Chapter 3

# Composite Solutions for Construction Sector

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Additional information is available at the end of the chapter

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**Abstract**

FRP composite materials have been successfully used for several decades in the aerospace industry, while their use in Civil Engineering is relatively recent and generally in the form of sheets and strips employed to strengthen existing reinforced concrete structures. Since the construction of the first all-FRP-composite bridge in 1982, in Miyun, China, FRP composites have been gradually gaining acceptance as a new construction material for bridges and footbridges with some notable applications in Spain. Their use offers a number of advantages with respect to traditional materials:

(i) Since FRP composite members are lighter than those built using concrete and steel, they need less powerful equipment for their transport and installation;

(ii) Their lightweight fosters prefabrication, speeding up construction processes, thus helping in the reduction of the impact of worksites on their surrounding areas;

(iii) FRP composites can curb maintenance cost of infrastructures since they do not suffer from galvanic corrosion.

In this chapter, the successful ACCIONA FRP composite structures are going to be described, demonstrating that the use of these materials is a feasible solution in infrastructure sector.

**Keywords:** composite materials, civil works, bridges, footbridges, lighthouse, carbon fiber, glass fiber

## 1. Introduction

The development of humanity as we know it today has been closely associated with the development of infrastructures. The first civilizations that lived between the valleys of the Tigris and Euphrates performed diversions of water to be able to cultivate land. Nobody can imagine the Roman Empire without the "roman via" that linked all the points of the Empire spanning thousands of miles (Omnes Viae Roman Ducunt) [1]. Currently, the population of big cities grows around 200,000 people per day, which requires the creation of new, more efficient and sustainable infrastructure to serve this growing population in urban areas [2].

The global construction industry has grown from US$7.4 trillion in 2010 to US$8.5 trillion in 2015 and is projected to grow up to US$10.3 trillion in 2020, when measured at constant 2010 prices and exchange rates (real 2010 US$).The global construction industry has regained growth momentum, with the pace of expansion accelerating from an annual average of 2.7% a year in real terms in 2011–2013 to 3.1% in 2014. In 2015, a further rise to 3.8% in 2015 was forecasted and then an average annual increase of 3.9% over 2016–2020 [3].The construction industry represents around 6% of global GDP and still growing. In developing countries such as India, this industry generates about 8% of GDP, being also one of the highest single-consuming industries (consumption of 50% of the world steel production) causing between 25 and 40% of carbon emissions to the atmosphere [4].

The construction sector has historically adapted technologies and innovations slower than other sectors which avidly welcome them [4]. That has translated into less productivity in relation to other sectors [5].

Recently, some companies have begun to incorporate new ways of performing both design and execution of work processes The outcome of this effort is, for example, the implementation of the BIM methodology in companies like ACCIONA, which means not only a transformation of the processes and the incorporation of new softwares in the workplace but also a new definition of the roles in the company [6]. Further progress is being made with the incorporation of scanning lasers, drones and other information systems in the worksites not only in ACCIONA but also in other construction companies [7–9].

In the field of new materials, the construction sector has made a significant research effort in recent years. There is an extensive bibliography on incorporation of nanoparticles to the concrete to provide greater durability or to improve mechanical properties, and self-healing materials have been developed to use them in roads or buildings [10–12]. Currently, there are coatings in the market with different properties depending on the application in which they are to be used (multifunctional coatings) for instance with photocatalytic properties for reduction of environmental pollutants [12, 13].

There has been significant progress in the use of composite materials for the manufacture of structural elements in the construction sector. A composite material can be defined as a combination of two or more materials that results in better properties than those of the individual components used alone [14].

In the construction sector, composite materials are considered those formed among others by polymeric resins combined with fibers (fiber reinforced polymer composites (FRP)). The resin matrix mainly acts protecting and distributing loads among the fibers which in turn provide strength and stiffness to the composite material. Selecting a specific orientation for the fibers, it is possible to tailor the mechanical properties of the composite material in the different directions of the space in order to match the mechanical requirements placed in each specific direction by the acting loads. The excellent properties against corrosion in chemical environments, electromagnetic transparency, and the reduction of up to 10 times the weight of the structures in relation to those made with traditional materials such as steel or concrete allow to consider composite materials a viable solution for the infrastructure sector. What is especially appealing of these materials is the fact that they do not suffer for electrochemical corrosion which instead affects steel used in civil and industrial structures commonly in the form of profiles and bars. It is worth noting that steel corrosion is the main cause of damage and losses for infrastructure. Corrosion problems are exacerbated by high temperature, humidity and the presence of salts. For these reasons, reinforced concrete and steel structures located close to or in the sea, in water treatment or in chemical plants, and bridges located in cold regions where deicing salts are massively used are exposed to severe corrosion phenomena [15–17].

Another characteristic of composite materials that is very attractive for construction activities is their lightweight since it enormously simplifies transportation and installations of structural elements, fostering structure prefabrication. Lightweight and high prefabrication heavily contribute in accelerating the construction process, in reducing the need for high capacity cranes, and in improving safety at worksite. Accelerating the construction process offers great advantages in densely populated urban areas where it allows reducing disruption times and the consequent indirect losses [18, 19].

