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Subjects:
Architectural/Design
Building Case Study
Construction
Façade Design

Keywords:
Composite
Construction
Façade

Publication Date: 2015

Original Publication: Global Interchanges: Resurgence of the Skyscraper City

Paper Type:
1. Book chapter/Part chapter
2. Journal paper
3. **Conference proceeding**
4. Unpublished conference paper
5. Magazine article
6. Unpublished

Fiber Reinforced Polymer (FRP): A New Material Used in Façades of Tall Buildings

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Abstract

Current architecture is changing the traditional concept of buildings meaning it is essential to rethink about the materials that are involved in construction. One of these challenges is to build high-rise buildings with different shapes increasingly complex and sophisticated.

Talking about materials used in tall building facades, it is important to consider its behavior regarding several aspects: wind load, weather conditions, sustainability… Fiber Reinforced Polymer (FRP) has become an excellent alternative because of its properties: resistance, lightness, good behavior against corrosion… FRP have been successfully used while ago in aeronautic and naval industries.

As an example of the use of FRP in towers the project of BBVA headquarters in Madrid, designed by Herzog&DeMeuron, will be presented; a 100 m high building with an external solar protection system comprised of several fins made in FRP. These elements are up to 10m high and 2,5m wide in a unique piece without joints.

Keywords: Composite, Façade, FGRP, FRP, Polymers

Contemporary architecture has evolved from known forms in which lines and right angles ruled, towards an architecture full of formal freedom, where the designs neither follow established rules nor have an external form based on pure geometric element but are outlined by freeform lines that reside in the mind of the Architect. This formal freedom of expression has been widely implemented in high rise buildings, with increasingly larger heights and flowing and aerodynamic shapes that meet the special needs of such type of constructions.

This new way of thinking about architecture brings about a need for a change in building methods, and consequently, in the materials that are used in designs and buildings. For these reasons, construction is introducing a new family of materials that are generated in response to the final product needs. "FRP composites" can be included in this range of new materials.

FRP composites materials can be used in both façades and building envelopes, and in their main components. Its wide application is also supported through the implementation of 3D software and FEM calculation programs during the idea and development phase of the projects, to calculate this type of materials and geometries.

Case Study: Shading Protection Fins in New BBVA Headquarters in Madrid

General concept of building

The New BBVA Headquarters in Madrid (see Figure 1) is a complex of buildings hosting the offices of all employees of one of the biggest banks in Spain, with a unique and distinguishable corporate image. The building complex is formed by three story low-rise buildings hosting most of the offices and common service rooms and a central ovoid shaped building situated between the low buildings, commonly known as "La Vela", where the institutional and representative areas are placed. The low volumes are connected by walkways with landscaped courtyards between them. The tower building rises 100 meters and is distributed in 19 floors. The width of the building nears 16 meters. The main curtain wall façades face a North/South aspect and a metallic curve skin wraps the whole length of the edgewise of the tower.

In both the horizontal building and the tower, the main façade is designed combining innovative shading elements, which are the object of this paper since they are self-supporting elements made of polyester resin reinforced with fiberglass with an inner metallic structure. Apart from providing the façade with solar protection, they provide the building the aesthetic that the architects were looking for. (see Figure 2)

Sun protection fins in the tower

“La Vela” tower includes the shading protection fins on the south-facing façade in several floors to serve a double purpose:

- To give sun protection.
- To hide facilities.

The fins conceal the machinery and equipment located on the technical floors which serve the offices. The ground floor, the second floor, the intermediate restoration floor, the ninth floor and the highest levels at the top of the tower 18th and 19th, also exhibit these characteristic shading elements, which due to their greater height, and to the cantilever of the concrete slabs, do not provide enough protection by themselves.

In particular, the upper level at the top of the building is considerably higher at nearly 10.5 meters. In addition to the vertical fins, some horizontal louvers are located between them to provide horizontal stabilization and to increase the much-needed protection from the sun.

Definition of the Fins

Design

The design of the fins meets their specific geometry, construction system, functional requirements and also structural needs to support their inherent weight in addition to wind loads.

