# Structural Strengthening with FRP Systems

## A review of research and applications in Portugal

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The technical and economic advantages of fiber-reinforced polymer (FRP) structural strengthening systems have attracted the attention of the Portuguese scientific community since the mid-1990s. Research has been mainly conducted at universities in collaboration with fabricators and suppliers of FRP. This strategy has intensified over the last 20 years, as research began to focus mainly on the assessment of externally bonded reinforcement (EBR) for the flexural strengthening of reinforced concrete (RC) beams, followed by the assessment of EBR for shear strengthening.[1,2]

At the beginning of this century, research was initiated on the use of the near-surface-mounted (NSM) technique for the flexural and shear strengthening of RC beams. Work also began on the development of the constitutive laws for the bond between FRP systems (mainly laminates of rectangular cross section) and surrounding concrete.[3,4] Research on the use of FRP for the strengthening of columns was initiated in the middle of the first decade of this century,[5,6] and the behavior of strengthened systems under high temperatures has been significantly investigated since the beginning of the last decade.[7-11] The research has been predominantly experimental, but it has been comprehensively complemented with analytical and numerical investigations. While the focus has been on the strengthening of RC structures, notable work has also been conducted on the strengthening of masonry and timber structures, with an emphasis on structural and durability performance.[12-16]

Several Portuguese researchers are active members of international committees on the use of FRP for structural strengthening, including committees from ACI, the International Federation for Structural Concrete (*fib*), and the International Union of Laboratories and Experts in Construction Materials, Systems and Structures (RILEM). Portugal has also hosted international conferences, including the International Conference Composites in Construction (CCC2001) in Porto, October 10-12, 2001, and the 11th International Symposium on Fiber Reinforced Polymers for Reinforced Concrete Structures (FRPRCS-11) in Guimarães, June 26-28, 2013. Such conferences, as well as other research activities, have contributed to the use of FRP in important strengthening projects in Portugal.

This article highlights FRP structural strengthening research projects and applications that have been carried out in Portugal over the last 30 years. Although several interesting research projects and applications are not mentioned due to the lack of space, we believe the list provides a representative description of the work.

## Research Projects on Strengthening

### FRP systems for RC beams and slabs

Early research focused on the experimental behavior of RC beams and slabs strengthened in flexure with carbon fiber-reinforced polymer (CFRP) materials by using the EBR technique.[1] Debonding of the CFRP material at the RC elements extremities was the dominant failure mode. The research was accompanied by design recommendations.

The efficacy of the NSM and EBR techniques for shear strengthening of concrete beams was investigated via an experimental program that included beam specimens strengthened with CFRP installed as NSM laminates, EBR laminates and wet lay-up sheets, strips of wet lay-up EBR sheets in U configurations, and NSM laminates embedded in vertical or inclined (45 degrees) pre-cut slits on the beams' lateral faces.[3] The NSM technique was the most effective system, especially in shear strengthening. Relative to EBR systems, NSM techniques were shown to provide faster and easier application,[17] have higher load and deformation capacity, and have less brittle failure. Further research has demonstrated that NSM reinforcements are less prone to premature bond failure and have certain confinement and

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protection because they are introduced into grooves made in the concrete cover.[17]

Research was also performed to evaluate the effectiveness of the NSM technique for the flexural strengthening of statically indeterminate RC members, including the effect of strengthening arrangements on moment redistribution.[6,18-20] It was demonstrated that it is possible to increase the load-carrying capacity up to 50% and a moment redistribution of almost 30%, as long as proper flexural strengthening configurations are adopted. Parametric numerical studies were performed with statically indeterminate RC shallow beams for assessing the influence of the existing flexural reinforcement ratio for the positive and negative bending moments versus the flexural strengthening ratio in the hogging and sagging regions of these elements. This influence was assessed in terms of maximum load-carrying capacity, ductility, and moment redistribution when the NSM technique is applied.[20]

