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THE PRESERVATION OF HISTORICAL MASONRY HERITAGE STRUCTURES USING ADVANCED COMPOSITE MATERIALS

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ABSTRACT

In the last two decades advanced composites (Fiber Reinforced Polymers) or FRP materials have gained worldwide acceptance for structural strengthening. Because of their attractive advantages, FRP materials are very appealing to be used for retrofitting heritage structures. The causes of degradation of historical structures include environmental degradation, displacements such are those from foundation movement, overloading caused mainly by seismic actions. Historical structures are usually lacking the design for lateral loads which makes them in need of retrofitting. Some of the salient features of composite materials include very high tensile strength to weight ratio. The light weight of FRP helps in maintaining the seismic properties of the structure. This review paper highlights the most important items that must be considered when rehabilitating historical structures. In this paper some selected FRP strengthened heritage structures are presented located in different places around the world in Egypt, Greece, Italy, Portugal, Peru and USA. Each case presents a unique intervention philosophy and different utilization of FRP materials in restoration work. Structural safety considering preservation guidelines to keep the historical value of the structure. Some of the key aspects concerning this effective structural strengthening method, are preserving the aesthetic of the structure through minimum invasiveness and reverseability, material compatibility and long term performance and optimal material selection. Although multiple field applications for strengthening heritage masonry structures with FRP currently exist, there is still an urgent need for extensive systematic investigations of rehabilitation of heritage structures and for establishing standardized guidelines and techniques for maintenance and rehabilitation of cultural heritage.

KEYWORDS: Aesthetic appearace, Advanced composite materials, Fiber reinforced polymers, Heritage structures, Masonry, Stone, Structural strengthening.

INTRODUCTION

Conservation, reinforcement and restoration of Architectural Heritage requires a multidisciplinary approach. Value and authenticity of Architectural Heritage are currently saved through advanced structural techniques. A high proportion of the World's Architectural cultural heritage were built in stone. Most of them are exposed to structural weakness resulting from various causes of deterioration. This is caused by increasing static or dynamic actions or the reduction of strength. This problem threatens both human lives and the cultural Heritage. FRP application is an ideal solution for the structure to resist dynamic actions for its very high strength to weight ratio they can also improve strength, stiffness and ductility dramatically (ACI 440.7-10). Masonry is a brittle material suited to carry compression stresses, when upgraded with FRP a new system is formed which can be characterized as a pseudo ductile materials system. This system behaves as if it is ductile even though the individual components of the system may fail in a brittle manner. Although there were fewer researches on the use of FRP composites in the retrofit of URM walls than that of RC beams and columns, some progress was achieved in understanding the basic mechanics and establishing design guidelines and preventing the premature peeling off mode of failure (ACI 440.7-10).

Still experimental and theoretical studies which address the problem of FRP strengthening for different types of masonry, in particular that dealing with heritage masonry structures and FRP strengthening of natural masonry, need some more efforts. Previous research results have shown that debonding of the FRP laminate from the masonry substrate is the controlling

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mechanism of failure (Abdul Rahman 2006) and may have a direct relationship with the porosity of the masonry unit. Finally, design recommendations for the strengthening of masonry heritage structures with FRP have to be developed.

SIESMIC RETROFILLIG OF MASONRY HISTORICAL BUILDING

The static and seismic retrofitting design for masony historical building, has to follow a right hierarachy of intervension, taking into account the importance of improving the seismic behavior of the masonry structure (Asteris et al 2015). It is necessary to guarantee a closed box behavior for the whole structural body or in case of complex buildings to guarantee a closed box behavior of each building's wing. Thus it is fundamental to distinguish the intervensions for gloal behavior improvement from those related to local reinforcement. Asteris et al. (2015) propos a scheme of intervensions hiererichy and therefore a related design process and road map together with the explanation of a correct design philosophy of the static and seismic retrofitting of masonry buildings.

STONE CONSERVATION

The deterioration of stone is all too familiar to anyone who has looked closely at a historic stone building or monument. The majority of stones are subjected to gradual deterioration. External appearance may be sufficient in some instances, to detect deterioration, but they can be deceptive (Price 1996). It is not unusual to find a stone surface that looks perfectly sound, but that sounds hollow as soon as it is tapped. The complex phenomenon of stone decay and what's going on beneath the surface needs to be measured , and to be taken into consideration when using adhered fabrics.

MATERIAL COMPATIBILITY

A full understanding of the material compatibility between masonry units and the used composite material is essential for any conservation and restoration project. The characteristics of materials used in restoration work and their compatibility with existing materials should be fully established . Epoxy resins are applied to the surface of stone to provide effective bond between FRP and stone . The literature supports the use of epoxy resins to solve many problems in conservation of building stone treatment , they are recalled negatively as viscous, non-penetrating, crust forming, yellowing systems that, at best, are only useful as structural adhesives. Yet the success of numerous treatments relegates this reputation to only one class of epoxy resins and not the entire family . Epoxy chemicals are used to strengthen and protect weathered stone against further deterioration by a process known to conservators and conservation scientists as consolidation (Charles 1992).