Figure 1. Interior view of the building complex (Source: ENvolventes ARquitectonicas - ENAR)

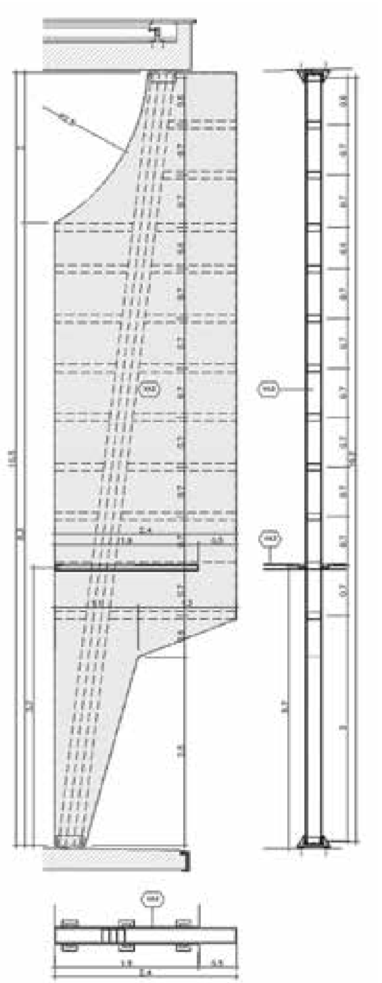

Figure 3. Drawing of the tallest fin of the Project (Source: ENvolventes ARquitectonicas - ENAR)

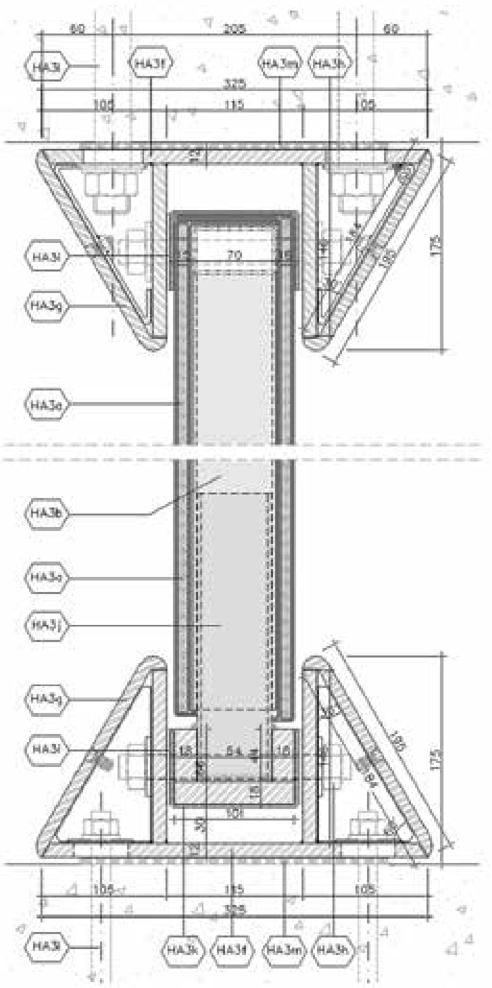

Figure 4. Detail of the anchorages of the fins (Source: ENvolventes ARquitectonicas - ENAR)

Figure 2. View of the shading elements on the top of the building (Source: ENvolventes ARquitectonicas - ENAR)

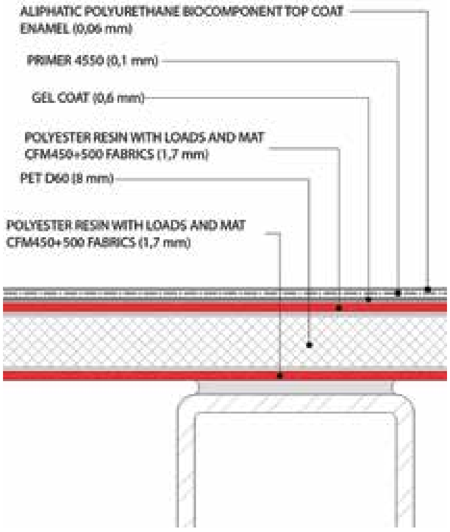

Figure 5. Composition of the FRP composites sandwich Shell (Source: ENvolventes ARquitectonicas - ENAR)