## FRP systems for RC columns

External jackets of FRP are typically used to increase the deformation and load-carrying capacity of RC columns. The effectiveness of FRP jacketing depends on how the lateral pressure is transmitted to the column, which depends not only on the stiffness of the FRP and concrete strength class but also, and mainly, on the aspect ratio of the cross section (larger over smaller length) of the column. This efficiency increases with the stiffness of the FRP and the concrete transversal deformability of the column. It also increases with the decrease of the aspect ratio of the column cross section.[5,6] Experimental work on circular and rectangular columns strengthened with CFRP and AFRP (aramid FRP) jackets showed that both FRP materials can significantly increase the axial load capacity (an average axial capacity increase of up to 153% was registered).[5] It was also observed that square cross sections and sharp edges could result in inefficient use of FRP jacketing. High levels of confinement in RC columns can be achieved with discrete confinement of FRP systems, depending on the number of strips, their spacing, and the stiffness of each strip.[21] Placing the FRP strips between the existing steel hoops has been demonstrated to be very effective from both technical (load and deformation capacity) and economic (reduced use of materials and faster application) viewpoints.[21]

The discrete confinement made by CFRP strips of wet layup sheets was combined with CFRP laminates applied according to the NSM technique to increase the energy absorption capacity and the flexural strength of RC columns with a square cross section, and an increase of about 109% and 39% on the energy dissipation and load-carrying capacity was obtained, respectively.[22,23]

## New FRP systems

The embedded through-section (ETS) technique consists of bonding reinforcement materials in holes drilled in the core of a concrete element's cross section. ETS systems have been used successfully for the shear strengthening of RC beams and slabs.[6,24-26] Tests of RC beams with T cross sections showed that CFRP and steel bars installed using the ETS technique are well bonded to the concrete substrate and are confined by the surrounding concrete.[25] These result in high tensile strains in the ETS reinforcement, allowing significant increases in the shear capacity relative to the reinforcement applied according to the NSM and EBR techniques.

The ETS and NSM techniques have been combined for an application of a new type of CFRP reinforcement for the simultaneous flexural and punching/shear strengthening of RC slabs and beams.[27] This system comprises a CFRP laminate with bent ends. The ends are applied according to the ETS technique, while the central part of the laminate is installed according to the NSM technique. A simpler configuration of this CFRP reinforcement—with only one bend extremity (stick-shape) and faster application—is being developed in a joint research program between industry and academia, with successful application on the flexural strengthening of cantilever-type RC elements.[28]

To increase the safety of this strengthening technique in a fire scenario, a cement-based adhesive (CBA) is also being developed in the scope of this project, and its effectiveness is being investigated by performing pullout tests at ambient and high temperatures with NSM CFRP laminates with a pretreated surface for improving their bond to the CBA.[29] Despite that the average bond strength at ambient temperature with the CBA is not yet as high as obtained with epoxy adhesives with untreated CFRP laminates,[30] test results are already encouraging at high temperatures.[31]

FRPs that combine two or more types of fibers within the same polymeric matrix have a potential for hybridization. Experimental work developed to study hybrid FRP materials, produced by the hand lay-up method using different combinations of the unidirectional fabrics, shows that the combination of high-modulus carbon fibers with E-glass, basalt, or standard carbon fibers can assure a pseudo-ductile tensile behavior.[32,33] The abrupt and fragile failure observed in typical single fiber type FRPs is transformed into a controlled and slower failure in the hybrid composites. Also, hybrid materials have been successfully used for the confinement of concrete columns with circular cross sections to maximize the lateral strain efficiency of FRP jacketing.[33]

## Prestressed FRP systems

Prestressed FRP reinforcement has been used to increase the load-carrying capacity at serviceability limit state (SLS) conditions and to decrease the width of existing cracks, deflection, and stress level of the steel reinforcements in RC structures.[34-40] It has been shown experimentally that when RC members are strengthened in flexure with prestressed CFRP laminates using the NSM technique, there is a significant reduction in concrete cracking and an increase in steel yielding loads. Despite prestressing, NSM CFRP laminates do not necessarily lead to significant changes in the load-carrying capacity of the strengthened element when compared with a passive NSM CFRP solution. Because tensile rupture of the CFRP is the governing failure mode in all of these systems, a notable increase of the load-carrying capacity at crack initiation, SLS deflection, and at yield initiation of the steel reinforcement with the prestress level has been demonstrated in the experimental tests.[36,38,39] The efficiency of NSM prestressing[39,41,42] and NSM hybrid (passive and prestressed reinforcements in the same application) methods for flexural strengthening of RC beams have also been investigated throughout experimental, numerical, and analytical work.[40,43] In the NSM hybrid technique, the CFRP laminates also failed by tensile rupture; however, the RC elements strengthened according to this technique showed higher energy absorption capacity and deformability performance. The research work also included a comparison of potential use of fully bonded, partially bonded, and hybrid partially bonded systems for the flexural strengthening of RC structures.[40,43]

