the bond between concrete and externally bonded CFRP was modeled using a cohesive zone modeling (CZM) approach. The CZM approach couples Mode I (normal/peeling) and Mode II (shear) fracture behaviors, enabling interaction between opening and sliding mechanisms at the concrete–CFRP interface consistent with the Mohr–Coulomb criterion. Based on the initial results, the FE model demonstrated good agreement with the available experimental data in terms of failure modes, crack patterns, and load–displacement responses (within a 10% variation). The calibrated FE model will be further used to conduct a parametric study on the influence of variables that were not examined in the experimental testing phase of the project.

**KEYWORDS**: Reinforced concrete; U-wraps; Finite element; Cohesive zone modelling.

# STUDY OF THE SHEAR STRENGTH CONTRIBUTIONS IN PBO FRCM SHEAR-STRENGTHENED BEAMS

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**ABSTRACT**
Fiber-reinforced cementitious matrix (FRCM) composites are increasingly used for the strengthening of existing reinforced concrete and masonry structures. These systems consist of fiber bundles arranged in an open-mesh textile embedded in an inorganic, cement- or lime-based matrix. They have proven to be effective for the flexural, shear, and torsional strengthening of reinforced concrete (RC) members. Shear strengthening of existing RC beams can be performed using three configurations: side-bonded, U-wrapped, and fully wrapped. FRCM can have a continuous or discontinuous layout, and a different number of strengthening layers can be used. The shear strength of RC beams strengthened with externally bonded composites is usually computed as the sum of the contributions of the concrete, Vc, internal transverse reinforcement (if any), $V_s$, and composite, $V_f$. The value of the contribution of the different shear resisting mechanisms (i.e., $V_c$, $V_s$, and $V_f$) is usually computed following the Mörsch truss model.
This work analyzes the shear strength contribution provided by U-wrapped FRCM in RC beams. In particular, the experimental results of five flexural tests on real-scale RC beams shear-strengthened with U-wrapped PBO FRCM composites are presented and discussed. The strains measured in the FRCM textile and in the internal transverse steel reinforcement are used to compute the FRCM, steel, and concrete contributions to the beam total shear resisting force, following the Mörsch truss model. The results presented provide useful insights on the role of the different parameters involved in the beam shear resisting mechanisms, contributing to the body of knowledge on this topic.

**KEYWORDS**: Shear strength; FRCM; RC beams; Externally bonded reinforcement.

# SS18 - Advances in the investigation of bond-dominated problems of organic and inorganic composites: new approaches, unexplored issues, and future challenges

# FRP-TO-SUBSTRATE BONDED JOINTS MADE WITH BRITTLE OR DUCTILE ADHESIVES UNDER THE PULL-PULL TEST

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**ABSTRACT**
The larger number of studies devoted to fibre-reinforced polymers (FRP)-to-substrate joints subjected to the pull-push test justifies why the debonding processes developed in this case are better understood than those where the bonded joints are subjected to the pull-pull test. To mitigate that gap of knowledge, the present work proposes a new closed-form solution for FRP-to-substrate bonded joints made with brittle or ductile adhesives when subjected to the pull-pull test configuration. The analytical model is based on a trapezoidal bond-slip relationship, which enabled us to simulate the debonding of FRP-to-substrate joints using a ductile adhesive. For bonded joints with a brittle adhesive, the original trapezoidal shape can be simplified to a triangular shape, thereby expanding the range of simulations of debonding processes for different FRP-to-substrate joints subjected to the pull-pull test. This generic closed-form solution allowed us to identify four possible debonding processes for the FRP-to-substrate joints made with a ductile adhesive. From a series of generated cases covering double-strap CFRP-to-steel joints, all the debonding processes are analytically modelled, and the results are compared with those obtained from the finite element method (FEM). Additionally, another study found in the literature was considered and simulated with the current proposed analytical model. Since the analytical results showed a good agreement with all the studied cases and work found in the literature, the proposed analytical model is validated, making it a valuable tool for the improvement of the actual knowledge on the bond behaviour of FRP-to-substrate joints subjected to the pull-pull test configuration.