We should not ignore that the use of these materials also presents a challenge with its performance against fire and automation in manufacturing. In the first case, intumescent coatings and resins with improved fire resistance and reaction times that significantly reduce the associated problems have been developed. With respect to automation in the manufacture of these structures, it depends on the type of resin to be used, as well as on the design of the final structure, so it is a field under research [18, 19].

ACCIONA, a pioneer in the application of these materials within the construction sector, has designed, manufactured and installed three vehicular and two foot bridges, a lighthouse, spiral staircase, and couple of other innovative solutions using composites during the last decade. A recent innovative application developed by Acciona is the composite plate, an alternative to steel and concrete in the construction of high-speed railway tunnel infrastructure (**Figure 1**).

**Figure 1.** Left: construction plates' detail, Right: tunnel with construction plates solution.

In this chapter, we have described in detail three successful cases that demonstrate the use of the composite materials in the construction industry with emphasis on the technological challenges and the benefits provided by the composite materials.

## 2. First CFRP vehicular bridge designed, manufactured and installed in Spain



### 2.1. Introduction

This project consists of carbon fiber girder and concrete slab. Carbon fiber girders, the main element of this bridge, were manufactured off-site followed by quick transportation and easy installation at site using inexpensive easily available standard cranes, thanks to the lightweight properties of composite. Apart from lightweight, these materials also provide long life with almost negligible maintenance [20–23] (**Figure 2**).

The bridge is straight, with a 2% slope. It consists of four spans: two middle spans of 13.0 m and two end spans of 10.0 m, resulting in a total length of 46.0 m. The deck overall width is 8.0 m and has been constructed of three continuous beams of carbon fiber and a reinforced

**Figure 2.** Composite bridge in Asturias (Spain).

concrete slab. The deck is supported by 6.50, 6.62 and 6.75 m high columns. The bridge is composed of the following structural elements:

- The deck slab consists of a glass fiber preslab that supports a 20.0 cm thick reinforced concrete slab, with upper and lower rod mats, constructed of rods with a diameter of 16.0 mm, placed at 20.0 cm intervals.
- Three box girders have a trapezoidal cross section with: 1.2 m top, 0.8 m bottom, and 0.8 m web. The entire section of the bridge girder is a thin-walled carbon fiber laminated with 9 mm thickness at web, 7 mm at the top and 17 mm at the bottom. The core of the thin-walled beam is filled with polyurethane.

The reinforced concrete piers have a 2.0 m with 0.6 m cross section and are joined at the top by 8.0 m with 0.6 m rectangular capital, which supports the beams. This capital is the only support for the beams. The abutments have been constructed of traditional reinforced concrete, capable of accommodating the loads transmitted by the deck.

The girder-slab cross section, shown in **Figure 3**, consists of layers of low-modulus (140 Gpa), high-strength (~1.5% strain to failure) carbon fiber fabrics preimpregnated with epoxy resin.

The carbon fiber–reinforced polymer (CFRP) girder is manufactured by wrapping preimpregnated carbon fiber fabrics over the polyurethane mold, followed by application of vacuum for removing the air entrapped between the carbon fiber fabrics and finally application of hot air for curing the laminate. The cure cycle is adjusted in such a way that the final laminate exhibits a glass transition temperature (Tg) of more than 120°C.

To manufacture the top and bottom flange of the girder, precalculated layers of nonwoven carbon fiber fabrics were laminated along the principal girder axis (0° direction), and for the webs, nonwoven, unidirectional fibers alternately aligned at ±45° were wrapped over the polyurethane mold. The individual lamination layers laminated at 0° had a finished thickness

