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Practical applications of fiber reinforced polymers in retrofitting of RC and masonry structures

Engin Cuneyt Seyhan
Regional Application Manager Europe, Master Builders Solutions, *engin.seyhan@mbcc-group.com*

Abstract

The aging building stock is turning to be an urging problem for Europe, and it costs even human lives in some cases. Significant part of this building stock along with infrastructure were constructed with substandard characteristics such as poor-quality material, insufficient flexural strength, wrong reinforcement details and improper design of structural system. On the other hand, Europe has highly seismically active zones where devastations are inevitable after even moderate earthquakes. In the light of these facts, countless structures are in need of retrofitting, particularly in seismic areas, while high costs, disturbance to occupants, historical heritage and environmental restrictions are major obstacles for retrofit interventions. Many substandard reinforced concrete (RC) and masonry structures should be seismically retrofitted to reduce their vulnerabilities against earthquakes. Financial constraints, disturbance to the occupants and disruption of functions of the structures are the main obstacles for proper seismic retrofitting of these substandard existing structures. Traditional retrofitting methods such as concrete and steel jacketing, are not applicable in many cases due to high disturbance to occupants and long duration of retrofitting, which may be very critical for commercial, industrial and public buildings. Besides, these methods are also not preferred for historic structures due to the incompatibility of the concrete with traditional lime-based mortars (e.g. Roman cement) and the heavy visible impact to the architectural design. In the last two decades, use of fiber reinforced polymers (FRP) in construction industry has become quite common. Academic researches go back even a decade earlier. FRPs offer practical and innovative solutions for seismic retrofitting due to their lightweight, high tensile strength and noncorrosive character. Besides, the disturbance to the architectural design of the structures are quite limited when they are retrofitted with FRPs. This opens new possibilities for masonry buildings and historic structures belonging cultural heritage.

Key words: FRP reinforcement, reinforced concrete, masonry, retrofitting, seismic

1 Seismic hazard in Europe

A significant part of Europe is located on a highly active seismic zone, where devastating earthquakes occur periodically. Especially Turkey, Italy, Greece, Iceland, Albania, North Macedonia, Romania, Montenegro and partially Spain, Croatia and Bosnia carry significant earthquake hazard. Based on the past experiences gained in these countries, it can be noted that even moderate earthquakes in magnitude can be fatal when they happen in rural areas. Although the magnitude of an earthquake is measured based on the energy release, the intensity and devastative power of the earthquakes are related to the structures subjected to the motion. There is a diverse picture in Europe when it comes structural safety since social and economic development differences are sharp even between some neighboring countries. But there are also some common facts which is valid for almost all countries in Europe. Majority of the existing building stock including infrastructure in Europe was constructed on the ruins of second world war in a rush and under financial restrictions and with pour technology & practice. Many of the reinforced concrete structures were constructed with substandard characteristics. Lack of earthquake resistance design, poor quality concrete, wrong reinforcement details and insufficient flexural strength are among the most common deficiencies. Majority of masonry structures were also constructed in relatively old times without any earthquake resistance design aspects. Furthermore, traditional residential buildings located in the rural areas were constructed without consideration of construction codes, quality control processes, simply without any kind of basic engineering services. This disturbing fact significantly increases the fatality rate of the earthquakes in Europe. Recent earthquakes occurred in Croatia, Italy and Turkey prove that the vulnerability of the building is the key for devastating power of the seismic actions.

2 Damages to reinforced concrete structures

Reinforced concrete (RC) structures are relatively rigid structures when compared to steel and wooden structures. The limited deformation capacity RC structures results with visible damages after earthquakes with certain magnitude. These damages can be classified under two categories based on the structural relevance of the affected member.

2.1 Damages to non-structural members

The first damages are commonly observed in non-structural rigid elements such as renders and infill walls. Cracking on the render is the initiation of the earthquake damages. These cracks then propagate through the connections of separation wall with beams and columns. These damages are not considered as a threat to the structural system of the building. They can be cosmetically repaired, and the building can gain its functionality back quickly.

The second phase in the damage propagation is the damages occurred in the infill walls. The type of the damage varies depending on the material used to construct the wall. Cross type cracks and spalling are the most common damages seen on these elements. In addition, there might be damages around the doors and windows mounted in the walls or the wall can fall partially or completely out of plane when not constraint tightly by surrounding RC frame.

2.2 Damages to structural members

Columns, beams, slabs, shear walls and foundation elements are the main load bearing elements of the reinforced concrete structural system. Damages occurred on these elements must be observed carefully since these damages are the signs of weakening in load bearing ability of the structure.