Prestressing RC elements with EBR CFRP laminates can lead to a significant improvement, not only in sustaining cracking and yielding loads but also the maximum load when compared with passive EBR strengthening. While premature debonding is generally the governing failure mode in the passive approach, in the prestress method, the FRP's tensile capacity can be attained with the use of efficient anchorage systems.[34,44] The efficiency of two commercially available anchorage systems was investigated—the mechanical anchorage (MA) system that is formed by metallic anchorage plates at the laminate's extremities and the gradient anchorage (GA) system that uses the adhesive's ability to cure fast at high temperatures to gradually transfer the prestressing stress to the concrete substrate over several consecutive areas at the strip end. A total of 12 RC slabs were tested to failure, leading to the conclusions that: prestress can significantly improve the ultimate load; the surface preparation plays an important role in the systems' performance (sandblasting led to higher maximum load and deflection); and premature debonding failure can be delayed or even avoided due to the anchorage system. The long-term durability of both MA and GA systems was also investigated by exposing 16 strengthened RC slabs to a sustained loading and to four distinct environmental conditions for approximately 8 months.[44] After the exposure period, the slabs were tested to failure by using a four-point bending test configuration, where it was observed that the environmental conditions and the sustained loading, separately or combined, led to small losses of load-carrying capacity and ductility.[44]

The performance of the other two EBR systems for prestressing with CFRP laminates was assessed on T cross section RC beams.[45] The experimental program included a commercially available MA system, which had to be applied on the sides of the beam due to the relatively small width of the beam's soffit in comparison to the width of the conventional anchorage devices.[45] Another new prestressing system was used, which was designed for positioning the laminate at the beam's bottom surface of relatively small width.[45] The strengthened beams showed good ductility at their flexural failure, with maximum CFRP strains of about 70% of the CFRP's ultimate strain, due to the adequate anchorage of the laminate ends provided by this patented system.[46]

The evaluation of prestress losses is of utmost importance for the application of these techniques in real structures. Low levels of strain losses upon the prestress application can be expected for the NSM (about 3%[38]) and EBR (about 2.5%[44]). An investigation of RC beams flexurally strengthened with NSM CFRP showed prestress losses mainly in the bond transfer length, which is relatively small, while in the remaining zone, negligible losses were observed over a 40-day monitoring period.[47] The investigation included 10 prestressed beams and the highest CFRP strain losses were relatively small and were observed in the first 6 to 12 days after prestress release, suggesting the prestress effectiveness of NSM FRP is not compromised in the long term.[47]

The success of the prestress application with EBR or NSM systems is highly dependent on the performance of the bonding agent. In fact, cold-curing epoxy adhesives showed significant creep deformation,[48-50] which can be a relevant property for the long-term behavior of the FRP system. Tensile creep tests of epoxy specimens were performed with different load levels (20, 40, and 60% of the adhesive's tensile strength) for a period of 1000 hours.[47] Tests results showed a linear viscoelastic/viscoplastic behavior up to 60% of the adhesive's tensile strength, with primary and secondary creep stages that could be parameterized using the modified Burgers model equation. It is noteworthy that the viscoelastic properties of epoxy adhesives change with their age, with the tendency of stabilizing at the age of 7 days.[50] In fact, epoxy specimens exposed to a creep load of 30% of their ultimate tensile strength at 1, 2, 3, and 7 days of age had creep coefficients of 4.1, 2.1, 1.9, and 1.3, respectively, within a period of 49 days.[48] Alternatively, epoxy adhesives can be cured fast at high temperatures[49] to avoid higher creep deformations at early ages.[48] A significant improvement on the short-term and creep tensile behavior of epoxy adhesives can be achieved if degassing is implemented after the mixing process upon its application.[49] Finally, it should be noted that regardless of the manufacturing process (conventional, accelerated with elevated temperature, or with the degassing process), the hygrothermal conditions have a huge influence on the creep behavior of epoxy adhesives, with high relative humidity yielding higher creep loads or even failure.[49]

Most of the research work on the prestressed FRP structures dealt with simply supported conditions, and few attempts have been made to investigate the behavior of continuous FRP prestressed beams. A comparative study of continuous beams prestressed with bonded FRP and steel tendons was performed with particular emphasis placed on the moment redistribution.[51] This numerical investigation showed that by increasing the reinforcement index of prestressing tendons, failure mode of FRP prestressed concrete beams would change from tendon rupture to concrete crushing, with the crushing failure always taking place in steel prestressed concrete beams. Regarding the moment redistribution, AFRP prestressed concrete beams demonstrated behavior comparable to steel prestressed concrete beams, whereas the CFRP tendons had lower moment redistribution than steel tendons.