TYPES OF TREATMENT IN HISTORIC PRESERVATION

The state of the art of historic preservation generally recognize four types of treatment: **Preservation**: which is stabilization or arresting deterioration. **Rehabilitation**: for restoring to service, includes alterations, but requires retention of character-defining features. **Restoration**: choosing a time or period of significance, and returning the structure to its state at the time in question. **Reconstruction**: depicting by new construction missing structures or features. SHPO's generally don't like reconstruction, but will allow it if the original state of the structure is adequately documented.

FRP APPLICATION

Brushing is a suitable application procedure for some types of stone. However, for many types of low-porosity stone, this method does not provide adequate penetration. The porosity of different types of stone plays an important role in the bond strength , and the depth of penetration of the epoxy , which depends on the nature of the stone, and the composition and viscosity of the consolidation system . Studies have shown that if a volume of liquid, rather than the thin film provided by brushing, can be maintained against a surface, very substantial penetration will result. Methods of application of epoxy to different types of stone can be driven from methods used for consolidation process (Charles1992) . While peeling off of FRP adhered fabrics have a high probability to occur while treatment of fresh stone, the much weaker, weathered stone is expected to take up resin and the peeling off decreases substantially considering a good consolidation process took place before FRP application . During the consolidation process the solvent evaporates, the consolidant penetrates deeply enough to reach undeteriorated stone and remains as a thin layer. This makes it suitably polymerized and bonded to the internal surfaces and between the stone particles. The product can be viewed as a porous "composite", this would be the ideal substrate for applying FRP.

LONG-TERM PERFORMANCE

FRP is a good structural solution , but we have to be sure that it will keep on performing well in the long run when exposed to the weather year after year. Accelerated weathering chambers are extensively used to simulate weathering but it is unsure that they will accurately reflect the long-term behavior of the structure 3. The best solution is to monitor various strengthened structures in order to obtain actual results. FRP materials are susceptible to degradation from ultraviolet radiation, particularly those that contain E-glass fibers or epoxy resin. Therefore, specifications require all FRP installations to be coated with a UV protective coating system. It is expected that recoating will be required during the life of long term repairs.

HISTORIC STRUCTURES AESTHETIC

One of the most important factors that should be considered in architectural heritage is the cultural value and aesthetic of the structure, which cannot be assessed by fixed criteria. Safety evaluation combined with an understanding of the historical and cultural significance of the structure should be the basis for conservation and reinforcement measures. Where urgent measures are necessary to avoid imminent collapse they should avoid minimal permanent alteration to the fabric. It must be clear that the value of each historic building is not only in the appearance of individual elements, but also in the integrity of all its components . Each intervention should be in proportion to the safety objectives, keeping intervention to the minimum necessary to guarantee safety and durability with the least damage to heritage values.

REVERSIBILITY

A very important advantage in the use of FRP adhered fabrics as an innovative method is the reversibility of the system. It can be easily removed and replaced with more suitable measures if new knowledge is acquired. Types of reversible FRP strengthening solutions include confinement reinforcement to masonry using unbonded strips, or intermittently bonded to masonry or FRP bonded sheets which are used as tensile reinforcement to masonry.

RESTORATION TECHNIQUE

According to ICOMOS guidelines (ICOMOS), repair is always preferable than placement , the choice between “traditional” and “innovative” techniques should be determined on a case-by-case basis with preference given to those that are least invasive and most compatible with heritage values, consistent with the need for safety and durability, FRP technique can be least invasive choice when compared to traditional technique for structural strengthening such as using steel or concrete kerbs, small x-frame steel braces inserted in zones under the windows , vertical FRP bars or ropes may be placed through drilled holes ideally near the corners of the masonry to eliminate vertical tensile stresses produced in the walls by high seismic actions.

PRESERVATION OF HISTORICAL STRUCTURES USING FRP

Over the past few decades, interest in preserving heritage masonry structures has led to the need of the development of appropriate architectural and structural methods. In historic buildings, interventions are a compromise between carrying out as little work as possible, so as not to interfere with the original concept of the building and the need to insure safety requirements. The following is a review of some selected heritage structures in which FRPs were used for rehabilitation. Each case presents a unique intervention philosophy and different utilization of FRP materials in restoration work.