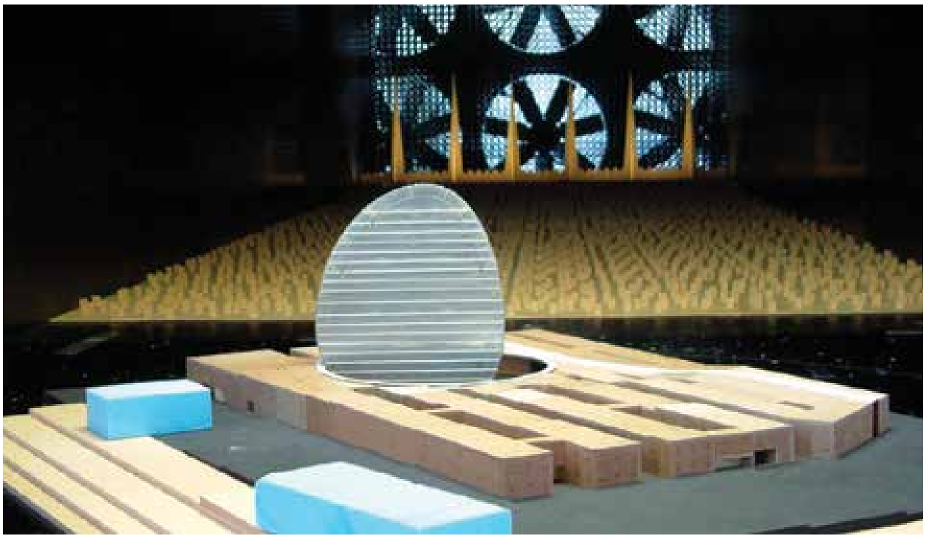

Figure 6. 1:250 scale model of the building to carry out the wind tunnel test (Source: ENvolventes ARquitectonicas - ENAR)

The main façade, which consists of a traditional curtain wall system between concrete slabs, steps back to allow the cantilever of the slabs to reach enough width to provide the façade with sun protection. Additionally, the shading fins are fixed over these concrete cantilevered pieces, projecting outwards with the singular geometry and shape which makes them as characteristic as a flag. The fins are 2400 mm wide, and have a variable height to accommodate the curvature of the geometry at the top of the building, ranging from 3580 mm to 10270 mm, all of them with a thickness of 210 mm (see Figure 3).

The fins are fixed over the concrete slabs with lacquered steel anchor treated against corrosion for environment type C4 in accordance with the UNE-EN ISO 12944 standard. These anchoring elements allow a two-way setting out in both parallel and perpendicular directions to the façade. They are "π" shaped and will be covered with caps to hide both anchors and mechanical fittings, once the fins are installed, showing an enclosed and compact element that mimics the fins (see Figure 4).

Further elaborating on the anchoring system, the fins are fixed from the top, hanging from this point and allowing free expansion at the bottom part, stabilizing wind horizontal loads. The composition of the shell of the fins is a sandwich structure which increases their resistance without higher costs of materials, due to the large volume of material they imply. A structural frame of steel tubes makes up the main nerves of the fins providing the required rigidity to the whole assembly and distributing loads to the anchors. The envelope of FRP composites is glued over the inner steel structural frame with structural bonding.

The sandwich composition of the shells consists of an inner structural core of PET (polyethylene terephthalate), 10 mm thick, which guarantees the stiffness of the panel and two sheets of polyester resin reinforced with fiberglass. The PET core separates the exterior faces of the panel and provides resistance to bending and shear stress. The resin includes alumina loads to reach an appropriate performance against fire (see Figure 5).