### Bond behavior of FRP systems

Knowledge of the bond between the FRP material and the concrete substrate is of utmost importance and has been studied over the last few decades. A research program was developed to further study the bond between NSM CFRP laminate strips and concrete.[52] Based on the results, it was concluded that the bond performance is highly influenced by the bond length, whereas the concrete strength has negligible effect if it is above a certain minimum strength limit. The experimental results were also used to validate a numerical method developed to solve the second-order differential equation that governs the slip phenomenon.[4] The developed analytical method was based on the approach used for bonding of steel bars to concrete, and is a practical tool for the assessment of the anchorage length of the FRP at service and ultimate limit state conditions. This research also included the development of numerical tools for a simulation of the material nonlinear behavior of NSM systems, and their implementation in FEMIX software developed by Portuguese researchers based on the finite element method.[53]

Despite the extensive work on the bond behavior of FRP strengthening systems, reliable conclusions for practical application are difficult to find due to the different test methods adopted. With the aim of finding the most suited bond test setups for FRP systems, 11 laboratories and seven manufacturers and suppliers cooperated in an international research study to investigate the bond behavior of NSM strips and bars, the influence of different test setups, and the influence of concrete strength.[54] This work was developed within the framework of the European-funded Marie Curie Research Training Network, EN-CORE, supported by Task Group 9.3 (which is now 5.1) of *fib*. With this research, it was possible to verify that a single shear bond test setup is more reliable due to its higher feasibility in comparison to the double shear test setup; the surface treatment and axial stiffness of the FRP highly affect the bond behavior; and the bond failure mode and strength are almost unaffected by the adopted concrete strength classes.

Considerable research has been conducted to provide an in-depth assessment of the EBR bond behavior. An experimental study on the bond between CFRP laminates externally bonded to three different substrates (timber, concrete, and steel) indicated that FRP systems applied on timber substrates have the longest effective bond length and can sustain the highest tensile stress.[55] It was also observed that the local bond-slip constitutive law simulating the bond to the concrete substrate could be approximated with exponential curves, whereas for the timber and steel substrates, trilinear and bilinear laws were determined, respectively. By performing double shear tests on concrete elements strengthened with externally bonded GFRP (wet lay up method), the cohesion and friction angle were determined to define the Mohr-Coulomb failure criterion for modeling the bond between these materials.[56] Three classes of concrete were considered for the double shear test program as well as distinct levels of lateral confinement (compression stresses on the interface of 0.0, 0.5, and 1.0 MPa [0, 73, and 145 psi]). The experimental work showed a higher bond strength for specimens with a higher concrete strength class and with greater lateral confinement. In fact, the authors reported that without lateral confinement, the cohesion may vary with the concrete strength up to 100%, that is, from 1.72 MPa (249 psi) in the C12/15 concrete (average compressive strength of 20 MPa [2900 psi]) to 3.44 MPa (499 psi) in the C45/55 concrete (average compressive strength of 53 MPa [7690 psi]).

It is noteworthy that several state-of-the-art documents have also been published recently by Portuguese researchers. In 2015, a document on the bond behavior of NSM FRP systems applied to concrete was published, which focused on the physics of the phenomenon, common failure modes, relevant guidelines, and typical bond tests.[57] This research also included a database comprising 431 bond test records, which were used to verify the accuracy of existing design guidelines and to calibrate some analytical formulas. In 2018, a document on the durability of the bond between EBR FRP and concrete—including detailed information regarding the properties of the materials (adhesives and adherents), joint characteristics (design, execution, and curing conditions), and in-service conditions (moisture, temperature, freezing and thawing, chemical environments, ultraviolet (UV) radiation, and fire)—was published.[58] This document also included a large compilation of experimental test results on the effect of in-service conditions on the behavior of adhesives, FRP materials, and on the FRP-concrete bond. In 2021, another literature review was published on the bond behavior of FRP bars to concrete, which includes studies on the short- and long-term durability properties.[59] This work also included a database with results from a total of 1002 pullout tests, collected from existing literature, to clarify the relevant parameters that influence the bond of FRP bars to concrete.