The Comrehab Project, Lisbon (Portugal)
The Baixa Pombalina downtown area was built after the earthquake of 1775 .The main problems included building extra floors, alternations in ground floors by, weakening of walls and foundations, careless introductions of steel and reinforced concrete elements. It was aimed to improve the seismic behavior of old masonry building by protecting the residents lives in case of a relatively frequent medium earthquake prevention of collapse for the maximum earthquake Silva 2000. Old buildings, were either made of two layers of good quality stone enclosing a lower quality filling, or consisting of successive layers of stone laid with lime mortar.The suggested structural solution was using confinement connectors for providing adequate confinement and increasing the compressive strength Figure 1(a). Their function is to increase wall strength through bracing , capable of preventing its bulging through the relative displacement of its two faces . Under compression forces the laminate will tend to separate, consequently it will be prevented by the tension resistance of the connectors and tie rods. In order to increase the walls bending resistance both in plane and out of plane. FRP was designed as a composite material of high strength fibers, pre-impregnated with epoxy resin .The reinforcement laminate could be assembled “in situ” or prefabricated. Its function was to resist the tension and compression forces . FRP was applied in two layers that would work together, thus making a resistant membrane or laminate, in just one or in both wall faces. The fist layer, designated as bond ply, is made of flexible uni-directional stripes of fibers pre-impregnated with non-polymerized resin with appropriate out life. The width of the stripes varied between one and a few decimeters. These stripes,

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diagonally placed in the wall face, follow its irregularities, particularly the joints between successive stone or brick layers, which were previously enhanced and cleaned Figure 1(b) .

In relation to the traditional strengthening methods, this system presents the following advantages: Lower disturbance of the users which is particularly important in residential buildings . Lower intrusiveness in what concerns the original structure, of particular importance in architectural heritage buildings. After rendering the system it becomes completely invisible. The increase in thickness is irrelevant , in the order of a few millimeters only and can be hidden in the render thickness . Reversibility, of particular interest for architectural heritage. The connector plates Figure 1(c) could be disassembled, the tie rods could be removed, and afterwards the laminate could be cut and striped.

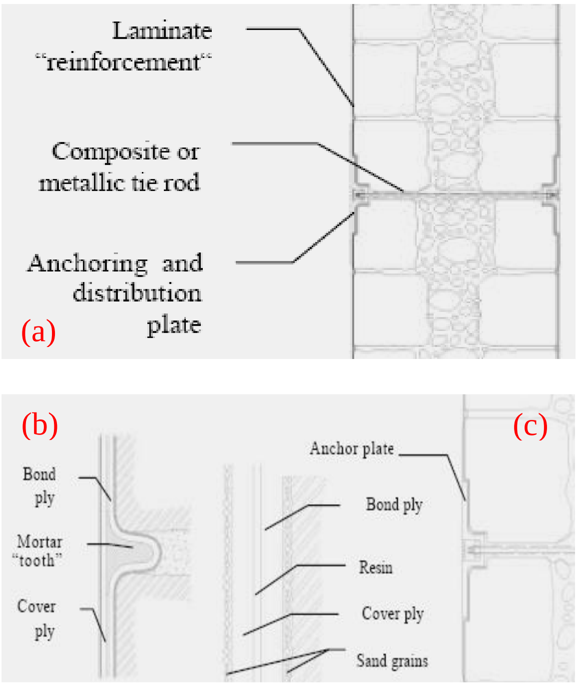

Figure 1 - Confinement Connector (a) , General and Adherent "Tooth" Detail (b)[10]

The St. Francis Basilica in Assisi (Italy)

It was built on an active fault line, Assisi was struck by two major earthquakes on Sept. 26, 1997, causing two large sections of vaulting of the 700 years old , upper church to collapse. The vaults included precious frescoes by two leading 13th century painters . The earthquake also caused large cracks and permanent deformation over all of the vaults of the basilica, leaving them in a very dangerous condition. The catastrophe received world-wide attention and subsequent restoration efforts received international assistance. The failure mechanism of the vaults close to the façade, resulted from the progressive loss of curvature of the ribs, then a "hinge" was produced in the middle and finally the rib collapsed, drawing the vault down Figure 2 (a). One of the urgent measures taken in the first month was applying bands of synthetic fibers over the cracks of the extrados. Then it was decided to use composite materials (aramide fiber, fiberglass and marine mahogany plywood) to build a series of very thin ribs on the extrados of the vaulting, following a typical Gothic design and leaving the original structure clearly visible Figure 2 (b). The ribs were fashioned in situ so they could be shaped adjusting their height in relation to the deformation of the underlying vaulting. Thus, in order to control the larger deformations of the vaults, the composite ribs system was connected to the roof structure by a system of suspension steel bars with helicoidal springs not preloaded. The ribs were formed out of fabric made of aramidic fibers, and bonded with the epoxy resins around a wooden core , with longitudinal strips of aramidic fibers on the intrados (subjected to tensile stress) and glass fibers on the extrados (subjected to compression stress). The aramidic fiber fabrics completely covered the wooden core and then extended out onto the extrados of the vaulting and are bonded to it. The reinforcement had to be connected to the masonry of the vaulting in part by directly bonding it with the epoxy resins and partly by pins driven into the masonry. These pins were made of unidirectional aramide fiber and epoxy resin driven into the body of a brick. The tests revealed the rib prototypes' remarkable capacity for retaining resistance after surpassing the elastic limit and the yield point, with good ductile performance even after several loading cycles. The restoration project coasted about $60 million . The amount of money spent on the project was justified, according to officials, because re-opening the church to tourists would help improve the economy, which had crumbled along with the basilica.