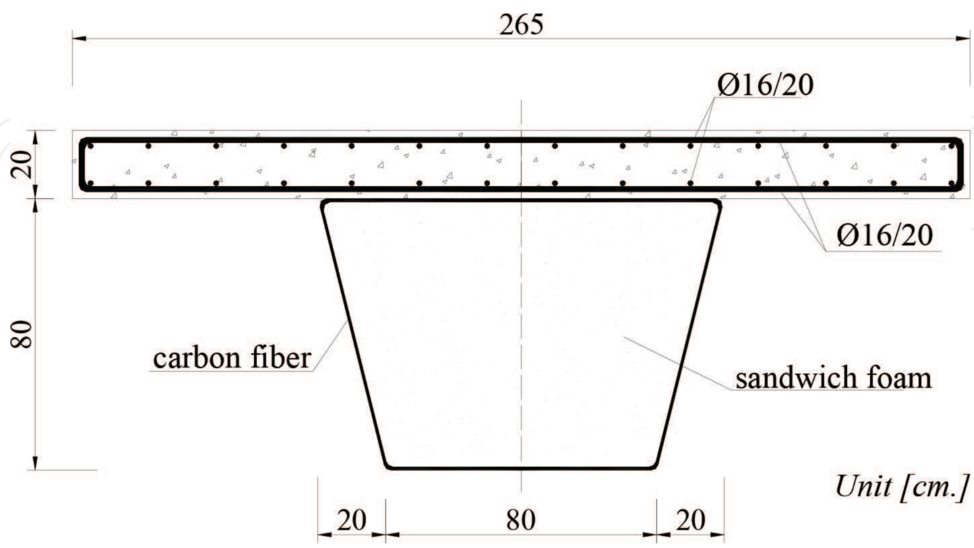


**Figure 3.** Section through the specimen at midspan.

of 0.59 mm, whereas the combined ±45° layers had 1.58 mm. For the top flange of the box beam, the layup is $[(0, \pm45, 0)]_2$, for the lower flange it is $[(0_5, \pm45, 0_2)]_2$, and $[\pm45_7]$ for the webs, and the layup order given is from the perimeter into the core. In addition to these, all four corners of the beam cross-section have 220 mm transition zones from the webs to the flanges: in the top flange, the configuration is $[(\pm45,0, \pm45, 0)]_2$ whereas at the bottom flange corners, it is $[(0_2, \pm45,0_3, \pm45, 0_2)]_2$. The bottom flange contains the highest percentage of unidirectional fibers (0°) in order to provide maximum strength in tension. The percentage of carbon fiber used in the top flange is lower as compared to the bottom flange as the concrete slab will carry the compression load.

An ambitious research, design, manufacturing, and testing process was followed in order to demonstrate the technical viability and cost-competitiveness of composites bridges. An integrated monitoring system was set up on the bridge for real-time strain and temperature data acquisition.

### 2.2. Experimental

*2.2.1. Preliminary design and structural behavior test*

*2.2.1.1. Materials*

In order to select the optimum material for the manufacturing of the bridge elements, laminates made with different materials and configuration were tested for mechanical, chemical, and physical properties. The test values obtained were later compared, and the optimum values were used in the design calculations. These tests were conducted at different government approved laboratories.

*2.2.1.2. Connectors*

For the bridge to perform well under load, it is inevitable to have a good connection between the CFRP girder and the concrete slab. Ten different types of connectors were tested using the pullout test, and these tests were performed using different connector design and the bonding system. Based on the test results, an Alkali resistance glass fiber pultruded profile was chosen as the connector. These pultruded connectors are easy to manufacture off-site and quick to install on site. This concept of connecting the concrete slab with CFRP girder is a technological innovation in itself being the first structural application.

*2.2.1.3. Joining of bridge girders*

The bridge was designed using long continuous girder to give it the total length of 46 m. For the ease of transportation from the manufacturing facility to the installation site, girders were manufactured in 10 and 13 m lengths, which means, in order to get a single long continuous girder of 46 m, two girders of 10 and 13 m need to be joined on site. A joining protocol was made, which consists of following steps: (i) preliminary treatment of the surface and (ii) placement of dry glass fiber fabrics over the CFRP girder, where they were impregnated with the resin. The joints were given precalculated taper in order to ensure gradual distribution of the

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stress along the joint. Of a preliminary treatment of the surface, the use of an impregnation system with two different types of resin and the application of dry laminates were impregnated as they were placed on the beam. To complete the procedure, the joints were made with tapered laminates to ensure a gradual stress distribution in the joint. To better understand the joint behavior under the designed load, a series of tests were conducted. The test consisted in applying a pulling force to a specimen formed by the joining of two plates. After completing the pulling tests on joined laminates and knowing their behavior, a further flexotension test was conducted, on a reduced scale specimen (with a scale factor f = 3). In this test, another layer of laminate was added to the joint and was accepted as a final solution during the construction of the bridge.

#### 2.2.1.4. Buckling tests

Two different buckling tests were carried out on the laminates, to ascertain their behavior, verify the current theories about the stability of orthotropic plates and quantify the effect of the polyurethane core.

In order to accommodate the two different types of tests, a device was developed to simulate the desired contour and the required load conditions. The first test was a uniaxial compression test, in which the load is applied to the top and bottom edges, while the unloaded edges of the specimen are constrained by knife-edge supports, constraining the out-of-plane displacement and rotation about the horizontal axis.

The second test consisted in applying a force along the plate's edge, thus simulating an instability caused by shear stress. The load is applied to a profile secured to the plate right edge. This load is applied until the plate becomes unstable. In this case, the plate is bolted to the edge profiles

### 2.2.2. Reduced scale test

Deflection, strength, and buckling are equally important aspects in the design of composite girders. As mentioned in the preliminary design, the deflection of a composite girder has two components, bending and shear, $\delta = \delta b + \delta S$. The bending deflection $\delta b$ is controlled by the bending stiffness *(EI)* and the shear deflection $\delta S$ by the shear stiffness *(GA)*. Shear deformations are neglected for metallic girders because the shear modulus of metals is high ($G \approx E/2.5$), but shear deformations are important for composites, because the shear modulus is low (about E/10 or less). The significance of the shear deflection $\delta S$ with respect to the bending deflection varies with the span; the larger the span, the lesser the influence of shear (compared with bending).

In preliminary design, an average modulus of elasticity Ex can be easily obtained. Then, the geometry can be designed to achieve the required bending stiffness. Selecting laminates with high values of 0° layers yields the highest modulus Ex, but such laminate may have low shear modulus Gxy, which may result in unacceptable values of shear deflection. Also, a laminate with high values of 0° layers will have low shear strength Fxy which may be inadequate to carry the shear loads. The shear deflection is computed after the geometry has been finalized.