## Durability of FRP Systems

One of the best advantages of FRP materials is their high durability, especially the corrosion resistance. However, despite the FRP's high durability, FRP strengthening systems often experience serious deterioration due to the poor thermo-hygro-mechanical performance of the adhesive and substrate in some conditions.[7,8,60-63]

### Durability and long-term behavior

The durability of three types of commercially available CFRP laminates was experimentally assessed through aging for a period of up to 18 months under selected environmental conditions: (1) immersion in demineralized water and saline or alkaline solutions; (2) quasi-100% humidity; and (3) accelerated weathering chambers with UV radiation. The specimens tested in conditions listed in (1) were subjected to immersion at room temperature, and 40 and 60ºC (104 and 140ºF), for the specimens tested in the environment (2), the temperature was kept at 40ºC.[60] Results showed higher degradation after immersion in water and saline solutions, while the degradation due to UV radiation was confined to the top surface of the laminate only. For each type of immersion, higher temperatures promoted a higher degree of degradation. The durability of an epoxy adhesive was also investigated under the following aging conditions during a 2-year period: immersion in water and salt water at 20 and 40ºC (68 and 104ºF); quasi-100% humidity at 40ºC; and an outdoor aging.[61] Results showed an irreversible degradation of the thermo-hygro-mechanical properties of the epoxy.

The durability and long-term behavior of RC slabs strengthened with NSM CFRP strips were thoroughly investigated experimentally, including their constituent materials (concrete, epoxy adhesive, and CFRP strip).[63] It was verified that the mechanical behavior of concrete and CFRP strips was marginally affected by the 2-year exposure to the adopted environments. In contrast, significant changes were observed in the epoxy adhesive. The results also showed marginal influence of the environmental conditions and fatigue action on the structural performance of the strengthened RC slabs.

An ongoing research project is investigating the durability of commercially available epoxy adhesives and CFRP laminates under outdoor conditions (natural aging).[62] This research involves 10 years of exposure to four outdoor conditions: carbonation, freezing and thawing, elevated temperatures, and airborne chlorides from seawater. From the already obtained results, the CFRP laminates were marginally affected by the studied environments, whereas the epoxy adhesives showed an increase in the glass transition temperature, $T_g$, and a reduction in the tensile properties, after 2 years of exposure.

### Fire and elevated temperatures

One of the most critical aspects of FRP materials and corresponding strengthening systems is their performance under fire conditions.[7-11] Despite their potential and widespread use for the repair of existing structures, the strength and stiffness of FRP systems are severely deteriorated when exposed to elevated temperatures, above $T_g$ of the polymer resin.[9-11] The influence of the elevated temperatures on the mechanical behavior of epoxy adhesives typically used to bond FRP materials in civil engineering application was recently studied.[9] Shear and tensile tests were conducted at elevated temperatures (up to 120ºC [248ºF]) on commercial adhesives, where it was determined that these adhesives are highly affected by temperature, especially at temperatures higher than the adhesive's $T_g$.[9]

In another experimental program to assess the influence of high temperatures on the bond between EBR CFRP strips and concrete, double-lap shear tests were carried out in steady-state (constant temperature of 20, 55, 90, and 120ºC [68, 131, 194, and 248ºF], while the force was increased), and transient temperatures (constant load of 25, 50, and 75% of their ambient temperature strength, while the temperature was increased) conditions.[11] Results show that at elevated temperatures, the failure occurred in the adhesive, while at ambient temperature, the failure occurred in the concrete substrate. A significant decrease on the bond strength and stiffness, and an increase of the effective bond length were registered with the increase of the temperature, mainly above $T_g$. It was also verified that the use of mechanical anchorages can yield a more uniform axial strain distribution and improve the bond strength at elevated temperatures, despite the great reduction in the bond strength.[10,11]

Experimental research has shown considerable losses in the efficiency of a commercial anchorage system when exposed to elevated temperatures.[10] In fact, the failure mode changed from FRP rupture (at its maximum tensile capacity) to debonding (adhesive failure) with a reduction of 44 to 59% of the pullout force, depending on the temperature and level of confinement stress (lateral pressure introduced by the anchorage system).