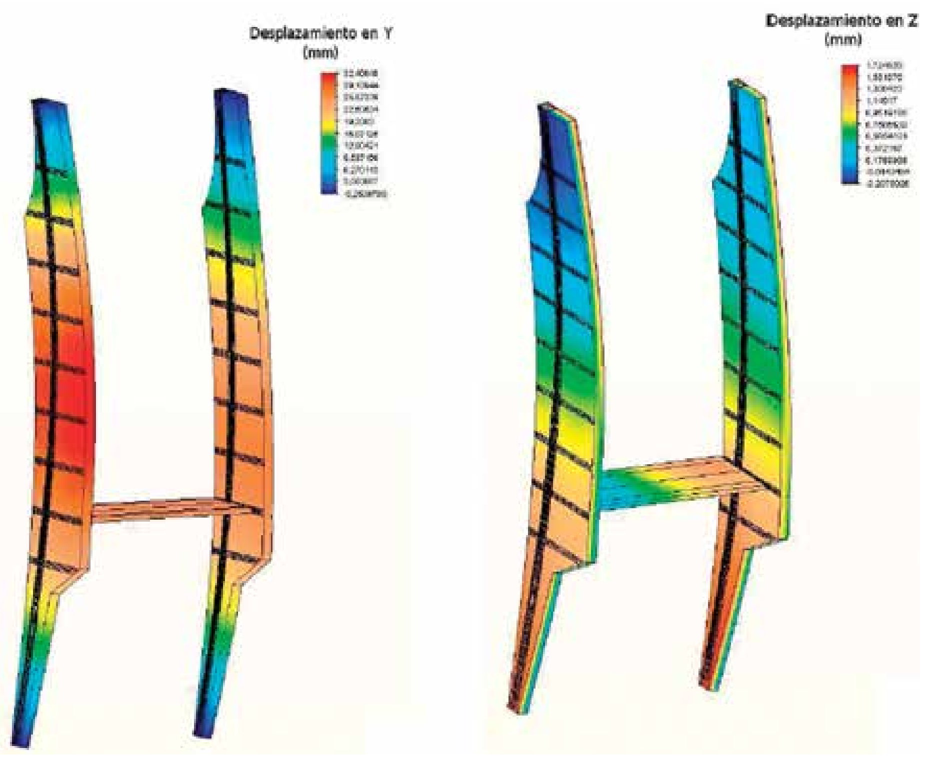

Figure 7. Calculations performed though FEM software (Source: ENvolventes ARquitectonicas - ENAR)

Calculation

Since the fins are located in a high-rise building, a wind tunnel test was carried out to analyze the loads to which they were subjected. The test was developed in two different variations, using a 1:250 scale model of the whole building first to obtain global and local loads, and using a scale model of the fins later, to obtain specific loads on these particular elements (see Figure 6).

The most unfavorable data of 1,90 kN/m2 was used to perform all necessary calculations for all components of the fins, including their inner steel structure, the FRP composites panels and the adhesives, plus a calculation of the components as a whole. The fixing elements were calculated to ensure the proper transmission of loads to the structure of the building. All elements were cross referenced verifying their resistance and strain levels. The maximum deflection set up was L/150, as at the present there are no a reference standards for this type of elements.

Calculations were performed through the utilization of Finite Element Method (FEM) software, modeling the materials, joints and setting the loads and coaction systems. Movements and loads resulting from thermal variations and temperature changes are also taken into account in the calculations (see Figure 7).

Manufacturing Process of the Fins

The production process of the shading protection fins of the building is developed in different steps which are explained below:

Preparation and cleaning of the moulds

As the fins have a preset wide but they vary in length to accommodate the curvature of the upper concrete slab, the moulds include a movable part at the top which allows height regulation and the manufacture of all different sizes.

A separating agent impregnation is applied to the moulds every twenty or thirty fins are manufactured, but care must be taken because too much impregnation can cause the Gelcoat spilled later hardens and need to be removed from the mould before time, so the finish could present bubbles as result.

It is important to perfectly clean the surface of the mould, remove any dirt, scratches or foreign elements which could lower the quality of the surface finish of the fins (see Figure 8).

Applying the Gelcoat

A 600-micron thick layer of Gelcoat is applied on the open mould by spraying. The thickness is controlled by gauges.