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Figure 2 – (a) The Failure of the Vaults(a) and construction of the ribs (b) Strengthening of the St Francis Basilica in Assisi [10]

El-Eini dome and Sodoun dome (Egypt)
Eight hundred year old historical structures strengthened using CFRP in Egypt by Mahfouz and Rizk 2003. Bricks suffered from severe deterioration, and the domes were seriously cracked. Some cracks were in the body of the domes only, which made the domes behave like a set of isolated arches. Other cracks extended to the supporting ring beams and resulted in a probable loss of equilibrium that if left without repair would have definitely led to a total collapse of the historic structures. **El Eini Dome** Figure 3(a) is a historic spherical brick dome resting over cylindrical brick walls , it suffered from sever multiple penetrating cracks that occurred in the body of the dome. The dome in the cracked condition behaved like a set of isolated arches jointed at the top portion of the dome. In order to maintain the structural stability, the supporting cylindrical portion of the structure was confined using two layers of CFRP sheets . Due to the severity and the large number of the cracks in the body of the domes, it was decided to use additional confining at various levels of the dome. Although, all the repair work for the El-Aini dome fell under the contact critical category, special treatment of the surface of the dome using fiber cement mortar was performed at the locations of CFRP due to the poor condition of the dome surface. Brick powder was used as a topcoat on top of the CFRP, resulting in no alteration to the shape, color, and the configuration of the historic structure.

Sodoun brick dome *(Egypt)*
The dome is shown in Figure 3(b). It is a historic brick dome having an irregular external configuration. It was supported by a brick cylindrical wall resting on the top of a number of brick posts suffering from sever multiple penetrating cracks. The cracks occurred in the body of the dome and in the supporting wall resulting in structural instability. In order to maintain structural stability, the supporting cylindrical portion of the structure was confined by installing two layers of CFRP wrapping sheets. Due to the irregular configuration of the outer surface of the dome, the stitching repair method using both U shaped CFRP sheets and CFRP laminated inserts was used.

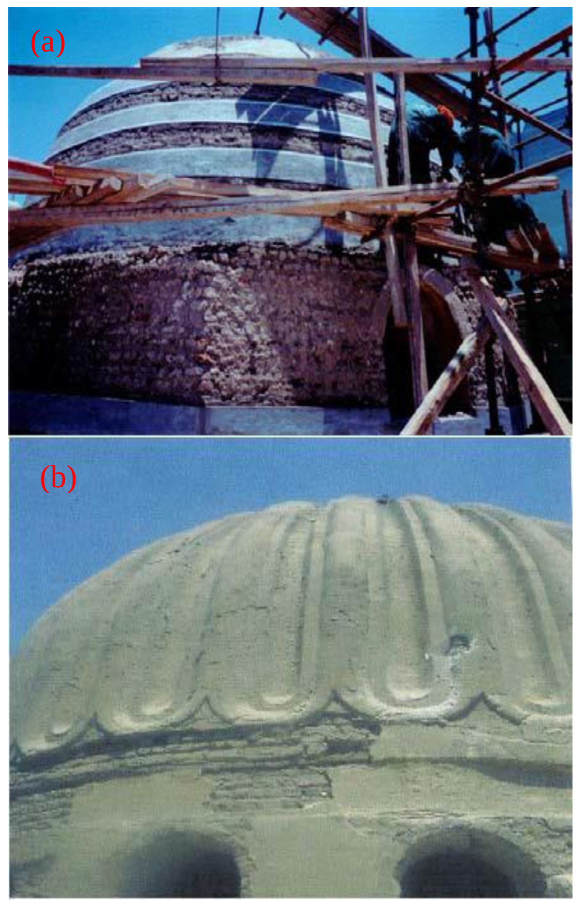

Figure 3 – (a) El Aini Domes (b) Soudoune Dome after Being Repaired Using CFRP[17]

The Church of Panaghia Faneromeni, **Egion, *(Greece)*** FRP tendons were used successfully in strengthening Figure (4). This was conducted by Triantafillou & Fardis. The authors presented detailed concepts, models and analytical results on the applicability and effectiveness of unbonded FRP tendons used to apply circumferential prestressing to the external walls of historic masonry buildings Figure 4. Their results demonstrate that the two transverse confining stresses applied by the FRP tendons increase the strength (under both gravity and horizontal loads) of masonry substantially Triantafillou, T., 2004.