**KEYWORDS**: FRP composites; Debonding; Ductile adhesives; Bond-slip; Closed-form solution.

# EFFECTIVENESS OF FRP ANCHORS IN THE STRENGTHENING OF RC STRUCTURES

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**ABSTRACT**
FRP strengthening of deficient or degraded reinforced concrete structures is a popular technique in the current construction practice. This is because of the significant advantages, such as ease of installation, light weight, market availability, and good mechanical performance. Although several experimental and analytical studies demonstrated the effectiveness of FRP systems in increasing the strength or ductility of reinforced concrete structures, debonding failures in the strengthened elements significantly limit the exploitation of the full strength of fabrics or laminates due to the low tensile strength of the concrete. In this context, mechanical anchors have been demonstrated to provide a significant contribution into enhancing the tensile strength of the FRP reinforcement thanks to additional load transfer and redistributed stresses patterns to the concrete substrate. Their use may significantly increase the effective maximum strain attained in the FRP reinforcement, thus resulting in higher performances and a more efficient use of these materials. This paper provides a general overview on the use of FRP spike anchors to enhance the bond strength of FRP systems bonded to concrete supports. An in-depth literature review about the use of spike anchors has been conducted to select design formulations and collect a dataset of experimental tests of bond tests on FRP fabrics anchored with these systems. Then, the experimental results are compared with some design formulations available in literature.

**KEYWORDS**: Concrete; FRP reinforcement; Debonding; Spike anchors; Bond tests.

# MECHANICAL AND PIEZORESISTIVE PERFORMANCE OF SELF-SENSING TEXTILE-REINFORCED MORTAR COMPOSITES FOR MASONRY STRENGTHENING

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**ABSTRACT**

This study examines the mechanical and self-sensing performance of textile-reinforced smart mortar (TRSM) composites containing carbon microfibers (CMF) to enable strain sensing. A lime-based mortar made of natural hydraulic lime and silica fume was developed, with 0.1% CMF added by binder weight to improve electrical conductivity and crack bridging. The experimental program included mechanical testing, electrical resistivity measurements, and piezoresistive evaluation of TRSM composites under monotonic and cyclic tensile loading.

The results show that adding CMF notably enhances both the mechanical and electrical performance of the mortar. Flexural and compressive strengths increased by 67% and 34%, respectively, while electrical resistivity decreased by about 37%, indicating the formation of conductive pathways within the matrix. Tensile tests further indicated a 21% increase in ultimate strain and better stress transfer within the composite system. The piezoresistive assessments revealed highly repeatable strain-resistivity responses under cyclic loading, with strong linear correlations (R2> 0.8) and gauge factors of 126 under cyclic loading and 80.3 under monotonic loading. These findings demonstrate that the TRSM composite maintains reliable strain sensing even after microcracking and cyclic damage occur.

Overall, the findings confirm that incorporating low doses of CMF into TRSM composites can produce multifunctional materials with improved mechanical performance and robust piezoresistive sensitivity, making them promising candidates for integrated strengthening and structural health monitoring applications.

**KEYWORDS**: Textile-reinforced mortar; Carbon microfibers; Piezoresistivity; Self-sensing materials; Strain monitoring.

# UPDATING OF THE DESIGN RULES FOR THE BOND BEHAVIOUR OF FRPS IN THE CNR-DT 200 R2/2026

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**ABSTRACT**

In recent years, strengthening existing structures with fiber-reinforced polymer (FRP) materials has become one of the most widely used techniques for improving or restoring the performance of masonry or concrete structural elements. Despite the numerous national and international guidelines, some issues related to the behavior of reinforced elements, for which adhesion with FRP reinforcement is a dominant factor, still need to be clarified or better explored for design purposes. The current wide availability of experimental tests and analytical or numerical studies on the behavior of concrete or masonry elements reinforced with FRPs has allowed researchers to acquire more-detailed knowledge of bond-related phenomena. This has led to an updating of the Italian guideline CNR-DT 200 (the last revision, R1, dates to 2013), both in the Italian and English version. This paper aims to illustrate the main innovations introduced in the new version of the document, CNR-DT 200 R2/2026, on some bond-related phenomena and clarify the procedure adopted for evaluating new design provisions, all based on the 'design by testing' procedure suggested in Eurocode 0. In particular, the following issues were discussed:

- design formulations for end debonding strength and effective bonded length in concrete and masonry elements externally bonded with FRP materials;
- estimation of effectiveness of anchoring devices into improve the bond strength and delay debonding failures;
- bond strength model for Near Surface Mounted systems.

**KEYWORDS**: Strengthening; FRP EBR; FRP NSM; Bond strength model; Anchors; Design provisions.

# FREEZING AND THAWING DURABILITY OF SUSTAINABLE TRM SYSTEMS: A PRELIMINARY STUDY

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**ABSTRACT**
The present study is aimed at examining bond performances of sustainable TRM systems applied to masonry substrate when exposed to adverse environmental conditions. To this end, direct single-lap shear tests were performed on masonry specimens after they were subjected to freeze-thaw cycles in a climatic chamber. Specimens were made of clay bricks or yellow tuff units and comprised a TRM strip consisting of a bidirectional basalt or unidirectional steel textile embedded in inorganic matrix. The final goal is to attempt to improve sustainability in the field of strengthening or repairing existing structures, since building industry is recognized to be one of the major causes of pollution. This objective was pursued by employing two different cement-free mortars for TRM systems: a proprietary NHL commercially available mortar and a ground granulated alkali-activated blast furnace slag-made one. Indeed, it is well-known that Portland cement production process is responsible for massive greenhouse gas emissions as well as the waste of huge amounts of water and natural resources; therefore, this is the reason why the present experimental program investigates efficiency of cement-free mortars in strengthening systems. It must be underlined that the experimental campaign presented in the paper is a little part of STRIPES research project, funded by PNRR-PRIN 2022.