An experimental and numerical investigation of RC beams strengthened with EBR CFRP laminates was performed using fire protection systems (FPS) composed of calcium silicate boards and layers of vermiculite/perlite cement-based mortar with thicknesses of 25 and 40 mm (1 and 1.5 in.).[7] The results showed great improvement in the fire resistance with these FPS, with debonding failure occurring after 23 minutes for the unprotected specimen, between 60 and 89 minutes for the 25 mm thick FPS, and 137 to 167 minutes for the 40 mm thick FPS. Additionally, numerical simulations using finite element models calibrated with experimental results were carried out for designing different FPS for RC members flexurally strengthened with CFRP laminates.[8] Based on these simulations, it was concluded that regardless of the FPS, the NSM-strengthening systems exhibit better performance than their EBR counterparts, with the EBR system showing a shorter period to attain the CFRP-concrete interface's $T_g$.[8]

In addition, a state-of-the-art review of research on the fire behavior of FRP-strengthened RC structural elements—addressing the mechanical behavior of FRP systems (constituent materials and bond to concrete) at elevated temperatures and reviewing experimental and numerical studies on the fire behavior of FRP-strengthened RC beams, slabs, and columns—was published.[64]

## Field Applications

In general, repairing an existing structure is more sustainable than a new construction. And in some cases, due to the historical or social interest of certain structures, structural


**Fig. 1: Strengthening of a concrete bridge with externally bonded CFRP materials: (a) sealing of cracks; (b) pre-impregnation of CFRP sheets; (c) application of CFRP sheets; (d) EBR CFRP laminates; (e) technical inspection; and (f) finished strengthening (from Reference 65)**

rehabilitation is the only option. Consequently, nowadays, there is a growing need for repair and strengthening solutions that are more efficient and sustainable. Due to the already described advantages of the FRP systems over traditional materials such as steel and concrete for the structural rehabilitation and strengthening, the use of FRP repair materials has been increasing, with growing numbers of applications.

This section presents a brief description of five applications of FRP systems in Portugal: strengthening of RC bridge girders with insufficient steel reinforcement; column jacketing in an old fluvial station; retrofitting of RC slabs damaged in a fire accident; strengthening of the Vasco da Gama Bridge piers; and flexural strengthening of RC slabs with prestressed CFRP laminates.

## Strengthening of concrete bridge, A2 expressway, Alcácer do Sal

The A2 expressway is the second largest Portuguese highway (240 km [150 miles] long) and connects Lisbon to Algarve (the country's southernmost mainland province). The first section of the A2 was opened in 1966, and the latest one was completed in 2002. In 2015, during an inspection, deterioration was detected, including various cracks on the side faces of the transversal girders and cracking of the side and bottom faces of the beams near the bridge supports.

It was determined that an insufficient bonded length of the transversal steel reinforcement intended to support torsional effects existed, leading to slipping of the reinforcement and high tensile strains on the concrete (and cracking) near the supports. To solve this problem, first the cracks were sealed with an epoxy adhesive (Fig. 1(a)), and then, to reinforce these sections, high modulus CFRP sheets were placed (Fig. 1(b) and (c)) to resist stresses due to torsional effects. To optimize the cost, without compromising the durability or safety, high-density CFRP sheets (400 g/m$^2$ [1.3 oz/ft$^2$] area weight) were selected and applied using a wet lay-up method, aided by a pre-impregnation machine (Fig. 1(b)), which resulted in a quick and efficient application of the FRP system. Regarding the transversal girders, it was concluded that the cracking was the result of a specific traffic load (vehicles with exceptional overloads), and EBR CFRP laminates were applied as a repair method (Fig. 1(d)).

## CFRP jacketing of concrete columns, Estação Fluvial Sul e Sueste, Lisbon

The Estação Fluvial Sul e Sueste is a fluvial station built between 1929 and 1931 and opened on May 28, 1932 (Fig. 2(b)). This building, classified as a structure of public interest, was closed in 2011 due to structural problems. For the revitalization program of Lisbon's waterfront, in 2019, the building was selected for a repair. After structural analysis, different solutions were proposed to address various issues with the structure, including strengthening of beams by increasing the cross section with concrete jacketing, and strengthening the central columns with CFRP jacketing. It was verified that the rupture of the columns was expected to occur due to inefficient column confinement. Thus, additional confinement was provided by applying unidirectional CFRP strips of the sheet with an epoxy adhesive (Fig. 2(a)). The adopted FRP system was easy to install and did not change the original architectural appearance of the repaired structural elements (Fig. 2(c)).