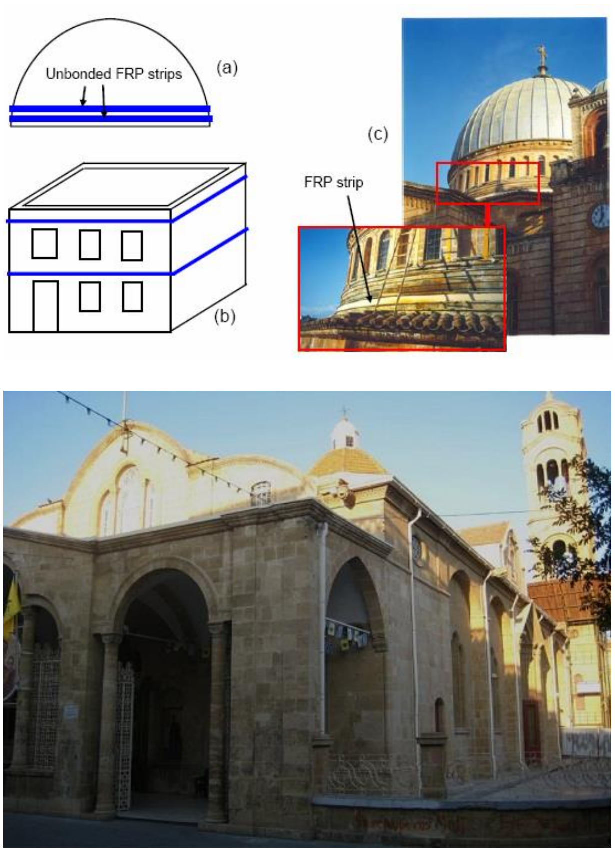

Figure 4 - Use of FRP Tendons in the Church of Panaghia Faneromeni, (a), (b), (c), Egion, Greece[21]

The cathedral church of Arequipa, (*Peru)*

It was first built in 1629. Due to the earthquake of June 23, 2001, that affected most of the southern part of Perú, the towers of the cathedral of Arequipa, built integrally with a volcanic stone called sillar, suffered extensive damage. As a consequence, the left tower partially collapsed, whereas, the right tower remained standing but in an unstable condition (Torrealva et al. 2003). Several reasons make the cathedral the most representative building, it is the highest building in the urban downtown, which is located in the heart of the city, and it is built with sillar. Actually it is the silent witness of important historical events. It is one of the most important classical monuments of Perú. The left tower suffered the collapse of the third and part of the second body; thus, the complete reconstruction of these two bodies was required. The right tower suffered extensive damage in the second body, losing part of its mass, and finally staying in an unstable equilibrium condition. FRP composites were selected for the rehabilitation project of the cathedral of Arequipa by Torrealva et al. 2003. The reinforcing strategy is described of the masonry right tower of the cathedral with CFRP laminates , which were used to provide tensile strength and confinement to the central core of the tower. An internal steel structure was placed in order to stabilize it for possible aftershocks. It was decided to leave the internal frame in place so the dismantling of the second and third body of the tower was not necessary. The proposed structural intervention consisted of placing additional reinforced concrete columns at the bottom of the tower, next to the pillars, and the rebuilding of the missing part in the second body. The second body was reinforced with CFRP laminates, which were used to provide tensile strength and confinement to that section of the tower. After completing the CFRP installation, carved stones were placed on top of the laminates to keep the original appearance. The reinforcing configuration consisted of vertical CFRP strips . To provide continuity in the section of the second body where a change of cross section and stiffness existed. To restrain the lateral expansion of the second body under axial loads caused by an earthquake, it was determined to place CFRP laminates in the hoop direction. The splice length was staggered along the height to prevent having a weak area prone to debonding of the laminates. A new masonry wall was built with carved sillar blocks on top of the laminates to keep the original appearance of the tower. It was required to anchor the CFRP reinforcement. As part of the overall rehabilitation program an RC ring beam was planned to be built in that region to provide confinement. Thus, it was decided to anchor the FRP reinforcement around that beam. The geometry of the tower was modeled with a commercially available CAD program and the frequencies and vibration modes were computed using a commercially available finite element program, the dynamic analysis of the towers was performed independently of the main structure and with a fixed base as a boundary condition. A static analysis was also performed with horizontal forces .The results of the analyses indicated that the location of the high concentration of stresses was consistent with the damage observed in the tower.

