First Middle East Conference on Smart Monitoring,
Assessment and Rehabilitation of Civil Structures
8 – 10 February 2011, Dubai, UAE

SMAR 2011

Innovation on advanced composite materials for civil engineering and architectural applications: case studies

E.Agneloni[1], P.Casadei[2], and G.Celestini[3]

[1] President The First Brick Network, Perugia, Assisi, Milan, Rome, Verona, L'Aquila, Italy, Dubai, UAE
[2] Technical Director Fidia srl – Technical Global Services, Milano, Italy
[3] Technical Director TEC.INN. srl – Innovative Technologies, Perugia, Italy

ABSTRACT: Due to their light weight, high stiffness-to-weight and strength-to-weight ratios, and high resistance to environmental degradation, resulting in lower life-cycle costs, advanced composites materials, commonly known with the acronym FRP-Fiber Reinforced Polymers, are increasingly being considered for use in civil engineering applications, ranging from the retrofit and rehabilitation of buildings and bridges to the restoration and strengthening of historical-monumental masonry structures. Thanks to the recently published Italian FRP guidelines, CNR-DT 200/2004, by the Italian National Research Council, there has been an increasingly demand of their implementation for general strengthening and retrofitting applications as well as seismic mitigation of structures and infrastructures, and the recent earthquake of L'Aquila has decree their use as the most efficient technological solution for strengthening, repairing and seismic upgrade of most structural elements in existing buildings, showing also, for the first time, the official implementation of Ultra High Tensile Strength Steel fiber sheets. In the following pages, several case studies are reported demonstrating the different field of applications of the different fibers and technological solutions.

1 INTRODUCTION

After an initial phase of experimentation and research, validated by extremely positive results, the use of advanced composite materials in the civil engineering industry, is, now days, a well established reality. Currently the most retrofit and strengthening projects, regard buildings, industries, infrastructures and, particularly in seismic areas, masonry historical structures. In the last years, the technological innovation in the aforementioned sector has been characterized by an important acceleration. The boost of such technology started in the 90's, when innovative fiber materials, thanks to their very competitive weight to strength ratios, high durability and ease of installation, represented the most ideal substitute of the widely applied technique of "Béton Plaque" (steel plate bonding).

1.1 Innovative materials

FRP systems in the civil repair industry are used to strengthen existing structures/infrastructures (Casadei et al., 2008). Structures may need strengthening due to deterioration, design/construction errors, a change in use or loading, or for a seismic upgrade. In particular this last issue has become of high priority in Italy and in all seismic countries, where new and updated seismic codes have come into place. FRP essentially works as reinforcement in concrete-masonry structures and provides strength where they are weakest or in need of enhancement. FRP may be used on beam or slab soffits to provide additional flexural strength, on the sides of beams to provide additional shear strength, or wrapped around columns to provide confinement and additional ductility (a primary concern in seismic upgrades). Among many other applications, concrete and masonry walls may be strengthened to better resist seismic and wind loads, concrete pipes may be lined with FRP to resist higher internal pressures, and silos and tanks may be strengthened to resist higher pressures. On historic structures FRP are mainly used to strengthen masonry domes and vaults providing a link among the several portion of the elements without adding any additional mass and most importantly avoiding the most critical failure modes of such type of structures, contrasting the formation of hinges and retarding/avoiding premature collapse.

FID-Carbon/Glass/Aramid fiber sheets | FID-Steel 3X2 Brass coated UHTSS steel fiber sheets | FID-Steel 3X2 Galvanized UHTSS steel fiber sheets | FID-Basalt fiber sheets | Biocomposites as FID-Hemp/Flax fiber sheets

Figure 1. Innovative materials for retrofitting, strengthening and seismic upgrade.