**KEYWORDS**: Sustainability; TRM systems; Direct shear test; Alkali-activated slag; Freeze-thawing aging.

# EXPERIMENTAL ASSESSMENT OF BOND STRESS TRANSFER MECHANISMS FOR GFRP REINFORCEMENT IN CONCRETE

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**ABSTRACT**
The use of glass fiber reinforced polymer (GFRP) reinforcement is increasingly recognized as a sustainable and durable alternative to steel in reinforced concrete members, particularly in aggressive environments where corrosion is a critical concern. This study investigates the bond behavior between concrete and pultruded GFRP bars manufactured with E-CR glass fibers and a thermoset vinyl-ester/epoxy resin matrix. The bars are surface-treated through sand-coating and continuous helical winding to enhance mechanical interlock and bond performance, in accordance with current qualification guidelines. The experimental program includes pull-out tests designed according to the RILEM Recommendation to evaluate the influence of bar diameter on the bond stress–slip response and on the mechanisms governing bond failure. Mechanical characterization of the concrete was carried out through compressive and pure shear testing following the JSCE-SF6 standard. The pull-out test results are analyzed in terms of bond stress–slip curves with particular attention to peak and residual bond strength and the corresponding slip values. Correlations between bond performance and concrete mechanical properties are established, providing a basis for the development of predictive bond models for design applications. The findings contribute to the optimization of GFRP reinforcement detailing and confirm the suitability of these bars for long-service-life, low-maintenance structures, promoting resilience and environmental sustainability in future construction practice.

**KEYWORDS**: GFRP reinforcement; Bond behavior; Pull-out test; Concrete shear strength; Durability and sustainability.

# KNOT EFFECT ON FRCM BOND BEHAVIOR. EXPERIMENTAL AND NUMERICAL INVESTIGATION

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**ABSTRACT**

The fiber-matrix interface bond drives the bond behavior of inorganic matrix fiber-reinforced composite systems (FRCM) and depends on several parameters, such as the fiber type, the fiber surface treatment, and the mortar characteristics. This study focused on the effect of the knot of a glass-fiber open textile coupled with two types of mortars (lime and cement) of different physical and mechanical properties. An experimental campaign was conducted to characterize the constituent materials, performing bending and compression tests on mortars, and tensile tests on both mortars and glass-fiber. Moreover, to experimentally investigate the knot presence effect, two different pull-out tests were performed on the systems: the multifilament pull-out test and the knot-effect pull-out test. Both consisted of a lamina-shaped sample of dimensions 10x60x220 mm3 glued to two aluminum plates and tested under displacement control with a pull-pull configuration. In the first one, only a multifilament was embedded in the mortar, so no knot was present, while in the second, a single yarn was pulled out of an embedded five-yarn textile. From the results was possible to determine the effect of the knot presence or absence on the global behavior, and how the mortar granulometry affected its imbuement capacity, influencing the results.

**KEYWORDS**: Bond behavior; FRCM; Finite difference method; Pull-out; Knot effectiveness.

# EXPERIMENTAL AND ANALYTICAL STUDY OF THE STRESS-TRANSFER MECHANISMS IN DOUBLE-LAP FRCM SPLICE JOINTS

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## ABSTRACT

Fiber-reinforced cementitious matrix (FRCM) composites, consisting of high-strength fiber textiles embedded in inorganic matrices, have emerged as a sustainable and durable alternative to traditional fiber-reinforced polymer (FRP) composites for strengthening reinforced concrete and masonry structures. Their mechanical response, however, is strongly influenced by the efficiency of the stress-transfer between fibers and matrix, as well as by the interfacial bond characteristics that govern load distribution and failure mechanisms.

This study builds upon previous research on FRCM coupons comprising two textile layers with a single-lap and extends the analytical and experimental investigation to double-lap configurations, where load transfer occurs symmetrically through two bonded interfaces. The experimental program includes tensile tests on polyparaphenylene benzobisoxazole (PBO) FRCM specimens with varying overlap lengths, designed to explore the effect of bond geometry and matrix–fiber interaction on the applied load–global slip response. Experimental results are interpreted to identify distinct stages of bond activation, interfacial debonding, and textile slippage.