Preparation of the hand lay-up

The Gelcoat must be at little tacky to the touch before is completely dry to ensure the chemical bonding with the layers that will be applied later, and it is the time to place all the components of the sandwich such as shell fabrics, inner core and interior fabrics. The composition is as follows:

- CFM 450 fabrics
- Biaxial 500 fabrics
- PET type core 8 mm thick, with a density of 60 kg/m3 and 100 kg/m3 in the anchorage area.
- Biaxial 500 fabrics
- CFM 450 fabrics

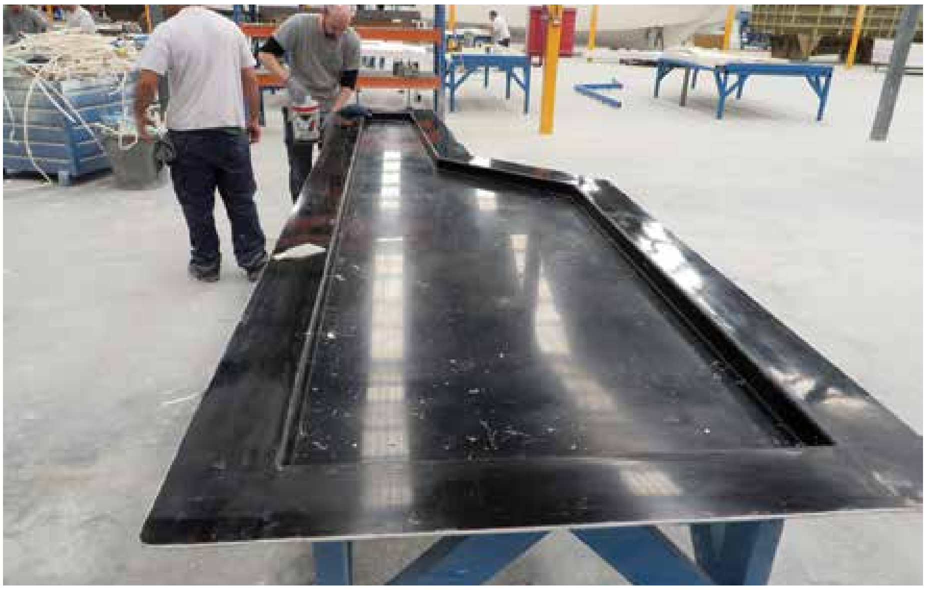

Figure 8. Mould of a Shell (Source: ENvolventes ARquitectonicas - ENAR)

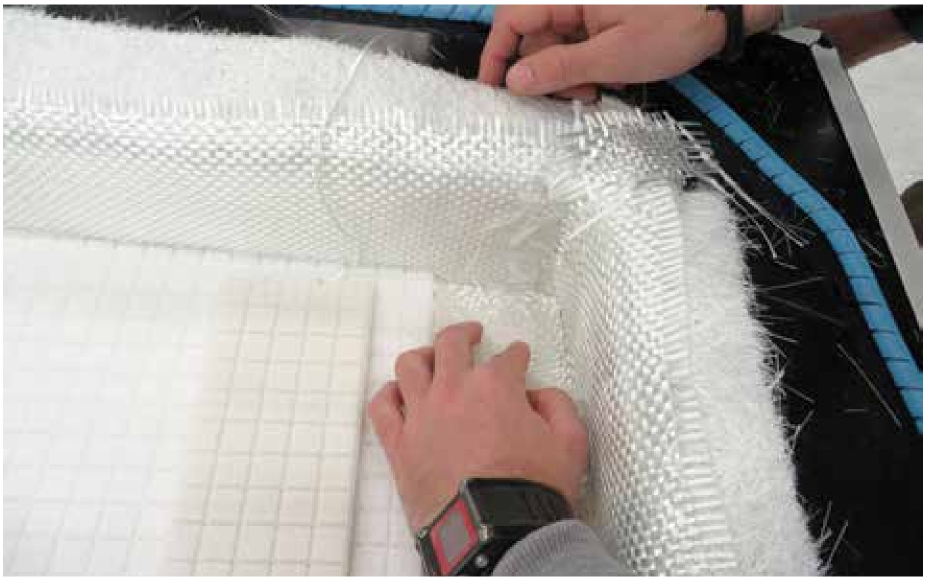

Figure 9. Placing the fabrics (Source: ENvolventes ARquitectonicas - ENAR)

Figure 10. Infusion process (Source: ENvolventes ARquitectonicas - ENAR)

Figure 11. Placing the interior structure of the fins (Source: ENvolventes ARquitectonicas - ENAR)

Figure 12. A fin with the two half-shells joined (Source: ENvolventes ARquitectonicas - ENAR)

It is necessary to adjust properly the components against the mold within the boundary to guarantee a right workpiece edge (see Figure 9).