1.2 Carbon, Aramid And Glass Fibers

Fiber reinforced polymer (FRP) materials are composite materials consisting of high strength fibers in a polymer matrix. The fibers in an FRP composite are the main load-carrying element and exhibit very high strength and stiffness when pulled in tension. An FRP laminate will typically consist of several million of these thin, thread-like fibers. The polymer matrix (sometimes referred to as the resin) protects the fibers from damage, ensures that the fibers remain aligned, and allows loads to be distributed among many of the individual fibers in the composite. There are a variety of fiber types and resins that may be used to create an FRP composite. Fibers are selected based on the strength, stiffness, and durability required for the specific application, and the resins are selected based on the environment the FRP will be exposed to as well as the method by which the FRP is being manufactured. Among several possibilities, the fiber types that are typically used in the construction industry are carbon, glass, and aramid. In selecting the type of fiber to be used for an application, there are a few things to consider. Glass FRP is excellent for seismic upgrades where the seismic loads only temporarily engage the FRP. In cases where stresses are sustained in the FRP (such as in bending and shear strengthening), glass FRP should be avoided because of creep rupture effects. Carbon is much more suitable in these applications. Similarly in exterior applications, carbon FRP will be much more durable. Aramid fibers are indeed mostly used now days in masonry applications to realize connection between the strengthening layer, commonly of carbon or glass fibers, and the main structural members thanks to their better performance towards concentrated shear stresses that make them the most suitable for this type of application.

1.3 Basalt Fibers

Basalt fibers have the ability to combine tenacity and impact resistance of aramid fiber and durability, fire resistance, creep resistance and no susceptibility to hydrolysis phenomena typical of glass ones. These fibers are ideal for those applications that require high static and impact resistance, insulation properties, electromagnetic transparency, and durability in aggressive environments. They are an excellent alternative to fiberglass and aramid fibers since they have a comparable stiffness to aramid and better corrosion resistance with respect to glass. These fibers can also be extensively used in the retrofit of structures subjected to dynamic effects generated by either earthquake, high winds or blasts, and impact loads caused by flying debris or projectiles thanks to their toughness similar to the one of aramid fibers.

1.4 UHTSS Steel Fibers

Nowadays are available also another family of composite materials similar to FRP, made of fine ultra high tensile strength steel filaments (UHTSS), twisted to form cords and tailored similarly to unidirectional (carbon, aramid or glass) fiber sheets in order to then be easily installed on site with the manual lay-up technique (Casadei et al., 2005 and Casadei et al., 2008). The twisting of the filaments allows some mechanical interlock between the cords and the matrix, and may also induce an overall ductile behaviour upon stretching. The cords are also coated with brass or galvanized with zinc making the material potentially free of any corrosion and suitable for different kind of environmental exposure. The great advantage of such materials is that they can be either impregnated using epoxies, then called SRP (Steel Reinforced Polymer), or using mortars, then being called SRG (Steel Reinforced Grout). The choice of the matrix is based upon the type of substrate where bonding the material and also upon the density of the sheet to be installed: higher density sheets may be impregnated only with resin matrices, while low and medium densities with either epoxies or grouts. Such materials present the same advantages of FRP in terms of lightness (slightly higher), strength (similar E-modulus and strength at rupture) and ease of installation as long as proper resins are used during installation (more tixotropic resins are necessary to allow holding such slightly heavier sheets particularly when installed overhead but no need of clamps are needed to support installation), but with several additional advantages that have made them very attractive for masonry retrofitting. The possibility of impregnating them with cement or hydraulic mortars allows a much easier installation for skilled workers and also a considerable reduction of primary material costs with respect to FRP. Secondly, being such sheets made of steel cords, they have a considerable shear strength, not present in other FRP materials, making them particularly attractive for uneven surfaces and also for mechanical anchors, prohibitive with typical FRP strengthening solutions.

1.5 Biocomposites

The interest in the bio-composites has grown considerably in recent years due to good mechanical properties, recyclability and low energy required for production with a consequent decrease of emissions of carbon dioxide, making them very attractive in retrofitting masonry structures and in general all type of structures that present low or poor quality materials, that do not require the need of high performance fibers. Among the countless bio-fibers, are of particular interest flax and hemp fibers for strengthening and retrofitting historical and civil structures. Like all vegetable fibers, have an extremely complex molecular structure consisting of a variety of biopolymers (lignin, crystalline cellulose, pectin..etc) and nano-structured architecture that give these fibers excellent mechanical properties when impregnated with either resins or mortars. The filament manufacturing, that combines combing and twisting of the single fibers, achieving long filaments and the way filaments are then weaved in forming textiles, makes these fibers ideal for structural retrofit just like previous engineered fibers.