An analytical model based on cohesive interface laws is then developed to simulate the stress-transfer mechanism in the double-lap configuration. The model parameters are calibrated against the experimental data and validated through a comparison of predicted and measured applied load–global slip curves. Results demonstrate that the proposed model effectively reproduces the mechanical response and confirms that the double-lap configuration enhances stress uniformity, bond efficiency, and ultimate load capacity compared to the single-lap case.

**KEYWORDS**: Fiber-reinforced cementitious matrix (FRCM); Lap splice; Bond; Analytical model; Cohesive material law.

# DETERMINATION OF THE DEVELOPMENT LENGTH OF GFRP BARS BASED ON PULL-OUT TESTS RESULTS

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## ABSTRACT

The structural response of reinforced concrete (RC) members reinforced with glass fiber-reinforced (GFRP) bars is governed by the bar-concrete interfacial properties, which can vary between different GFRP bars due to differences in their surface configurations. For this reason, determining how bond-dependent properties, such as development length, crack width, and deflection, depend on the parameters describing the bond behavior of GFRP bars is crucial for the de-sign of RC members reinforced with GFRP bars. The bond properties of GFRP bars are typically evaluated using pull-out tests due to the simplicity of the test setup. Short embedment lengths (2 to 5 times the bar diameter) are often selected, in an attempt to obtain a local relationship be-tween interfacial slip and shear stress, referred to as the cohesive material law (CML). However, it has been shown that the CMLs obtained from pull-out tests with short bonded lengths differ from those obtained with longer bonded lengths (20 to 40 times the bar diameter).

In this paper, an equation is proposed to calculate the development length, i.e., the bonded length required to transfer a given tensile force in the bar at the bar-concrete interface, in function of the parameters a CML. The equation is based on the bar-concrete interfacial CML obtained in a previous step of the research.

**KEYWORDS**: GFRP bar; CML; Pull-out test; Bonded length; Transfer length.

# ELEVATED-TEMPERATURE TENSILE TESTS ON A FLAX-TEXTILE FRCM

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**ABSTRACT**

In recent years, the construction industry has shown increasing interest in fiber-reinforced cementitious matrix (FRCM) composites featuring natural fiber textiles. These materials offer a promising solution for the externally bonded reinforcement (EBR) of masonry structures, combining sustainability with substrate compatibility. Specifically, flax-textile FRCMs merge good mechanical performance with low self-weight. However, organic components may degrade when exposed to environmental actions such as elevated temperatures.

This paper presents the results of elevated temperature tensile tests performed on a flax FRCM at 80 °C using the clamping-grip test set-up in accordance with Italian acceptance criteria (AC) and the European Assessment Document (EAD) 340275-00-0104. In the experimental campaign, a set of six non-conditioned specimens was tested as reference using the clamping-grip tensile tests set-up. Then, an additional set of six specimens was conditioned in a binder climate chamber and then subjected to sustained elevated-temperature clamping-grip tensile tests. Comparison is made between reference FRCM specimens and specimens tested at 80 °C. The findings offer valuable insights on flax-textile FRCM behavior under elevated temperature conditions.

**KEYWORDS**: Flax textile; Natural FRCM; Cyclic behavior; Tensile tests.

# EFFECT OF ANCHORS ON STRAIN DISTRIBUTION IN FRP REINFORCEMENT OF STRENGTHENED RC BEAMS

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**ABSTRACT**

Fiber-reinforced polymer (FRP) composites are considered an effective solution to increase the load-carrying capacity of reinforced concrete (RC) beams. When FRP strips are applied to the tension side of RC beams, they provide an additional tensile force. The effectiveness of FRP technology depends on the ability of transferring stress at the interface between composite and concrete substrate. Thus, FRP flexural strengthening is a bond-critical problem. Premature debonding occurs either at the end of the beam due to peeling stress or as a progressive phenomenon that initiates in the region of high moment and propagates towards the beam ends. To hinder the onset of debonding, FRP spike anchors or U-wraps can be used at the ends or along the entire length of the beam.

This work presents an experimental campaign designed to investigate the role of anchors in preventing the full debonding of the FRP strip. RC beams are cast and then strengthened with FRP anchors. The RC beams presented are strengthened with same numbers of FRP layers but different anchor configurations. The strain distribution in the FRP along the beam is obtained from digital image correlation. Mirror are used to take images of the intrados of the beam. The strain values are discussed in the context of design limits and debonding strain corresponding to single-lap tests of FRP-concrete joints that feature the same number of layers used in the beams and concrete strength equal to that of the RC beams.