Preparation of the resin infusion

At this point before infusing it is essential to create a successful vacuum with the vacuum bagging system. This technique removes trapped air between layers and compacts the fiber layers. A vacuum bagging film is placed over the mould, including vacuum tubing to connect the bag to the pump, and then the bag is sealed with sealant tape.
A connector between the tubing and the pump is required as well as a means of fitting the tubing into the bag to ensure a proper filling. When the resin infusion starts, vacuum pressure drives resin into the laminate, filling the mould uniformly.

There is more than one bag at a time working from a single pump, so several fins are infused at the same time (see Figure 10).

Demoulding and deburring

Following the curing period all molds are removed and it begins the process of deburring of the pieces. The edges on the perimeter are cut and half-shells are cleaned removing any dirt. Each half-shell is stored with its other half, carrying out quality control checks of all elements.

Before assembling the two halves a post-maturing process takes place in a furnace to prevent the formation of fissures or cracks in the painting finishing later.

Assembly of the half-shells

The two half-shells are laid over steel tables or beds which includes a perimetrical frame where the piece is fitted. The position of the interior steel tube structure is marked over the shells and holes for anchorages are drilled.

It is important to clean the surface of the steel tube structure too, and to place some spacers to ensure a proper adhesive thickness (see Figure 11). A primer must be applied in both the internal structure and the half-shells. The adhesive is applied with a pneumatic spray gun on one side and the same process will be repeated in the opposite side.

To join the two half-shells, mastic is applied into the joint between the pieces and then the top half-part is placed (see Figure 12).

It is necessary to adjust the bed on the perimeter to avoid movements and deviations of the fin during this assembly process, so pressure cats are used for this purpose.
When the adhesive and the mastic are cured, the fins are removed from the bed and all exterior surfaces are sanded to prevent pores and guaranty the adherence of the painting.

Figure 13. A fin after painting, during its curing process (Source: ENvolventes ARquitectonicas - ENAR)

The edges must be smoothen with the milling machine and then fins are ready for paint.

Painting process

First of all a primer is applied over the piece and once this primer has cured the entire surface of the fin is sanded and reviewed. Once the piece passes to the spray booth, a couple of painting coats are applied and allowed to dry (see Figure 13).

Placement on site

The assembly sequence of the fins on site starts with the setting-out of the anchorages and drillings, and after the holes are made, anchors can be placed.

The fins stored on site are raised up one by one and put on its site. Now it is necessary the setting-out and fine-tuning of the fins before blocking the anchors. Works are completed with the position of the cover caps of the anchorages (see Figures 14 and 15).

Talking about new materials in high rise buildings

Requirements

High rise buildings are constructions with special requirements regarding their use of materials, due to their behavior and construction is different particularly talking about the envelope and façade of these buildings. Such requirements include:

- Lightness. Materials used in these types of buildings must be light to prevent penalizing the structure in the base and make easier its construction, avoiding the need of great auxiliary elevation means.
- Resistance. Wind loads are considerable in high rise buildings, so the elements of the envelope are highly exposed to them needing higher resistance of materials than in other type of constructions.
- Stability. Temperature variations are also more significant than in traditional constructions, so more stable materials will work better.
- Breakings and detachments. It is essential the use of non-fragile materials to prevent the break-up and detachment of elements from a great height due to the inherent danger this implies.
- Conductivity. Elements of the

Figure 14. Installation of the fins on-site (Source: ENvolventes ARquitectonicas - ENAR)

Figure 15. Installation of the fins on-site (Source: ENvolventes ARquitectonicas - ENAR)

Material	Density (g/cm3)	Tensile Strength (Mpa)	Thermal Expansion	Thermal Transmittance (W/m2.K)
Polyester + Glass Fibers	2.00	340	5 x 10 -6	0.07
Steel	7.84	250	12 x 10 -6	50
Aluminum	2.70	200	24 x 10 -6	200
Reinforced concrete	2.50	250	2 x 10 -5	1.63
Glass	2.50	40	9 x 10 -6	1.05

Figure 16. Properties of different materials (Source: ENvolventes ARquitectonicas - ENAR)

envelope are highly exposed to electricity in thunderstorms, so electrically inert materials are the most advantageous in the constructions of these types of buildings.