1.6 The choice of the right composite system

When strengthening a reinforced concrete or masonry structure the right choice of the composite system, made of fibers and resin, is fundamental in order to improve the performance of the retrofit system and maximize the efficiency of the proposed solution on the entire structure. Stiff materials are indeed not as efficient on poor substrates as they are on good, sound ones; for such reason it is important understanding the properties of the materials onto which composite materials are going to be installed in order to choose the proper retrofit. In Figure 2 are represented different composite systems and their strength's and stiffness's. FIDFORTICA offered by FIDIA is the first system that not only offer different fibers but also has studied different epoxy resin's formulations, with low, medium and high modulus depending on the type of fiber and based on the type of substrate onto which composite materials are installed, engineered to follow all different fibers deformation, being so able to enhance FRP composite performance in terms of length of adhesion and strength of the retrofitted structural member (shear, flexure and confinement).

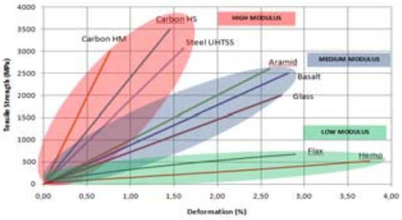

Figure 2. Comparison of different retrofit systems for strengthening structures.

2 ITALIAN SITUATION

In Italy, as well as in many other seismic countries, the use of advanced composite materials for strengthening and retrofitting existing structures has been heavily introduced in the market by recent earthquakes and natural disasters, supported by recently published design guide lines (CNR DT-200/2004). In particular the earthquake that interested the central Italian regions of Umbria and Marche in 1997-'98 has heavily pushed engineers and contractors on the use of the FRP technology thanks to the aforementioned qualities and, recently, the Abruzzo earthquake in 2009 was the impetus for a massive application of FRP in civil retrofitting. In particular, to strengthen structures against seismic/dynamic loads, FRPs are particularly efficient because, in front of very performing mechanical properties, they have very low weights and consequently they do not add any mass to the structure, and allow a quick installation with a great ductility enhancement for the entire structure, making them ideal for this type of retrofits. Nowadays the mainstream market of these materials in Italy is for both reinforced concrete frames and masonry historical structures where their implementation varies from: increasing the capacity of panels, arches, or vault; wrapping of columns to enhance their compressive strength and ductility; reducing thrust forces in thrusting structures; transforming non-structural members into structural members by increasing their stiffness and strength; strengthening and stiffening horizontal non-thrusting structures; wrapping buildings at floors and roof locations to improve vertical and horizontal strength to lateral loads, typically seismic actions. The following case studies represent a review of some among the most significant applications on concrete and historical structures reinforced, retrofitted and seismically upgraded using different types of advanced composite fibers and technological solutions.

3 ADVANCED COMPOSITE APPLICATIONS ON REINFORCED CONCRETE STRUCTURES: CASE STUDIES

3.1 Seismic upgrade of the entire concrete frame of the CTO Careggi hospital in Florence.

In order to defy earthquakes and so seismic shocks, the structure have been reanalyzed and designed to resist seismic loads that were not taken into account when the structure was first designed, due to a change in the current Italian design code. Since the new seismic loads where much higher, so that no retrofit could have possibly allow the structure to pass new design criteria, it was chosen to physically divide the structure in two parts by inserting shear walls that could absorb part of the in plane forces generated by an earthquake and also trying to rearrange masses in order to modify the center of stiffness of the reinforced concrete frame, making it more conform to resist torsion stresses.

Figure 3. View of the concrete frame of the CTO Careggi hospital strengthened with CFRP sheets.

Then once this initial remedies were defined, allowing to reduce the shear, moment and axial stresses acting on beams and columns, innovative retrofit using advanced composite materials was designed consisting in wrapping columns and beams using unidirectional carbon fiber sheets, enhancing shear capacity of beams and columns and increasing overall ductility of all vertical members.

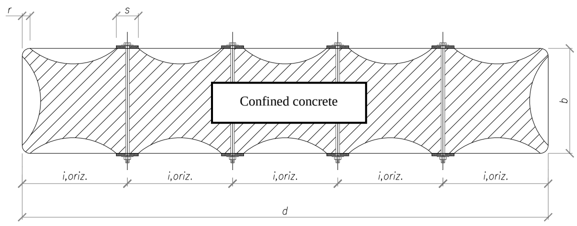

Figure 4. Confinement of rectangular section using FRP sheets and transversal steel bars.