**KEYWORDS**: FRP; RC beam; Bond; Anchor.

# FROM PULL-OUT TO STRUCTURAL TESTS: EXPERIMENTAL ASSESSMENT OF GFRP BAR BOND BEHAVIOR IN PLAIN AND FIBER-REINFORCED CONCRETE

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**ABSTRACT**

This study investigates the bond behavior of thermosetting glass fiber-reinforced polymer (GFRP) bars embedded in plain concrete (PC) and polyvinyl alcohol fiber-reinforced concrete (PVA-FRC). An experimental program comprising pull-out (PO) tests, notched beam (NB) tests, and full-scale reinforced concrete beam (RSB) tests was conducted to evaluate bond behavior across different structural scales. Digital image correlation (DIC) was employed in the beam tests to measure crack opening and derive the relationship between bar force and bar-concrete slip. The results show that PO tests provide a lower-bound estimate of the bond response observed in beam tests. The difference between PO and NB responses is more pronounced for FRC specimens, highlighting the contribution of fiber crack-bridging mechanisms. Comparisons between PO and RSB tests indicate a closer agreement, suggesting that PO tests may better represent the bond behavior occurring in structural members than NB tests. The presence of PVA fibers had a limited influence on the bond response measured in PO tests but significantly affected the behavior of NB specimens by reducing crack opening and redistributing stresses. Relationships between bar stress and crack opening obtained from full-scale beams were also compared with the predictions of ACI 440, showing generally good agreement. The results provide insight into the interpretation of bond tests at different scales and in-to the role of PVA fibers in GFRP-reinforced concrete members.

**KEYWORDS**: GFRP bars; PVA fibers; Bond; Pull-out test; Notched beam test; Flexural test.

# SS19 - Hybrid reinforcement systems (FRP+steel rebars) for durable and seismic-resilient concrete structures

# CRACKING OF CONCRETE TIE RODS REINFORCED WITH STEEL AND FRP BARS: MODELLING OF BARS-TO-CONCRETE BOND

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**ABSTRACT**
Hybrid reinforcement combining steel and fiber-reinforced polymer (FRP) bars represents an effective strategy to enhance both strength and ductility of reinforced concrete members. However, due to the markedly different mechanical and bond properties of steel and FRP bars, the serviceability behavior of hybrid-reinforced elements is strongly influenced by the bar-to-concrete interaction mechanisms. This paper investigates the cracking response of concrete tie members reinforced with steel and FRP bars through a nonlinear numerical model based on local bond–slip laws. The governing differential equations are solved using a finite-difference iterative procedure, accounting for the distinct bond–slip relationships of steel and FRP reinforcements. For steel bars, the Bertero–Popov–Eligehausen model is adopted, while for FRP bars different bond–slip formulations available in the literature are considered. Model predictions in terms of maximum crack width and crack spacing are compared with experimental results reported in the literature. Furthermore, results are contrasted with those obtained using a simplified analytical model assuming uniform bond stress distribution along the reinforcement. The comparison highlights that the local bond–slip approach provides accurate predictions (average ratio ≈ 1.05), whereas the uniform bond assumption leads to systematic underestimation of crack width (average ratio ≈ 0.85). The results confirm the fundamental role of realistic bond modeling in the serviceability assessment of hybrid-reinforced concrete ties.

**KEYWORDS**: Hybrid reinforcement; Concrete ties; Cracking; Bond; Model.

# RESPONSE OF HYBRID (GFRP+STEEL) REINFORCED CONCRETE COLUMN SUBJECTED TO SEISMIC LOADING

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## ABSTRACT

Recent advancement in the construction industry have led to the study of internal hybrid reinforcement systems [fiber-reinforced polymer (FRP)+steel rebars] in reinforced concrete (RC) structures. To better understand their behavior in concrete column, three experimental test was conducted. The test program involved concrete columns, longitudinally reinforced with either steel or hybrid systems (FRP+steel). All the columns were confined with glass FRP (GFRP) transverse reinforcement and subjected to quasi-static reversed cyclic lateral loading along with constant axial compression. Hybrid reinforcement systems aim to combine the stiffness and ductility of steel bars with the corrosion resistance, tensile strength, and linear elastic properties of GFRP bars. This comnination is intended to enhance initial and post-yield stiffness, improve energy dissipation, and reduce post-earthquake residual drift. Test results indicated that properly designed RC columns with longitudinal hybrid reinforcement can withstand significant deformations without strength degradation, meeting drift limits in design standards. These columns demonstrated acceptable levels of energy dissipation and ductility, outperforming those reinforced solely with longitudinal steel bars in terms of seismic resilience. These promising findings support the potential adoption of hybrid FRP+steel reinforcement in lateral load-resisting systems to improve earthquake resistance.