## Flexural strengthening of RC slabs, São Lázaro Carpentry, Lisbon

The São Lázaro Carpentry operated as an industrial carpentry until the late 1990s when a fire accident led to its closing. The building has a façade in the Art Déco style, with large windows to São Lázaro Street, and is a structure of public interest. Considering that the building suffered fire damage, there was a need to restore its structural capacity and adapt it to the new loading conditions and architecture alterations. The repair solution was to reinforce the RC slabs with CFRP laminates in both directions and to jacket columns with CFRP sheets. In total, 2500 m (8200 ft) of CFRP laminates with a cross section of 50 x 1.4 mm (2 x 0.06 in.) was applied using an epoxy adhesive (trademarked as S&P Resin 220 HP) as the bonding agent for the flexural strengthening of the RC slab, while the columns were strengthened with

350 m$^2$ (3767 ft$^2$) of CFRP sheet (300 g/m$^2$ [0.66 oz/ft$^2$]). The work was executed with quality standards, and the strengthening solution was purposely left exposed, becoming a permanent and integral part of the exhibition (Fig. 3). The work was fully completed in 2016.

## Strengthening of bridge piers, Vasco da Gama Bridge, Lisbon

The South Viaduct of the Vasco da Gama Bridge constructed in 1998 is 3825 m (12,550 ft) long and consists of a double deck with 45 m (148 ft) spans supported by 85 groups of four piers on cast piles located partly in the river and partly on land. The land-supported section of the viaduct passes through the salt pans of Samouco. Localized concrete delamination, cracking, or irregularities in the concrete cover were detected in the bridge piers and in the pile/pile cap transition zones, which led to the repair and strengthening. Work is underway on 42 piers (32 with 2 m [6.6 ft] diameter and 10 with 1.8 m [5.9 ft] diameter) with the application of two layers of carbon sheets (S&P trademarked as C-Sheet 240, 400 g/m$^2$), 300 mm (12 in.) wide, at 200 mm (8 in.) intervals, using the wet layup method and automatic S&P impregnation equipment (Fig. 4).

## Flexural strengthening of RC slabs in buildings

Due to excessive deformability, lack of flexural capacity, and cracks already exceeding the recommended width, RC slabs of a building in the Portuguese municipality of Alcochete were flexurally strengthened with prestressed CFRP laminates. The level of damage, the geometry of the structural elements, and the properties of the concrete and steel reinforcements were assessed by inspection and diagnosis of the building. For the design of the strengthening solution, a material nonlinear analysis was performed using FEMIX software capable of predicting the instantaneous and long-term deflection considering the crack propagation,[53] complemented by DOCROS software[69] for the evaluation

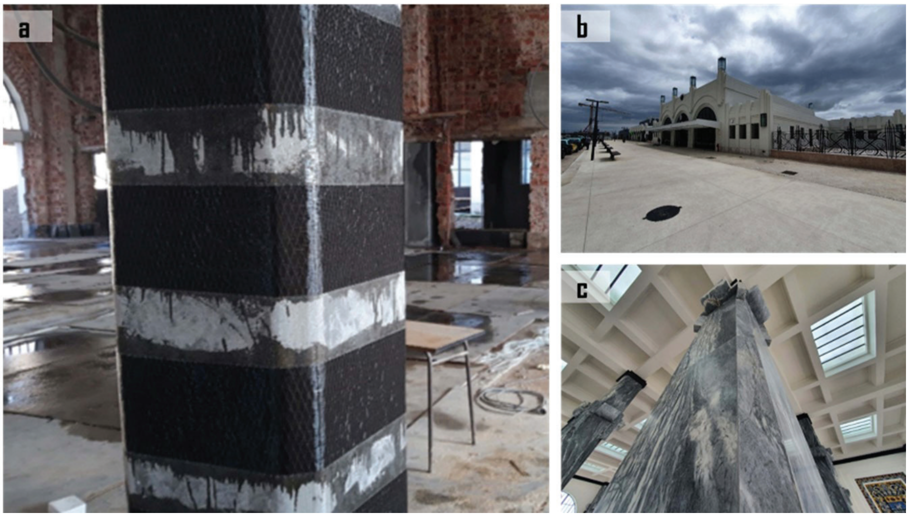

**Fig. 2: CFRP jacketing of columns on Estação Fluvial Sul e Sueste: (a) jacketing on RC columns; (b) the fluvial station; and (c) finished strengthening of columns (from Reference 66)**

**Fig. 3: Flexural strengthening of RC slabs using EBR CFRP materials: (a) and (b) the strengthened slab; (c) EBR strengthening of slabs; and (d) FRP jacketing of FRP columns (from Reference 67)**