A total of twelve thousands square meters of carbon fiber sheet were installed, using manual lay-up technology. Wrapping of columns was performed on all rectangular columns that had a ratio of sides less than two and with one of the sides less than 900mm. For existing columns and shear walls that had a geometry not consistent with these two parameters imposed by the Italian code (same conditions are also consistent with other FRP design guidelines around the world) initial design proposed the use of thick steel plates bolted around the section of the RC wall aiming to confine it, and so increasing its shear as well as axial load. By doing so, such design would have added several tons of weight to a structure, partially compromising the overall benefit given by previous use of composite materials.

Figure 5. Overview of all strengthening phases.

It has been at this point that innovation took place, through an extensive research campaign aiming to substitute the Beton Plaquè retrofit scheme with a solution that took advantage of UHTSS fiber sheet properties with more traditional wrapping techniques. UHTSS steel fiber sheets could indeed be used for wrapping the column and, at defined intervals, be mechanically anchored by means of transversal steel bars and longitudinal 10mm thick-100mm wide plates so incrementing the area of confined concrete as shown in Figure 4. Such design permitted basically to transform the wall into several adjacent columns all confined by the wrapping using steel fiber sheets, transversally and longitudinally by the presence of the bars and plates, yet considerably reducing the amount of weight added to the structure. Such retrofit scheme was tested on small scale similarly shaped concrete elements investigating the percentage increase of axial loads and consequently the overall ductility provided by the retrofitted element to the structure. Positive results supported the retrofit solution that was then implemented on all structural elements that needed such retrofit, for a total of almost three thousand square meters of UHTSS steel fiber sheets. In Figure 5, the different phases of installation are illustrated.

3.2 Seismic upgrade of a primary school in Rome.

The recent upgrade of the entire Italian territory into seismic zones of different intensity, has declared the need to first check and seismic upgrade all sensible structures and in particular schools and public offices. For this reason the Rome's school was subjected to a substantial non destructive testing campaign aiming to determine an adequate level of confidence for then conducting all design checks.

Figure 6. Overview of the additional stirrups made of UHTSS steel fiber sheet.

The reinforced concrete frame was found to be deficient in terms of ductility of columns and flexure and shear of beams. The designer decided to upgrade and strengthen the existing structure adopting innovative materials in addition to more traditional consolidation techniques such as amplifying foundations and rearranging the center of stiffness of the structure. To increase ductility and shear strength of columns, carbon fiber wrapping was adopted for one meter at the base and top end of the column. In order to increase flexural and shear strength of beams, since the beam had the same thickness of the floor system, it was not possible to retrofit it in shear by traditional U-wrapping. It was indeed necessary to design a solution that could be inserted within the thickness of the slab, trying to take the most advantage of the full depth of the beam in order to reduce drilling through the thickness and improve efficiency of the scheme chosen. In order to do so it was chosen to design the shear and flexural strengthening for the beams in need of such, using UHTSS steel fiber sheets impregnated with epoxy resin as shown in Figure 6. The new concept stirrup was made with UHTSS steel fiber sheets rolled to form a bar with thread at both ends to be inserted into the predrilled hole and opened at the extrados and intrados of the beam then anchored using negative and positive moment strengthening realized with same material.

4 ADVANCED COMPOSITE APPLICATIONS ON MASONRY HISTORICAL STRUCTURES: CASE STUDIES

4.1 FRP retrofitting of the vaults and of the arches and bell tower and srp strengthening of the ring curb beams of the "SS.Trinity Convent" In Orvieto.

The monastery of the SS.Trinity was built west of the city of Orvieto, in the valley of the river Paglia, in the early 1034, and then annexed to the monastery of the Benedictine nuns. In the centuries the structure has been subjected to several structural changes such as extensions, raisings and more, nevertheless several restorations aiming to solve the degradation acting on the structure. Unfortunately the monastery was yet left with no use till the early 2007, when the city hall of Orvieto decided to restore the structure and promote it under an intense project of restoration, aiming to respect and yet promote its historic and artistic value, aiming to realize a high-class hotel and conference center using its large rooms and open-sky cloister. In order to do so, there was a need to consolidate the entire structure, with the goal of maintaining its historic view yet reaching the current code standards for centers like the one wanted by the city hall. The design called for retrofitting all the superstructures, in particular the masonry vaults, floors and roofs in order to provide strength without increasing the masses, providing so a consolidation solution that could withstand the new Italian seismic code. It was then chosen to consolidate the vaults using unidirectional glass fiber sheets (painted in red in Figure 7).