**KEYWORDS**: Hybrid reinforcement; GFRP bars; Initial and post-yield stiffness; Ductility; Energy dissipation; Residual displacement; Seismic resilience.

# CRACK DEVELOPMENT IN GFRP-REINFORCED CONCRETE TIES: AN EXPERIMENTAL STUDY

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## ABSTRACT

Fibre-reinforced polymer (FRP) bars are being increasingly considered as a viable alternative to conventional steel reinforcement, primarily because of their resistance to corrosion and high strength-to-weight ratio. Despite these advantages, the interaction between FRP bars and concrete, and their influence on the cracking behaviour of members in tension or flexure remains partially understood. This issue is relevant since the evolution of cracking directly influences the tension stiffening effect, affecting the serviceability and long-term performance of reinforced concrete (RC) members. This paper presents an experimental study on the crack development and tension stiffening response of concrete ties reinforced with FRP bars. Three series of ties reinforced with Glass-FRP (GFRP) bars of identical nominal diameter but with different surface treatments (spiral ribbed, sand-coated and ribbed) were tested under direct tension and compared with a reference series reinforced with steel bars of the same diameter as the GFRP bars. The analysis considered the onset, propagation, spacing and width of cracks, together with the global load-deformation response. Alongside the tests performed on the GFRP reinforced ties, tensile tests on the GFRP bars and direct pull-out tests on concrete cylinders were also carried out. The results confirmed that surface treatment significantly influences the bond behaviour and, consequently, the ability of GFRP-RC members to mobilise tension stiffening. Compared with steel reinforcement, GFRP bars led to lower post-cracking stiffness and distinct crack patterns, confirming the need for specific predictive models that reflect their bond mechanisms to concrete. The results obtained herein constitute benchmark data for the calibration of analytical and numerical models about the structural behaviour of FRP reinforced concrete members.

**KEYWORDS**: FRP bars; Concrete; Crack width; Tension-stiffening; GFRP-concrete bond.

# SHEAR CAPACITY OF HYBRID FRP–STEEL CONCRETE BEAMS WITH DOUBLE-HELIX W-FRP REINFORCEMENT

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## ABSTRACT

A solution to reinforcement corrosion is to combine fibre-reinforced polymer (FRP) rebars for near-surface regions with steel rebars, provided with additional cover, to ensure ductility. However, this hybrid strategy can be ineffective when conventional metallic shear reinforcement is present, as stirrups are typically the first location where corrosion initiates in reinforced concrete members. The most immediate solution is the fabrication and use of conventional FRP stirrups; however, practical challenges associated with their manufacturing and installation continue to limit their widespread adoption. Previous research on wound fibre-reinforced polymer (W-FRP) reinforce-ment demonstrated the potential of this approach to fabricate pre-formed, non-corrosive web re-inforcement as a substitute for conventional stirrup shapes. This study investigates the shear be-haviour of prismatic concrete beams reinforced with steel and/or FRP longitudinal bars and incor-porating a specific configuration of double-helix W-FRP reinforcing cages selected for fabrication efficiency. These helices form a symmetric, truss-like reinforcement arrangement with intersecting fibres at the beam corners. Unlike steel, FRP reinforcement does not yield and exhibits markedly different tensile and compressive behaviour, which complicates the estimation of shear strength. Accordingly, a Eurocode-like mechanics-based analytical model is developed to predict shear re-sistance, explicitly accounting for: (1) the inclination of diagonal cracks, (2) the inclination of the double-helix reinforcement, (3) reduced strength at bent corners, (4) linear-elastic material behav-iour, and (5) the asymmetric tensile–compressive response of composites. The results demonstrate that calculation methods available in current design codes can dangerously overestimate shear capacity when non-metallic shear reinforcement is arranged with multiple angles of inclination.