If the shear deflection is excessive, the laminate or the geometry will have to be changed. The shear deflection is controlled by the shear stiffness (GA) of the section. Selecting a laminate with higher values of ± 45-degree layers yields higher values of Gxy. The webs and flanges can be made with different laminates, like in the case of box-beam sections for bridge girders, trying to maximize EX on the flanges and Gxy in the webs. During the test, two-point loads were applied to a continuous beam, which simulates one half of a girder of the bridge. The load was applied by two 500.0 KN jacks, located in the middle sections of the girder spans. The test girders were 7.7 m long and had a trapezoidal cross section, with 26.6 cm edges, a 26.6-cm bottom base, and a 40.0-cm top base. This deck was a 6.6-cm thick and a 66.6-cm wide concrete slab. The concrete compressive strength was evaluated at 25.0 MPa.

The three test girders have the same geometry, but different fabric patterns, namely:

- The first girder has been constructed of a hybrid fabric: glass fiber and carbon
- The second girder has been constructed only of a carbon fiber fabric.
- The third girder has been designed as the second one but included a joining element to assess the structural behavior of the bridge beam joints.

After reviewing the results obtained from reduced scale test, the following conclusions were drawn:

The ultimate load transmitted to the girder does not result in a design constraint, as the bearing capacity of both the hybrid and the carbon girders exceeds the load requirements laid down by the design standard.

Deflection represents most important constraint. The hybrid girder is less rigid than the one constructed of carbon fiber only.

In the plane of the loads imposed, the carbon beam offers an excellent structural response and, from both the resistance and deformation points of view, meets the requirements laid down by the applicable standards.

The connectors placed between the girders and the concrete slab behaved as expected, with the box upper fiber and the concrete slab experiencing a similar strain. The joint provided by the connectors ensures a perfect transfer of stresses between the carbon fiber beam and the reinforced concrete slab.

Both fabrication systems for the scale girders (layup and preimpregnation systems) offer big fabrication advantages, but greater fabrication accuracy and higher quality levels are obtained through the use of the preimpregnation and curing process with controlled temperature and pressure, which have proved more cost-effective.

### *2.2.3. Final test*

The purpose was to check, using real dimensions, the behavior of the assembly made up of the concrete slab and the polymer girder reinforced with carbon fiber.

The final test was carried out in a loading rig that was devised to generate both positive and negative bending moments varying along the bridge length in accordance with the loading

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protocol and design specifications in order to meet the requirements of the Spanish building codes as prescribed by the Ministerio de Fomento, which were RPX 1995 (design recommendations for composite-action highway bridges), IAP 1998 (prescriptions for loading protocols of highway bridges), and EHE 1998 (prescriptions for structural concrete).

The composite structure consists of the concrete slab and the thin-walled carbon fiber laminated girder. The reinforced concrete slab is 20.0 cm thick and 2.70 m wide. The concrete compressive strength is 25.0 MPa. The slab reinforcement is provided by bars with a diameter of 16.0 mm, placed at 20.0 cm intervals. The thin-walled laminated girder was laminated by hand layup on a polyurethane mold. This mold offers greater stability to sides and flanges and represents the so-called lost formwork. Similarly, provision has been made for a vertical diaphragm on the supports, to help transmit the shear loads to the support. In order to prevent any eventual buckling, the bottom flange has been provided with horizontal, sandwich type, stiffeners around the compression areas. In order to assess girder behavior, measurements of strain were taken along three sections of the girder using sensors and measurements of deflections by means of vertical clamps.

### 2.3. Conclusions

On the basis of the results obtained from the test, through the use of extension-meters and gauges, transducers and inclinometers, the following conclusions are drawn:

The girder meets the rigidity requirements (l/600 = 22.0 mm.), because during the test and under working loads, the displacement measured was 14.0 mm.

The joints between girders meet the design load requirements, because, due to the typology of the test, the joint section was subjected to the maximum positive moment, with an accompanying shear load greater than the maximum to be withstood by the structure. Given the fact that the strains at the joints are considerably smaller than the ones tested, an excellent behavior of the joints is guaranteed.

The strains experienced during the tests are 15% below theoretical values.

The stresses generated within the structure were 1.6 times greater than the increased design loads, offering an overall safety coefficient of 2.4.

As a consequence of the positive results achieved in this bridge, ACCIONA has built two more bridges in the recent years. All these cases demonstrate that the use of FRP girders for this type of bridges results to be competitive in comparison with the traditional steel/concrete solutions.

Of the other two bridges, the first one (twin bridges) situated in Madrid, and built in 2007, is characterized by three simple supported spans of 10, 14 and 10 m and a 20.40-m-wide box-girder deck. The deck girder is manufactured with a reverse "Ω"-shape cross section). Each of the girder is then made close connecting its top flange to a sandwich panel for the whole length of the girder. The sandwich has a polyurethane core and glass-fiber skins (**Figure 4**). The bottom flanges of the girder are made by hybrid glass-carbon fiber laminates with the considerable amount of the fibers oriented along the girder axis. The girder webs are made of sandwich panels with polyurethane core and glass fiber skins. Since the webs must essentially


**Figure 4.** M111 bridge (Madrid, Spain).

sustain external shear forces, the great amount of the fibers is placed so as to form angles equal to ±45° with the girder longitudinal axis. In order to increase the torsional rigidity of the girder beams, a number of transversal diaphragms are placed along the girder beams. These diaphragms also have a sandwich structure.