Figure 7. Retrofit of the masonry barrel and cross vaults with unidirectional GFRP sheets.

In order to absorb possible lateral loads coming from seismic shocks (Orvieto is indeed in a highly seismic area classified as "Zone 2", being 1 the most critical), the project called for realizing corbel ring beams with masonry reinforced with unidirectional high strength steel sheets (FIDSTEEL Hardwire® 3X2-medium density tape).

Figure 8. Strengthening of the ring corbel masonry beam with FID-Steel Hardwire®.

Previous tests conducted at the University of Perugia, showed how this solution could be particularly effective since it provided the same level of strength of an identical reinforced concrete beam, commonly and wrongly so used in the past for this kind of retrofit, with the big advantage of having a highly reduced self weight of the retrofit solution.

Figure 9. Strengthening of masonry arches using pretensioned FID-ASLAN 100 GFRP bars.

For this particular strengthening solution it was chosen to adopt an epoxy matrix to impregnate the medium density UHTSS steel fiber sheets, to ensure best adhesion possible between the masonry bricks and create the ring beam of the desired strength and stiffness. The cloister of the convent was constructed with several porticos with arches that the new design wanted to conserve. Since the arches needed retrofit, instead of using classical externally bonded sheets that would have compromised the architectural look of the masonry, it was proposed to retrofit the structure using GFRP bars inserted following the scheme below (see Figure 9). In order to assure an active strengthening solution, the bars where pretensioned using a dynamometric spanner to control the stress induced in the bar. The prestress applied force accounted for all reduction coefficients indicated in the CNR-DT 200/2004 design guidelines, for fiber glass bars subjected to creep in aggressive environment. Operatively the retrofit consisted of drilling holes into the masonry with precise diamond blades, then positioning the bar into the hole with the prestressing and anchor head on each side, once the prestress force is applied, the hole is injected with fluid epoxy resin and once the resin is cured, the prestress force released and the bar cut. Finally to mask the hole, a colored plaster was applied on the surface of the masonry.

5 CONCLUSIONS

Several innovative FRP systems have been presented showing the different advantages that each of them can provide to designers and contractors involved in these types of upgrade. Three case studies, among the many realized using innovative materials have been described showing how these advanced materials can be used for strengthening and retrofitting reinforced concrete as well as masonry historical structures providing a surely more effective technical as well as economic effectiveness of the overall work.

Figure 10. Views of some of the most significant structures retrofitted using innovative materials in Italy and abroad: Milano-Royal Palace, Perugia-Marble fountain, Firenze-Generali Insurance, Rome-Koch Palace Bank of Italy, Perugia- Flaminia Viaduct, Mogadiscio-Italian Ambassy, L'Aquila-Faculty of Engineering.

6 REFERENCES

Casadei, P., Nanni, A., Alkhrdaji, T., and Thomas, J., (2005). "Behavior of Double-T Prestressed Beams Strengthened With Steel Reinforced Polymer", Advances in Structural Engineering an International Journal (ASE), Vol. 8, No. 4, pp. 427-442.

Casadei, P., and Agneloni, E. (2008). "Advance composites applications on historical structures in Italy: Case studies and future developments" 6th International Conference on Structural Analysis of Historical Construction, Bath, United Kingdom, July 2-4, 2008, ISBN Vol.2:978-0-415-48107-6.

CNR-DT 200/2004, 2004:"Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Existing Structures" Published by the National Research Council (CNR), Roma, pp. 164.

"Compositi FRP: Linee guida per il rinforzo strutturale" published by NCT Global Media Editore, 2002, ISBN 88-900892-0-2.

FIDIA s.r.l. – Technical Global Services, www.fidiaglobalservice.com

TEC.INN. s.r.l. – Innovative Technologies, www.tecinn.com

THE FIRST BRICK of high tech network, www.thefirstbrick.com