**KEYWORDS**: W-FRP; Double-helix reinforcement; Hybrid frp–steel beams; Shear capacity; Analytical model.

# INTERACTION AND MOMENT-CURVATURE DIAGRAMS OF HYBRID RC SECTIONS WITH STEEL AND FRP BARS

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**ABSTRACT**

The deterioration of reinforced concrete (RC) structures in aggressive environments, mainly due to corrosion of steel reinforcement, motivates the use of more durable solutions. Although Fiber-Reinforced Polymer (FRP) bars provide excellent corrosion resistance, their linear-elastic brittle behavior limits their applicability in seismic regions. Hybrid reinforced concrete (HRC) sections, combining internal steel and external FRP reinforcement, offer a compromise between durability and mechanical performance. This study investigates the ultimate limit state (ULS) capacity of HRC sections by considering the complementary roles of the two reinforcement systems. A numerical integration algorithm implemented in MATLAB was used to generate axial force-bending moment (N-M) interaction diagrams and moment-curvature (M–χ) relationships. The model is applied to compare a European regulatory framework based on Eurocode 2 and CNR-DT 203/R1/2026 with the American framework based on ACI 318-25 and ACI 440.11-22. A parametric study is presented by varying reinforcement ratios and axial load levels to examine the evolution of failure domains and deformation capacity. The comparison highlights systematic differences between the interaction diagrams derived from the two different regulatory approaches. The use of *M–χ* relationships enable a quantitative assessment of the steel contribution to post-yield behavior, demonstrating its stabilizing role in HRC sections and its ability to mitigate brittle failure mechanisms typical of FRP-RC members. The investigation also led to the development of a parametric database of ULS responses across varying axial load levels and steel-to-FRP reinforcement ratios, allowing consistent identification of balanced transitions and failure-mode regions within the *N-M* interaction domains and M–χ relationships.

**KEYWORDS**: Reinforced concrete; Hybrid reinforcement; FRP bars; Moment-curvature relationship; M-N in-teraction diagram.

# SS20 - Designing learning: teaching methods for composite FRP structures

# EVALUATION OF FRP END DEBONDING ENHANCEMENT THROUGH TRANSVERSAL PATCHES


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## ABSTRACT

The prevention of FRP end debonding has always received special attention, and in the literature is possible to find many attempts with different techniques in trying to increase its pullout limit. Among the different possibilities, the use of spike anchors and mechanical fastenings has produced both experimental testing and interpretation rules. However, both of those layouts have drawbacks, and some attention was paid to solve the problem with transversal patches, which fasten the longitudinal strips without the need for drilling holes in the interface.

Although many experiments have been carried out with different configurations, the problem of evaluating the effect of the transversal patches has no clear common physical interpretation. Since simple transversal patches are acted in shear, they look very similar to the problem of shear resistance of thin webs of deep beams, but with the important difference that in the problem at hand, the material is not ductile and isotropic.

In the study, a first attempt to solve the problem is presented by using the debonding capacity of the approximate inclined tension struts, which is a function of the homogenised elastic modulus of the patch along all the possible directions emerging from the symmetry line of the longitudinal strip.

Starting from the physical model, an evaluation strategy is proposed, and the related formulas are derived. The comparison with the experiments shows a good correlation of the proposed theory with the results of the pullout tests.



**KEYWORDS**: FRP patch; End debonding enhancement; Shear capacity; Inclined tension strut model; Orthotropic material.

# FRP MATERIALS AND COURSES AT NORTH CAROLINA STATE UNIVERSITY

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**ABSTRACT**
With the appointment of Dr Seracino at NC State University a new graduate course was developed, CE 529: FRP Strengthening and Repair of Concrete Structures. The course is based on fundamental principles of behavior taken largely from the book *Design of FRP and Steel Plated RC Structures: Retrofitting Beams and Slabs for Strength, Stiffness and Ductility*. At the end of major topics, reference is provided to relevant sections in the ACI PRC-440.2 design guide. Approximately mid-way through the semester a practical design project is introduced based on an actual FRP strengthening project. The project aims to simulate realistic conditions with the opportunity for students to ask questions through a Request-For-Information. Guest lecturers are invited to present details of interesting field applications. Due to the practical nature of the course material, it is offered through the College of Engineering On-Line program. With approval of the instructor, undergraduate students may enroll in the course serving as a design elective in their undergraduate curriculum. In 2016 a Course Redesign Grant was awarded by NC State University to modernize and update CE 332: Civil Engineering Materials. As part of this redesign a new section was added on composite materials, including tension testing of GFRP reinforcing bars. CE 332 supports reference to GFRP reinforcement in other courses such as CE327: Reinforced Concrete Design. Future course developments are planned for CE726: Advanced Theory of Concrete Structures to integrate research topics on internal FRP reinforcement in new concrete structures.

**KEYWORDS**: Engineering education; FRP composite materials; Strengthening existing concrete structures; New FRP reinforced concrete structures.

# THE EUROPEAN MASTER COURSE IN ADVANCED STRUCTURAL ANALYSIS AND DESIGN USING COMPOSITE MATERIALS – FRP++

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**ABSTRACT**

The FRP++ European Master Course in Advanced Structural Analysis and Design with Composite Materials is a joint program established by the Universities of Minho, Girona, Naples Federico II and Toulouse, and INSA Toulouse. It delivers an integrated, high-level educational pathway addressing the key challenges of the composite industry. The curriculum emphasizes five core areas: (i) materials and manufacturing processes, (ii) mechanics and modelling, (iii) structural analysis and design, (iv) inspection, diagnosis, repair, and strengthening, and (v) sustainability and life-cycle assessment.