- Prefabrication. On-site working conditions are complicated so makes more sense the use of prefabricated elements, making the assembly easier and with less need of auxiliary means.
- Durability. It is also important the election of material with high cycle durability and a longer lifetime because in many cases replacements are complex if not impossible with affordable means.

"FRP composites" is the material that best meets all these requirements and for this reason its use is rapidly increasing in the construction building, coming from other sectors such as automotive, aeronautics or naval.

Definition

"FRP composites" is understood as a material composed of two or more components, which complement each other and work together, improving the properties of the elements separately. Mainly, the components of the FRP composites are divided into matrix and reinforcement. The matrix is the component that gives cohesion and unity to the final material, while the reinforcement is the component that provides the final material with the physical and mechanical properties.

In this family there are different types of composites as concrete in the construction, a mixture of cement and gravel combined with steel, or the most common FRP composites used today in many fields of activity, composed of polymer resins and all kind of fibers.
FRP composites are materials made and designed according to the needs and functions to perform, choosing the most appropriate components for each use. This is one of the great advantages of this kind of material, which is created especially for its function; both stress level and properties level.

Compounds

Besides matrix and fiber, loads or additives can be added to improve the final properties of the material, depending on its specific needs.

1. Matrix

The matrix is the component that gives cohesion to the material, giving to the piece its final geometry and assuming the role of stress transfer between fibers. Among different types of matrix there are the cementitious (used for the manufacture of concrete for construction), metallic, carbon and ceramics families, but the most important one is the organic matrix.

- Organic: These components are based on polymeric chains resulting from its chemical combination with various acids. The different types of organic matrix are:
  - Thermoplastic: Polymer chains linked by low intensity, which can be broken with heating on low temperature. (PVC, Polyethylene, Nylon, Polyamide)
  - Thermoset: Polymer chains linked together by bonds of the same intensity as the internal of each molecule, so they do not melt with temperature. This type of resins is mostly used for the manufacture of FRP composites materials.

The thermoset resins are the most used for making FRP composites materials for several applications and among them the following types can be distinguished:

- Polyester resin
- Vinyl ester resins
- Epoxy resins
- Urethane-Acrylate resins

2. Fibers

The fibers are the components that support mechanical stress and provide to the material with rigidity, strength and elongation, therefore, the higher percentage of fiber in the FRP composites, the better mechanical properties are got. Within the fibers the following families are identified:

- Glass fibers.
- Carbon fibers.
- Aramid fibers.

There are also other types of fibers in the market such as basalt fibers, boron, PBO or Hemp, but they are less used than the previously mentioned ones.

The fibers are selected according to the mechanical needs and final application of the material. For choosing the most appropriate one for each use it should be taken into account different factors, such as mechanical properties, compatibility with the matrix or the price.

3. Loads

Loads are components added to the mixture to conferring to the material with special and specific properties, such higher fire resistance, higher density, lower electric conduction, higher abrasion resistance, higher resistance to UV rays, greater specific weight, increased surface hardness or other properties necessary according to each different application.

The most commonly used loads are: talk, clay, mica, calcium carbonate, calcium silicate, titanium oxide, silica, glass microspheres, powdered metals, quartz, kaolin or alumina.

4. Additives

Additives are components added to the material to obtain an easier manufacturing, such mold release agents, stabilizers, fungicides, coloring...

Properties

The properties of these materials are highly variable depending on the chosen composition, since these materials are designed according to specific requirements, within their main properties can include:

- Lightness. FRP composites are lightweight materials mainly due to it is used with small thicknesses and because they have low densities which may be between 1,2 g/cm3 and such 2,0 g/cm3 depending on the choice of the resin and the percentage of fiber.
- Resistance. They can reach much higher resistance than the resistance of the steel depending on the selected fibers between 330 and 450 MPa.
- Corrosion. FRP composites are inert materials to corrosion, thereby preventing many problems of oxidation or incompatibility with other materials of use, in contrast to what happens with aluminum and steel.
- Conductivity. These are materials with very low electrical conductivity, except the carbon fibers, so it can be used for insulation and to avoid lightning and attraction of electrical elements in façades.
- Dimensions. FRP composites may reach larger dimensions than the usual materials used in construction, being able to manufacture 50 meters long pieces without intermediate joints.
- Dilatation. It is a material with a rather low linear expansion coefficient, which means that joints between the pieces can be smaller than with other materials.
- Thermal insulation. Being low conductivity material, it has a high insulation resistance so there is no need to place additional insulating materials, a great advantage.
- Fire performance. This is one of the possible drawbacks of these materials, but today, this problem has been solved by the use of urethane-acrylate type resins with alumina trihydrate loads, improving the fire resistance behavior, and carrying out all the requirements of construction regulations. Fire testing of the BBVA fins gave them a B-s2, d0 fire classification according to UNE-EN 13501-1:2007 standards, although a B-s3, d2 classification was required.
- Inserts and reinforcements. The material allows the fitting of metal pieces making easier the fixing of anchors and accessory elements. The FRP composites material also allows the adding of reinforcement points in specially requested areas, without having an aesthetics impact.

All these properties are summarized in a table (see Figure 16), setting a comparison between these materials and common materials used in architecture and facade claddings.

Finishes

The finish of these elements is usually painted. This paint can be directly manufactured by a gelcoat which is applied directly on the mold once the piece is unmolded. The gelcoat can also be part of the final product so it can be painted with polyurethane paint.

Sandwich structures

The laminates can be manufactured in sandwich structures, performing a double laminate with an inner core (case of the BBVA fins). Such structures are highly recommended for bending working requirements, since the flexural stiffness of a laminate depends on its thickness and it tends to the minimum possible. To provide this increased stiffness it is added an inner light core between the laminates. This light core increases the thickness and thus stiffness; it also must have good compression and shear resistance to pass efforts on the outer laminates.

Quality control

Testing the properties of these materials, taking into account their special manufacturing process which is adapted to every project, involves making a number of tests with the specific composition of the material for each project. These tests must be at least the following:

- Testing of fire rating.
- Bending resistance.
- Test of adherence.
- Ageing test.
- Tests of Resistance to UV rays.

Previous Applications

“FRP composites” have been used previously for a very long time and with proven efficacy in other fields such as boating, aeronautics, automotive industry, railway engineering, wind energy and civil construction.
In the field of architecture and construction its implementation until recently has been restricted to structural reinforcements with carbon fibers and epoxy resins, and to polymer concrete as prefabricated decorative elements or GFRC cladding elements.

There are currently some examples of its use in the field of technological facades, such as the Mobile Art Chanel or Contemporary Art Container or the Reina Sofía Art Museum.

Cost

It is a clear fact that any save in weight means some savings in cost, for instance in foundation, structure, etc. but in this case savings are possible not comparing square meters of surface (area) of material, which is also possible, but actually is much better to compare the cost of manufacturing each fin as a whole, including all the individual items making up the unity. The fins of BBVA, which are 5000 mm high and 2400 m wide on average, are cheaper made of double sandwich panel of FRP composites than made of other materials. More specifically, to manufacture them in precast ductile concrete is over 10 % more expensive; to make them comprised of steel tubes structure and a shell of aluminum honey-comb panel is over 20 % more expensive, or a shell of stainless steel means an increase of 50 % compared with the FRP composites. They would only be cheaper with a shell of lacquered aluminum or steel panel.

Advantages of using FRP composites

In conclusion, there are many benefits or advantages of using FRP composites over traditional materials in high rise buildings:

- The material is designed according to the requirements of each project.
- It offers the possibility to perform complex geometries and unlimited dimensions.
- It has high tensile, bending and compression resistance besides a great lightweight.
- Good behavior of the building against earthquake
- Thermal insulation great properties.
- Low electrical conductivity.
- Compatibility with materials used in building.
- High resistance to corrosion.
- Good maintenance.
- Long life cycle
- New application on the field of tall buildings.

Much like the building they serve, the materials and claddings used in facades of tall buildings are heavy. Unlike other building typology, tall buildings must be pioneers with the use of FRP composites to make the case that they can be light, thin and consequently of appropriate use. Currently the materials and claddings are thin but unfortunately they are also heavy. High rise buildings can extract the most advantages of the FRP composites.