In the year 2013, Acciona Construction designed and manufactured a Fiber Reinforced Plastic road bridge which was installed in Gabon (Africa) in 2014. The bridge girders, originally designed in steel reinforced concrete, were redesigned, employing FRPs to take advantage of the lightweight of these materials and the ease of off-site prefabrication.



The bridge deck, with a span of 17.00 m and a width of 6.00 m, is formed by two simply supported FRP girders with an overlying 0.25-m-thick concrete slab reinforced longitudinally and transversal with FRP bars. The FRP girder has a U-shape cross section with a maximum width of 2600 mm and a depth of 1150 mm. The top flanges are 450 mm wide, and the bottom flange is 1200 mm wide. The top flanges and the webs have a thickness of 37 mm, while the bottom flange is 35 mm thick. A sandwich panel is adhesively connected to the top flanges of the girder to be used as a formwork during the concrete slab casting. To increase the torsional stiffness of the girder and prevent shear-bending buckling of its webs, six transverse stiffeners are placed along the length of the girder. The girder is connected to the top reinforced concrete slab through FRP shear connectors (**Figure 5**).

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**Figure 5.** Iboundji bridge (Gabon, Africa).

As general conclusions, these composite bridges offer more design freedom. Compared with a concrete girder, which requires 28 days just for curing, the composite girder was ready for shipping in 15 days. No painting is required on these FRP girders. They are easy to transport, quick and easy to install on sites where high-capability cranes are not available. They provide better corrosion resistance than concrete and steel in coastal areas and require less maintenance.



## 3. First stress-ribbon pedestrian bridge in Spain

### 3.1. Introduction

In 2011, ACCIONA construction was involved in the design and construction of a stress-ribbon pedestrian bridge [23–26]. “Stress-ribbon bridge” is the term that has been coined to describe structures formed by directly walked prestressed concrete decks that have the shape of a catenary [26]. Their resisting structures consist of slightly sagging tensioned cables normally embedded in a concrete slab, which provides them a certain amount of bending stiffness, guaranteeing the distribution of local loads and the stability of the overall shape. The cables, which are normally made by steel, for the present bridge, were manufactured using a carbon fiber reinforced polymer material. Thanks to their low-specific weight (1.6 g/cm$^3$), these cables can easily be pulled from one abutment to the other and, since they do not suffer from galvanic corrosion, they are expected to be more durable than steel cables.

The pedestrian bridge, with a total length of 216 m, has three continuous spans of 72 m each. A 0.25-m-thick reinforced-concrete slab, supported by 16 CFRP cables, forms its cross section. After the construction of the abutments and piers of the bridge, the CFRP cables were pulled from one abutment to the other, using a set of guide wires, and anchored to the abutments. The cables were then tensioned one by one, using a hydraulic jack, until reaching an axial load level of 700kN. A series of prefabricated reinforced concrete slabs were then positioned side by side on top of them to form the bridge deck and loaded with big bags full of sand. With the cables tensioned by the weights of the big bags, concrete was poured in the joints between adjacent slabs. Once the concrete had hardened in the joints, the sand bags were removed unloading the cables that, trying to change their configuration, induced compressive stress in the concrete deck. In this way, it was possible to prestress the deck without embedding the cables in it.

The CFRP cables employed in the construction of the pedestrian bridge, with a diameter of 42 mm and fish-eye terminations at both their ends, are covered by an aramid sleeve to protect them from possible damage induced by accidental collisions with sharp-edge objects during their installation.

These cables were manufactured fixing two stainless steel rings at a relative distance equal to the final length of the cable and wounding preimpregnated carbon fiber tow around these two rings, in a configuration similar to that of a belt and a pulley system. The whole bundle of preimpregnated carbon fiber filaments is wrapped with a thermo-shrinkable film, which is then heated up to consolidate the cable cross section and give it a circular shape. Eventually, the cables are placed in an oven to cure the epoxy resin. In proximity of their ends, the cables separate in two halves to go around the steel rings, which have an outer diameter of 108 mm. The angle formed between the two halves of the cables, equal to 18°, is fixed, during the manufacturing process, inserting a polyurethane wedge between the two halves and wounding preimpregnated carbon fiber tow around the cable just after the point at which the two halves separate, in order to prevent the splitting of the cable once, it has been loaded (**Figure 6**).