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Figure 7 - Towers of Arequipa cathedral after earthquake, (a) Left tower, (b) Right tower[22]

James E. Flood historic building in ***San Francisco (USA)*** Figure (8) involved the main problems of removing sheet metal cladding that was installed, restoring the structure's original, hand-carved sandstone arches, cornices, parapets and balusters. These ornaments were eliminated by a tenant who, 40 years ago, opened up a store on the bottom three floors of the building, removing the building's original hand-carved ornamentation to properly install the sheet metal. Polymer concrete and GFRP were used to retrofit the building . Most of the molds for the cornices and arches were made from the building's original 1903 architectural drawings; some were made directly from existing ornaments. Materials used to make the molds included urethane rubber, FRP and wood materials, depending on the required shape . GFRPs were combined with polyester resin, and hand-laminated into open molds to make the cornices and arches. This combination of materials gave the outer surface of the cornices and arches the appearance of the original sandstone surface. While the cornices were made entirely from FRP, the arches required additional assembly. Once the fiber glass shell laminates were fabricated, the arch panels were anchored to a manufactured tubular steel frame. The frame acted as an intermediary between the fiber glass arch panel and the structural steel of the building. It also helped to keep the panels stiff and simplified their installation . The FRP approach proved to be a light-weight, realistic solution to this challenging renovation. This unique use of FRP in this project earned William Kreysler & Associates the California Preservation Foundation Annual Design Award of 1994, as well as the Composites Fabricators Association 1994 Ace Award for Composites Excellence.

Figure 8 - The historic James E. Flood building in San Francisco USA

Consolidation And Seismic Improvement Of S. Siro Pumping Station, St. Benedetto Po, Mantova *(Italy)*[18]

The plant, which dates to the early Thirties , hosts a battery of 8 lifting pumps for lifting water and stands as a strategic the defense of the territory against the floods of the River Secchia and the flooding of the upstream basin. The building shows a rectangular plant (92.4 x 15 m) and has a flat roof on two levels. Two medium intensity earthquakes in May 2012 revealed damages related to construction details and building vulnerability (transverse joints causing separate structures with different stiffness against horizontal actions, insufficient connection and reinforcement of R.C. beams supporting the roof). In order not to alter the characteristics of the cultural heritage building with too invasive interventions, the design was aiming to achieve an overall improving of the seismic behaviour, not the adjustment, planning to relocate the strategic function of the plant; it involves these works: Reinforcement of masonry parapets on the roof and their anchorage to the roof slab; On the roof, introduction over the structural joints of shock-transmitters and shear connections to block relative displacements in transversal direction; Over the roof, realization of a plane bracing system made of R.C. beams and steel trusses and rods; Ligature of the r.c. pillars placed on the perimeter of the pump room to the adjacent masonry walls with stainless steel bars Localized repairing of masonry and concrete cracks; Localized reinforcements with FRP stripes, this work took place from 2012 to 2014.

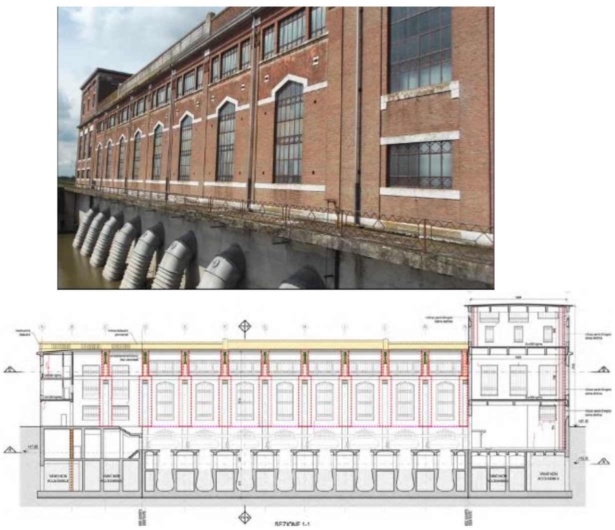

Figure 9- Siro Pumping Station, St. Benedetto Po, Mantova (Italy)

Restoration of The Holy Crown's Church, Vicenza *(Italy)* [18]

The church was built in 1260 in the Vicenza city. Since the 1303 was a court of the medieval inquisition and after it hosts tombs of influential people of the city. The intervention concerns the restoration of all the surfaces and the decorative paintings both in the internal and external parts, the rehabilitation of distributive and functional spaces connected to the church and the replacement of all technical plants. From a structural point of view, a large and diffuse series of interventions has been done with two aims: the first was the local consolidation of damages and degradations sprawl over the church and the second was the improvement of the seismic behaviour achieved by retrofitting interventions. The techniques were both traditional and innovative. The latter regards the use of FRP and stainless reinforcements. The repairing of cracks with 'scuci-cuci' technique by brick and mortar made with hydraulic lime and the recover, or when necessary the substitution, of damaged timber elements was designed and accomplished according the strictest restoration guidelines and criterions. Those interventions have been studied to have an high durability and they were as much reversible and simply as possible.