Columns are the most critical structural elements which affect directly the seismic behavior of the buildings. After having severe damages to certain number of columns (including column-beam joints), the building can easily loose its vertical stability during the earthquake and eventually collapses. Flexure and shear damages are the most common damage types for reinforced concrete columns. Lack of transverse reinforcement and insufficient flexural reinforcement in combination with poor concrete result with inadequate shear and flexural load capacity. In addition, buckling can be also observed in slender columns as a damage pattern.

Similar to columns, shear and flexure damages are also the most common damage patterns for reinforced concrete beams. Shear cracks use to appear near supports while flexure cracks are cumulated in the central section of the beams. Since earthquake loading has a transverse nature, shear cracks appear in cross shape in effect of flexure. Unlikely to the columns, failures in the beams generally are not heading the buildings to a total collapse. Moreover, it is even desired to have plastic hinges appear on the beams where the earthquake energy could be dissipated without demolishing of the building. Due to this phenomenon, columns are recommended to be designed stronger than beams.

Dimensional stability and design aspects make slabs, shear walls and foundation elements as relatively less affected structural members from earthquake motions. Nonetheless, still shear damages can be observed on the shear walls and flexure and punching damages may occur on slabs after a strong ground shake.

3 Damages to unreinforced masonry structures

It has been observed that countless masonry buildings were collapsed or severely damaged even during moderate earthquakes. There are several reasons lay behind his fact. First of all, there is a huge variety of masonry buildings constructed in different times and with different materials & techniques. This makes the damage assessment more complicated than the reinforced concrete structures which are relatively homogenous by their materials and building techniques. Despite all these difficulties and complexity in damage evaluation of the masonry structures, the main weaknesses can be sorted as poor material characteristics (e.g. mortar), inadequate brick unit, weak load bearing walls, wall openings, slender and unsupported walls, lack of vertical confining elements, soft story, insufficient shear base capacity, rigid and heavy structure, irregularities in plane and vertical directions.

4 Retrofitting reinforced concrete structures

Retrofitting need of reinforced concrete structures can be cumulated under three main bullet points: strength, stiffness and ductility. As a result of missing even one of these three points in a concrete structure results with significant damages. For bringing seismic resilience to the weak structures, they can be retrofitted to gain sufficient strength, stiffness and ductility.

There are different methods available in the construction industry to retrofit the buildings. Concrete and steel jacketing are the traditional methods, widely used for many years. But FRP composites have become very popular in the recent years due to the innovative solutions which they bring to overcome the common challenges with traditional methods. FRPs are light weight, high strength, easy to use, non-corrosive and far less disturbing to the occupants and architectural design when compared to traditional techniques.

4.1 Confinement of columns

Energy dissipation capacity of the buildings is one of the key performance parameters for earthquake resistance. The huge energy created by the shaking of the structure due to ground motions needs to be dissipated with the deformations occur on the same structure. Therefore, deformation capacity of the structure is the key for resisting to seismic actions. Limited deformation capacity may cause total collapse or severe damages to the buildings when it is combined with insufficient strength.

Columns play a key role for adequate deformation capacity of the RC buildings. Strong and ductile columns show large deformations under seismic actions which helps buildings dissipating the energy for structural survival. One of the most efficient ways to increase the ductility of the columns is wrapping it with FRP fabrics. These wraps can provide passive lateral pressure which results with increase in compressive strength and deformation capacity of the member.

FRP fabrics are available in different type of fibers, e.g. carbon, glass, aramid and basalt. Carbon fiber reinforced polymers (CFRPs), which have relatively high modulus of elasticity when compared to glass, aramid and basalt fibers are more efficient in confinement due to creating much higher passive lateral pressure. FRP fabrics, due to easiness of shaping like an ordinary textile cloth, are suitable form of composite materials for confinement of columns. FRP fabrics must be wrapped around the columns tightly avoiding voids between fabric and concrete surface as seen in Fig.1.

Figure 1. Wrapping a rectangular concrete column with uni-directional CFRP fabric

Since confinement is a contact critical application, the strength of the concrete substrate is not much critical as smoothness of the surface. Irregularities on the concrete surface cause stress concentrations at single points and this may lead premature fractures on the FRP wrap. It is recommended to limit the maximum size of irregularities down to ±1mm. Another key point in this application is using a high strength, low viscous, durable material as an adhesive for gluing FRP fabric on the concrete surface. Since FRP fabrics are weaved from perfectly dry fibers, the composite material can be created only on the job site. The selected adhesive not only bonds the fabric onto the concrete surface, it also creates a matrix around the dry fiber filaments and takes an important role on load transfer between the individual fibers. This is crucial for achieving successful composite effect. Otherwise, the loads applied to concrete element, cannot be carried successfully by FRP wrap.