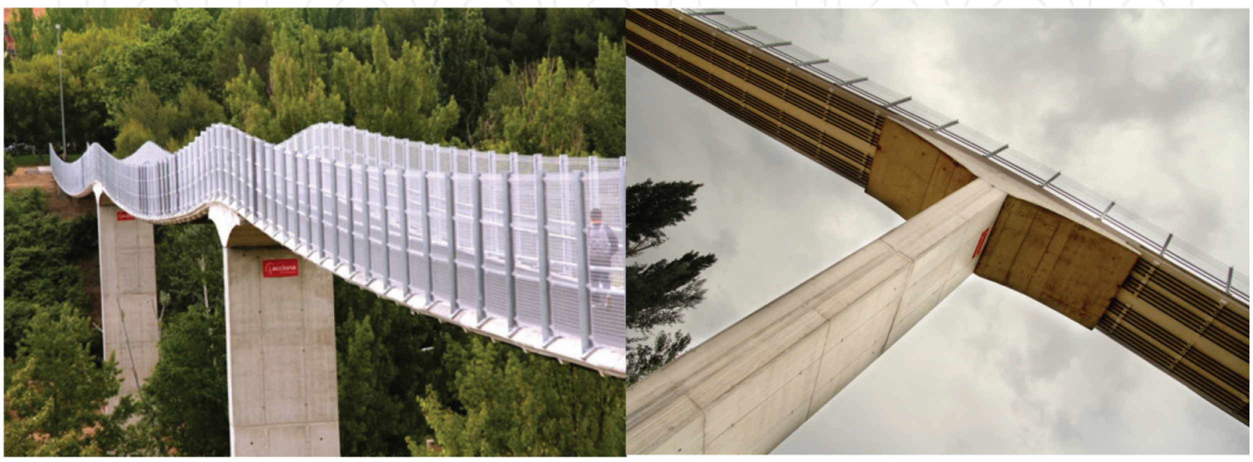

**Figure 6.** Left: Cuenca footbridge, Right: detail of the cables used.

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The possibility of using them in a pedestrian bridge was considered a good chance to gain knowledge about their behavior in view of their future application in the construction of suspended and cable-stayed bridges. This type of composite material cables is nowadays popular in sailboats rigging. The cables used in the construction of the present pedestrian bridge have diameters much greater than those of the cables currently employed in sailboats, since the magnitudes of the loads the cables need to resist are sensibly different for these two applications. Due to the novelty of the use of this type of cables in bridge construction and the considerable difference existing between their diameters and those of the cables normally produced for sailboats, it was decided to carry out a series of tests to assess their mechanical behavior.

### 3.2. Experimental

#### *3.2.1. Tensile tests on the cables*

Three cables, named SP1, SP2 and SP3, were submitted to tensile tests to assess their axial rigidity, their strength and to investigate the mechanical behavior of the laminates used to wrap their ends.

##### *3.2.1.1. Experimental setup*

The tensile tests were carried out using a horizontal servo hydraulic machine. This machine, specifically designed for testing cables, has a maximum load capacity in tension of 3000 kN and can accept specimens with a length up to 6 m. The machine can only measure and record the load applied to the specimen and the displacement of its moving head. To evaluate the longitudinal strains induced in the cables, two electric strain gages were glued on each of them, at two diametrically opposed points of their midspan section. The strain gages were applied directly on the CFRP cable surface, after the removal of the aramid sleeve and the thermal-shrinking film. Four more strain gages were applied to one end of the cable SP3, two in the longitudinal direction of the specimen and two in the circumferential direction, to evaluate the mechanical behavior of the laminate wrapping the cable end. The signals coming from the strain gages were digitalized and recorded using two strain indicators and recorders.

All the tests were performed under force control with a constant loading rate of 3080 N/s. Cables SP1 and SP2 were submitted to three load cycles between zero and the cable service load, 900 kN, and three load cycles between zero and the expected ultimate load of the cables, 1600 kN. If after these six cycles the specimen had not failed, the load was monotonically increased until reaching the cable failure. Cable SP3 was submitted to monotonically increasing load up to failure.

For all the tested cables, the values obtained for their axial rigidity were close to 170 MN, and their failures were explosive and always started from one of their ends. It can be noticed that, initially, for values of the applied load lower than 500 kN, the cable core and the surrounding laminate act as a solid section: the tensioned cable core, due to the Poisson effect, tends to contract transversally inducing circumferential compression strains in the surrounding laminate. Then, as the applied load increases, the cable core partially detaches from the laminate as shown by the fact that the value registered by one of the circumferential strain gages suddenly goes to zero. In other words, the tensile strength of the resin layer existing between the cable core and the surrounding laminate is locally overcome by the radial tensile stress acting in this region of the cable. As the load continues to increase, the surrounding laminate starts to be tensioned by cable core that tend to split.

### *3.2.2. Finite element model*

A finite element (FE) model was implemented in ANSYS® to analyze the behavior of the CFRP cables. Only one half of the cable was modeled, since the cable specimen is symmetrical. Solid 3D elements (SOLID186) were employed to model the cable: orthotropic material properties were assigned to the elements which model the CFRP cable, while isotropic material properties were assigned to the elements which model the steel ring. CFRP material properties were estimated using the Micromechanics Theory moving from the properties of the basic materials, e.g., epoxy and carbon fiber, provided by the suppliers and the results of thermogravimetric tests carried out on specimen SP0. Special shell elements TARGE170 Y CONTA174 were used for modeling the surface contact between the CFRP cable and the steel ring. The polyurethane wedge was not modeled, since it does not have any structural function. It can be observed that at the points where the two halves of the cable touch the steel rings the longitudinal strains attain the maximum value of 1.55%, which is close to the ultimate strain value given for the carbon fiber by its supplier. For the same value of the applied load, the value given by the FE model for the longitudinal strains at the cable midspan is equal to 1.02%, which is close to the values registered experimentally in correspondence to the cable failure. These results agree with the experimental observation that the cables always failed at one of their terminations.