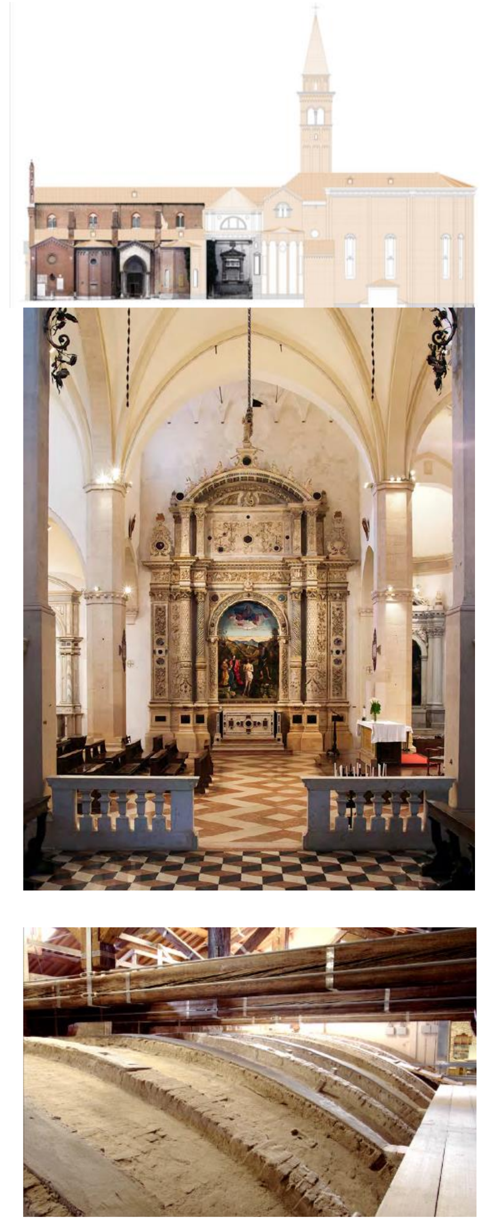

Figure 10- The Holy Crown's Church, Vicenza (Italy)

Restoration of Scaligera Arks In Verona *(Italy)* [18]

The family which reigned on Verona's city in the medieval age created a groups of Scaligera Arks that are monumental tombs of the regnant. The interventions were on two of them: once on the Cansignorio della Scala ark and the other on the Mastino della Scala one. The first is the Cansignorio della Scala's ark, it dates back on about. It is chronologically the latter and it is a precious demonstration of the extreme gothic style in the Padan area. Form a constructive point of view it shows as a complex sculpture made by Candoglia marble. The structural interventions, carried out from the 2006 to

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2010 concerns the improvement of the behaviour and the consolidation of the degradations and damages. The main concept was the minimum intervention with simple and localized insertion of highly durable advanced (stainless steel ties, titanium bushing and FRP) with the less number of drillings. Moreover the final intervention is low visible and completely removable. An important role was played also by the continuous SHM, it is active since the design phase, and still working on site. The role of this technology is manage the safety conditions of the monument with the minimum intervention on heritage, hence preserving as much as possible its significance. The intervention on the other ark regards strengthening of the horse leg was done by means of FRP.

Figure 11 - Restoration of Scaligera Arks in Verona (Italy)[18].

Development of an Anchorage System for FRP Sheets in Masonry Walls

One of the first experimental work that proved sucsess for anchoring FRP sheets in lime stones masonry walls were performed by the auther of this paper Abdul Rahman et *al.* (2005) ; (2006) ; (2007) in which the detailed procedure is explained and promising results were obtained for anchoring FRP sheets in stone to enhance the out of plane performance. The stone surface was brushed to install the sheet. For the anchored specimens , holes were drilled at the required locations then cleaned by vacuum . GFRP strip(s) were installed to the stone surface by wet lay up technique, taking into consideration not to cover the predrilled hole, To improve bond capacity of the GFRP sheet anchor spikes were developed with plain fibers. FRP anchor spikes were prepared in the lab using dry bundle of GFRP sheet bundle dry glass fibers together later impregnated with saturate thoroughly. Next, the impregnated fibers were covered with a tape around the steel bar and left to cure in ambient temperature. The leftover length of the anchor was used for bonding. With the same resin used for vertical strips, the spikes were inserted into the predrilled holes. Installation of GFRP sheets and anchors and spreading the dry fibers portion to be attached to the outer surface of the strips then fully impregnated with epoxy are shown in Figure (12). This work concluded that anchorage of GFRP sheets to limestone masonry is essential for preventing the premature failure due to GFRP debonding and increasing the ultimate out-of-plane capacity and ductilityof masonry walls.Using GFRP anchor spikes was proved to be is an effective anchorage method for GFRP sheets to limestone masonry. However reduced intrusive methods were still needed.