Bringing together the expertise of leading European Institutions, FRP++ fosters a multidisciplinary approach to structural composites, engaging specialists in engineering, materials science, and related fields. The program runs over one academic year (60 ECTS), culminating in a double master's degree. Its unique mobility structure requires students to complete coursework at one partner university and the dissertation at another, ensuring exposure to diverse academic and research environments. English is the sole language of instruction and assessment.

Through cutting-edge teaching in a research-driven context, students acquire advanced knowledge of composites while maintaining close ties with industry. The program emphasizes problem-solving and professional practice, preparing graduates to meet the demands of sectors such as construction, aerospace, automotive, aeronautics, and wind energy - fields where composites play a key role. By combining the latest research with practical applications, FRP++ offers a truly international education experience, equipping students with the skills and perspectives required to thrive in a competitive global market.

This paper highlights the program's objectives, structure, and operational framework.

**KEYWORDS**: European master course; Composite materials; Engineering education; Structural analysis; Design.

# NexGenFRP – COLLABORATIVE TEACHING INNOVATION FOR FIBRE REINFORCED POLYMERS IN STRUCTURAL ENGINEERING

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**ABSTRACT**

The NexGenFRP initiative addresses the urgent need to modernise structural engineering education in Europe following the integration of Fibre Reinforced Polymers (FRPs) into new European standards. While FRPs offer clear advantages— e.g. corrosion resistance and reduced environmental impact—their uptake in practice remains limited, largely due to gaps in higher education and professional training. NexGenFRP responds by creating a transnational, open-access framework of teaching resources that harmonises FRP education across Europe. NexGenFRP brings together six universities and professional associations to co-develop modular teaching materials, design examples, and case studies covering FRP reinforcement of new structures, strengthening of concrete, steel, timber, and masonry, and advanced applications such as 3D printing. Outputs will include six multilingual teaching modules, a MOOC and gamified tool, and a practitioner education toolkit featuring simplified guidelines, worked examples, and digital calculators. These resources will be piloted through academic courses, Blended Intensive Programmes (BIPs), and Continuing Professional Development (CPD) workshops, ensuring validation across students, lecturers, and practitioners. By embedding sustainability principles, life-cycle assessment, and digital learning tools, NexGenFRP proposes to strengthen the green and digital competences of future engineers. NexGenFRP aims to equip the next generation of engineers with future-proof skills, accelerating the safe, consistent, and sustainable adoption of FRPs across Europe.

**KEYWORDS**: Fibre reinforced polymer (FRP); Structural engineering education; Open educational resources (OERs); Blended learning.

# STUDENT-CENTERED RESEARCH ON UHPFRC FOR SUSTAINABLE INFRASTRUCTURE REHABILITATION

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**ABSTRACT**

The Coast-UHPFRC project integrates research on Ultra-High-Performance Fibre-Reinforced Concrete (UHPFRC) with student-centered learning, addressing both technical and educational challenges in the rehabilitation of aging coastal infrastructure. Coastal concrete structures are increasingly vulnerable to aggressive environmental conditions such as carbonation, chloride ingress, and sulphate attack, which cause spalling of concrete, corrosion of reinforcement, and ultimately progressive structural degradation. The project investigates the use of thin UHPFRC layers on critical concrete members to enhance durability, provide structural strengthening, and minimize life-cycle environmental impacts, including the use of non-corrosive, non-metallic fibers and fiber synergy to further improve performance in aggressive coastal environments. At the same time, Coast-UHPFRC demonstrates a model for teaching advanced composite materials in structural engineering through Collaborative Online International Learning. Students from EU-CONEXUS partner universities participate in case studies, numerical simulations, and interdisciplinary problem-solving exercises. This transnational, project-based approach exposes learners to state-of-the-art materials, digital design tools, and practical rehabilitation strategies, fostering technical competence, critical thinking, and cross-cultural collaboration. The initiative also addresses a key gap in composite material education: connecting innovative material science with practical design strategies under realistic environmental and structural conditions. By combining experimental research, advanced numerical modelling, and simplified design methodologies, the project generates knowledge that informs both academic curricula and professional practice. Coast-UHPFRC project demonstrates how transnational, research-driven teaching can enhance learning outcomes in composite material courses and prepare students to implement sustainable and resilient coastal infrastructure rehabilitation solutions.

**KEYWORDS**: Coastal infrastructure; Composite materials; UHPFRC rehabilitation; Transnational education; Collaborative online international learning.

**WE ACKNOWLEDGE THE COLLABORATION OF**

Ajuntament de Girona

eurecat
Centre Tecnològic de Catalunya

Universitat de Girona
Fundació UdG:
Innovació i Formació

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