With the aim of reducing the difference between the values of the longitudinal strains at the cable termination and those at the cable mid span, the effect of increasing the outer diameter of the steel ring, keeping constant the distance between the center of the ring and the point at which the two halves of the cable separate, was analyzed through the implementation of other 2 FE model models. In these two models, the outer diameter of the ring was set equal to 152 and 196 mm, values that correspond to an angle between the two halves of the cables of 25 and 32°, respectively. In correspondence to an applied load of 1600 kN, the maximum longitudinal strains at the cable termination obtained from the numerical simulations were 1.48% and 1.50%, respectively. It is apparent that no improvement of the cable strength is obtained following this approach.

## 3.3. Conclusions

It could be concluded that the results of tensile tests carried out on three cable samples exhibited linear elastic behavior up to failure. In all the examined cases, the cable failure was explosive and happened at one of its ends.

The results in terms of longitudinal strains obtained through a FE model of the cable showed a good agreement with the experimental values.

The change in the longitudinal strains at the cable termination due the variation of the angle between the two cable halves was numerically investigated. The results indicate that the strain values are not very sensitive with respect to the variation of this angle.

**Figure 7.** Almuñecar footbridge.

Related with this kind of infrastructures, ACCIONA has designed and built Almuñécar footbridge in 2010 in Madrid to substitute an old reinforced concrete footbridge crossing the Manzanares river. It has a span of 44 m and a width of 3.5 m. The girder, completely made of carbon fiber, presents a series of longitudinal and transversal stiffeners to be able to accomplish with the challenging architectural and structural requirements: a girder with a depth not greater than 1.20 m and with its inner surface completely covered with prefabricated reinforced concrete slabs. The girder was fabricated in at a manufacturing facility on the outskirt of Madrid, transported to the worksite during the night, and installed in less than 1 h. Before the placement of the concrete slabs on its inner surface, both the girder's ends were enclosed in their respective abutments, restraining in this way their rotations and controlling their deflection at the middle (**Figure 7**).

## 4. First composite lighthouse in the world

### 4.1. Introduction

A lighthouse, 32 meters high and entirely made of fiber reinforced polymers, was designed and manufactured by ACCIONA and was installed in only 2 h in the north extension of Valencia Port (middle east of Spain), in February 2015 [19–24]. This five-story structure, which weighs 19 tons, is formed by eight-carbon FRP circular hollow columns made by pultrusion and positioned at the vertices of an octagon. The five storeys are glass FRP and polyurethane octagonal sandwich panels made by resin infusion. An FRP spiral staircase is placed in the center of the structure, going from its base to its top. To increase the lateral stiffness of the structure, between each couple of consecutive storeys, its carbon FRP columns are connected along the structure perimeter by horizontal glass FRP pipes which form in this way four octagonal rings.

The lighthouse **Figure 8** is a five-storey structure supported by eight carbon FRP circular hollow columns whose center lines, at the lower storey, pass through the vertices of an octagon inscribed in a circumference of 4.15 m diameter and, at the upper storey, through those of an octagon inscribed in a 3.75-m diameter circumference. These 32 m long columns, manufactured by pultrusion with epoxy resin, have an outer diameter of 250 mm and a wall thickness of 20 mm. The five storeys, manufactured by resin infusion with vinylester resin, are 200-mm thick sandwich panels with 10-mm thick glass FRP skins and a polyurethane core with a density of 70 kg/m$^3$. The storeys are placed every 6 m, and each one has a different octagonal geometry depending on its position in the structure. A spiral staircase is placed in the center of the structure, going from its base to its top. The steps are manufactured by RTM and have a sandwich structure made of glass FRP skins and a polyurethane core. Each step has a 200-mm rise and is formed by a ring with 500 mm inner diameter connected to a 900-mm-length trapezoidal platform, with a variable tread width. The step rings, vertically aligned along the lighthouse central axis, form a cylindrical space which is filled with reinforced concrete, providing a stiffening core to the structure. To increase the lateral stiffness of the structure, the carbon FRP columns are connected by four octagonal rings placed between each two consecutive storeys. Each of these rings is formed by eight glass FRP pipes placed along the structure perimeter. The glass FRP pipes, manufactured by pultrusion, have an outer diameter of 190 mm and a wall thickness of 20 mm. The connections between columns and the horizontal glass FRP pipes are made by FRP rhomboidal diaphragms having a thickness of 42 mm

**Figure 8.** The FRP lighthouse (Valencia, Spain): Left: lighthouse detail, Right: general view of the lighthouse in Port of Valencia.

The base of the lighthouse is a 4-m-high reinforced concrete box with an octagonal prismatic shape. The lower ends of the lighthouse columns are embedded in the 1.10 thick box's bottom slab. The 0.35-m reinforced concrete slab which forms the box ceiling is perforated to permit the eight carbon FRP columns and the central reinforced concrete core to pass through it. Neoprene bearing collars are placed between the FRP columns and this concrete slab to restrain the horizontal displacement of the columns at this level. Before the lighthouse was commissioned, final tests were conducted to ensure it met load and wind requirements.