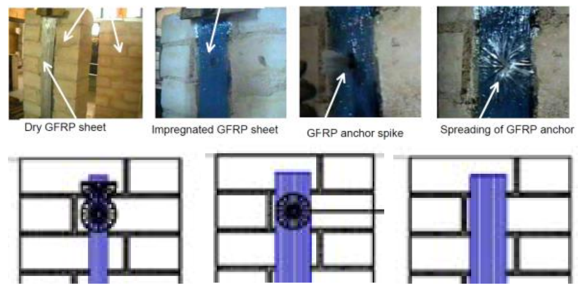

Figure 12 - Installation of GFRP sheets and GFRP anchor spikes using different configurations[1,2,3,4].

Reduced Intrusiveness Seismic Strengthening Techniques in Masonry walls

Several tradisional strengthening methods for masonry walls have been developed ACI 2007; CNR 2004; Jifu et al 2007). One of the low intrusive methods using FRP materials to suite historical structures is developed by (Cardoso et al. 2008). GFRP is chosen as sheets that is embedded into epoxy matrix on site allowing for reinforcement strips to follow deliberately created grooves. The proposed strengthening technique for traditional load bearing stone masonry walls typically 50-80 cm thick consists in the application of GFRP composite strips on one or preferably on both wall faces, connected to the masonry substrate through epoxy resin which also forms the matrix and mechanical anchorages. The anchorage system prevents slip and debonding of the GFRP composite strips from the masonry substrate and increases the wall lateral confinement and therefore its compressive strength. As a result, the reinforcement system has a double effect on masonry walls increasing bending strength and ductility for out of plane loads; and improving shear and compressive strength, for inplane loads. The strengthening technique as tested by Proença et al 2012 was found to be extremely effective, allowing high tensile stresses to be developed in the GFRP composite strips. These high tensile stresses are a consequence of the effectiveness of the anchoring technique and details, indirectly leading to different premature failure modes.

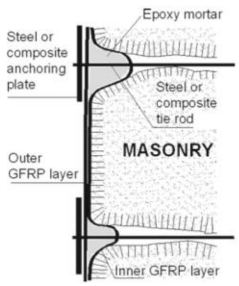

Figure 13 - Detail of the GFRP double layer reinforcement and anchorage system[8]

SUMMARY

The problem of keeping aesthetic appearance was treated in each of the previously mentioned projects in a different way .While in the St Francis Basilica of Assisi the construction of very thin FRP ribs on the extrados of the vaulting, left the original structure clearly visible[5]. For El-Eini domes in Egypt (Mahfouz and Rizk 2003) a special powder was made of the same type of the brick and it was used as a topcoat on the CFRP resulting in no alteration in shape color and configuration of the historic structure. In the Church of Panaghia in Greece unbonded strips color-matched with the underlying masonry were used (Triantafillou 2004). After completing the CFRP installation in the cathedral tower of Arequipa In Perú , carved stones were placed on top of the laminates to keep the original appearance (Torrealva et al. 2003). In The historic James E. Flood building in San Francisco, FRP was used in a unique way (Composites Preserve Architectural Heritage FRP Composites 1995) from the architectural point of view . It was hand-laminated into open molds to make the cornices and arches. This combination of materials gave the outer surface of the cornices and arches the appearance of the original sandstone surface.

CONCLUSIONS

FRP materials are proving to be an excellent alternative for rehabilitation masonry heritage structures, they provide additional strength and ductility to resist static and dynamic actions which is often the main cause of damage and collapse of historic buildings. Through the previous work it was found that FRP is a structural material that can be used in various innovate ways to strengthen heritage structures. This could be by forming very high strength structural elements with limited sizes and negligible weight . FRP anchors could be manufactured and applied to the body of the bricks to improve the bond between FRP and masonry. Less intrusive methods using FRP materials are developed. FRP bonded or unbonded sheets and FRP tendons provided a good , reversible and non invasive strengthening solution for historic masonry walls and domes.

RECOMMENDATIONS

Monitoring the behavior of the FRP retrofitted structures must be given a particular attention, in order to obtain information about long term behavior of this strengthening procedure which will help in the development of standardized guidelines and techniques for maintenance and rehabilitation of cultural heritage using advanced composite materials. More research efforts are still needed to benefit from the attractive advantages of advanced composite materials towards the development of more creative procedures of reduced intrusiveness seismic strengthening techniques.

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