**Fig. 4: Strengthening of bridge piers, Vasco da Gama Bridge (from Reference 68)**

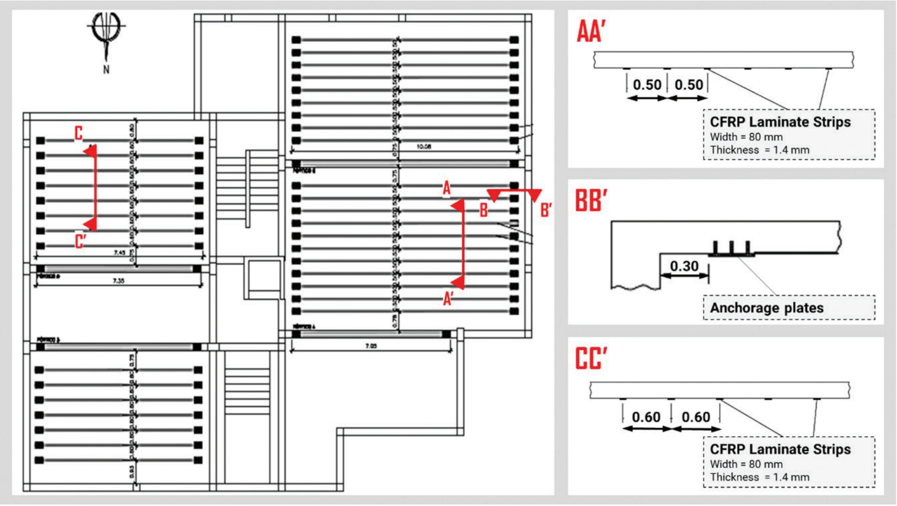


**Fig. 5: Typical configuration of the flexural strengthening with prestressed CFRP laminates**

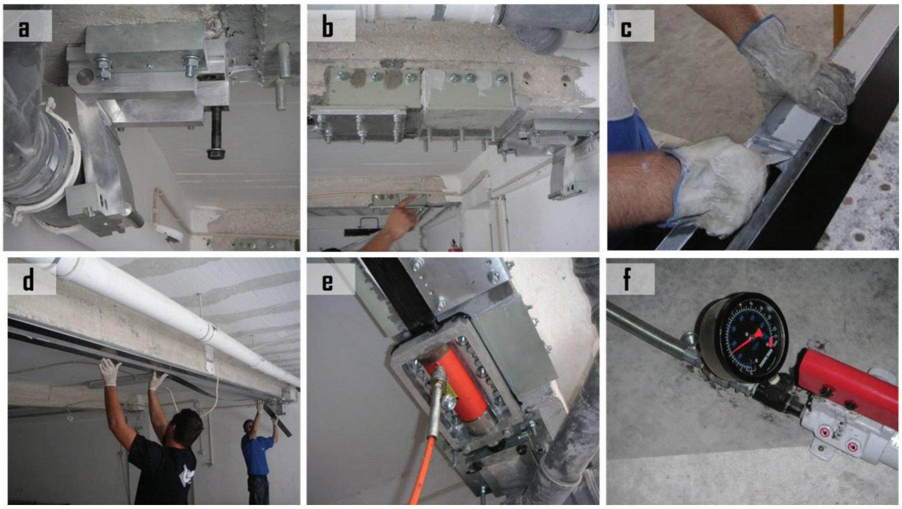


**Fig. 6: Main steps and procedures of flexural strengthening for one of the beams in the RC slab: (a) installation of the anchorage devices for prestressing the CFRP laminates; (b) installation of the metallic connectors to the beam; (c) cleaning and application of the epoxy adhesive on the CFRP laminates; (d) installation of the CFRP laminates on the anchor devices; (e) application of prestress in the CFRP laminate with a hydraulic actuator installed into the anchorage device; and (f) application of the specified design load**

of the moment-curvature of the representative sections of the slab, for the pre- and post-strengthened scenarios. The adopted flexural strengthening configuration is shown in Fig. 5, while Fig. 6 shows the main phases of the strengthening process.

## In Closing

As the work summarized in this article demonstrates, the strong cooperative efforts of FRP manufacturers, institutes of higher education, and research-oriented companies in Portugal have led to the successful development and implementation of new FRP strengthening systems. This success is demonstrated by the applications of these systems for strengthening of bridge girders, columns, and piers; flexural strengthening of RC slabs after an accidental fire; and flexural strengthening of RC slabs in a building.

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Selected for reader interest by the editors.

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