In the marine environment, to minimize maintenance costs, the use of FRP materials for the construction of durable and lightweight civil structures is an attractive and promising alternative to traditional materials, such as steel or steel reinforced concrete. Because of the particular mechanical behavior of FRP structures and the increased interest on this technology, many experimental and numerical research projects have been carried out in the last years, most of them focused on the static response of FRP structures but very few in the field of dynamic response. In the case of the FRP lighthouse, the flexibilities of the connections between structural elements have an important influence on the flexural-torsional vibration response of the structure, so an adequate numerical model can be calibrated based on the experimental results from free vibration testing.

### 4.2. Experimental

Because of the particular mechanical behavior of FRP, a study of dynamic response of the lighthouse has been carried out. The flexibilities of the connections between structural elements have an important influence on the flexural-torsional vibration response of the structure, so an adequate numerical model can be calibrated based on the experimental results from free vibration testing [27].

#### *4.2.1. Numerical simulation*

A three-dimensional finite element model of the whole structure is developed using SAP-2000 v16.1.1. The carbon FRP columns, the glass FRP pipes, and the central core column are modeled with frame elements, while the storeys and the rhomboidal diaphragms are modeled with shell elements. Each column is fixed at its base, while its contact with the top slab of the concrete box is modeled with a set of linear elastic springs radially connected to the column frame elements and having a stiffness equivalent to that of the neoprene bearing collar. Although carbon FRP columns and glass FRP pipes are orthotropic materials, the transverse elastic modulus $E_y$ is not used in the model since these parts are modeled with frame elements. The spiral staircase steps are not modeled since it is assumed they do not contribute to the stiffness of the structure. Nevertheless, their masses are considered adding them to the frame elements. The mechanical properties of each element are determined experimentally through static tests. A modal analysis of the numerical model of the structure is carried out to obtain the vibration modes and the corresponding frequencies, with the aim to compare them with those measured experimentally.

#### *4.2.2. Experimental test*

Three months after the installation of the lighthouse, wind-induced vibrations in the structure are recorded by a set of accelerometers strategically placed to determine its dynamic response. Eight unidirectional *DeltaTron Accelerometers Type 4508* are used, connected to its corresponding data logger *Brüel&Kjær LAN-XI 51.2 kHz - Type 3050*. At each storey, but at the lowest one (S1), two unidirectional accelerometers are placed, one oriented along X-axis and the other oriented along Y-axis.

At storeys S3, S4, and S5, each pair of accelerometers was fixed to a 5-kg steel block placed on the storey top surface near one of the carbon FRP columns. At storey S2, the accelerometers are fixed to small L profiles bonded to the storey top surface near the center of the structure.

Different data records are registered in order to compare the results of each measurement to detect possible random differences between them. The experimental vibration frequencies are determined by the fast Fourier transform (FFT), which converts the accelerations recorded in the time domain to the frequency domain. The measurements are made with a sampling frequency of 100 Hz. The choice of this frequency for data processing is set after analyzing several measurements with a higher initial frequency and after the observation that there are no excited frequencies in the structure higher than 50 Hz. As an example, **Figure 5** shows the registered accelerations and the corresponding Fast Fourier Transform for the pair of measuring points (X-axis and Y-axis) in storey S2 during one of these data records. After processing all the data records, the first ten frequencies are almost the same in most measurements with very little differences between them, so it can be assumed that the first 10 global modes of vibration of the structure correspond to these excited frequencies.

#### *4.2.3. Results of the test*

The experimental analysis carried out based on acceleration measurements has proven to be a good technique to obtain useful information about the structural behavior of the lighthouse from the free vibration of the structure. The analysis of the wind-induced accelerations by FFT identifies the first five modes of vibration of the structure, and the corresponding experimental frequencies are 1.309, 2.979, 3.922, 6.178, and 9.307 Hz. The frequency analysis is completed with a finite element model, with frequencies very close to those obtained experimentally. This model allows identifying the experimental modal shapes, where the first mode corresponds to the first flexural mode and the second one to the first torsional mode, being the following modes the second, third, and fourth flexural modes, respectively.

### 4.3. Conclusions

The main benefits of using composite materials in this project were:

- Quicker completion of construction work: the total manufacturing and installation time of the lighthouse is 40% lower than with the traditional process.
- Lower impact on port operations: apart from the fact that the total time of building the lighthouse is shorter, the time the port is affected is also much less because the assembly of the structure was done in the factory. This also means a smaller surface area and a shorter occupation time in the port, and less waste and noise in comparison with the work normally involved in the construction of a lighthouse.

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- Longer working life of the lighthouse: one of the main advantage of using fiber glass or carbon fiber composites in harsh environmental conditions is that they are not affected by corrosion. This makes them very attractive for use in damp or marine environments; lighthouses built with traditional materials usually suffer considerable degradation, which leads to a shorter working life.
- Reduction in construction and maintenance costs: the use of composites is more efficient in economic terms because the construction process is faster, and there is less need for the transport of materials. Furthermore, by resisting environmental conditions better, the lighthouse does not require investments in maintenance.
- A reduction of CO2 emissions in the construction process, due to fewer transfers of heavy materials and a lower level of extraction of aggregates. The environmental impact is believed to be 20% lower when using composites instead of traditional materials.

## 5. General conclusions

With all these successful cases and the respective outcomes, we conclude that composites (FRP) offer better performance as compared to traditional steel and concrete materials, especially in corrosive environments, in sites with limited access, in conditions requiring quick and fast installation and where aesthetic differentiations are required.

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