4.2 Shear strengthening of columns and beams

As it has been stated before, deformation capacity of the structure plays a key role for earthquake resistance. High deformation capacity brings higher energy dissipation ability and thus the structure can survive even the extreme seismic actions. This behavior can be achieved when the structural members, especially the vertical elements behave ductile. Brittle structural members limit the total deformation capacity of the structure and eventually end with premature failures in very early stages of the ground motion. This result either with severe damages or total collapse of the structure.

The forces applied to a building during an earthquake can be idealized as shear forced applied to each floor and shared by the vertical structural elements (columns and shear walls) proportionally with their rigidity. Therefore, the shear capacity of the vertical elements is quite critical for bearing the lateral forces occurred due to seismic motions.

Insufficient and wrong detailing of transverse reinforcement is the most common practice which limits the shear strength of the columns and beams. In order to increase the shear strength of these structural elements, FRP fabrics can be externally applied on the concrete elements as and additional transverse reinforcement. The alignment of the fibers can be same as existing transverse steel reinforcement. Since the shear strengthening of concrete elements is considered as bond critical application, it is crucial to have strong adhesion between FRP and the concrete. Concrete surface needs to be prepared carefully prior to FRP application. In case of poor concrete surface, it is recommended to do priming to enhance the substrate or even replacing the weak concrete cover with high strength structural repair mortars. After achieving sound, strong and regular surface, FRP fabrics can be applied on the concrete elements by using same adhesive as confinement application as seen in Fig.2.

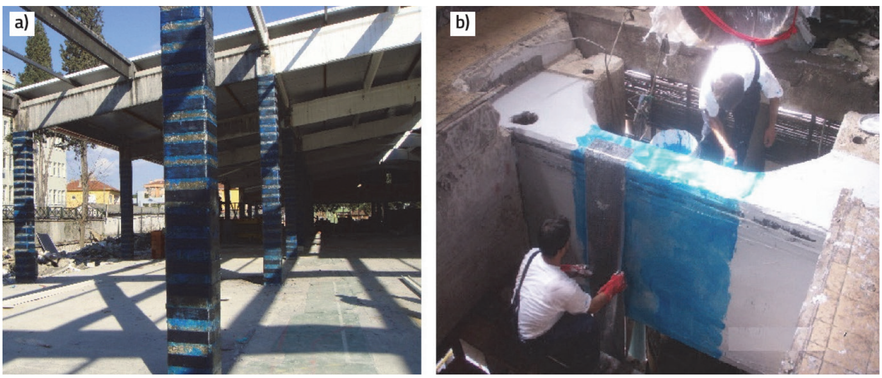

Figure 2. a) Shear strengthening of RC column; b) Shear strengthening of RC high beam

4.2 Flexural strengthening of beams and slabs

Beams and slabs are also critical elements of the structural system of the reinforced concrete buildings. Their impact on the seismic performance may not be as high as vertical elements but still they influence the energy dissipation capacity of the structure. Especially beams have a significant impact since they are directly connected to the columns and can influence the behavior of the columns.

In the basis of the earthquake resistance building design, engineers design the columns stronger than the beams to force the plastic hinges occur in the beams instead of columns. Plastic hinges occur on the beams allows the buildings deform safely and dissipate the energy. In the opposite case, the building loses its stability and collapses when enough number of plastic hinges occur on the columns. Besides, plastic hinges can only occur when the beam reaches its moment capacity before its shear capacity is reached out. Shear failure of the beam is quite brittle, and it is not desired for seismic resistivity. On the other hand, the flexural strength of the beams should be high enough for increasing the amount of the energy dissipated at the plastic hinges.

FRP fabrics and prefabricated (pultruded) FRP plates are commonly used as externally applied flexural reinforcement for horizontal structural elements. This application is also classified as bond critical application and thus it requires a strong and sound concrete substrate. Due to practicality and high tensile capacity, CFRP plates are preferred for flexural strengthening of beams and slabs. When compared to steel plates, it is much easier to handle and apply FRP plates due to their flexibility and light weight. FRP plates can be bonded to the concrete substrate by using a high performing epoxy based thixotropic adhesive which does not require further fixation until curing. The cohesiveness of the epoxy adhesive is high enough to keep the FRP plates stay bonded overhead during hardening, Fig 3.

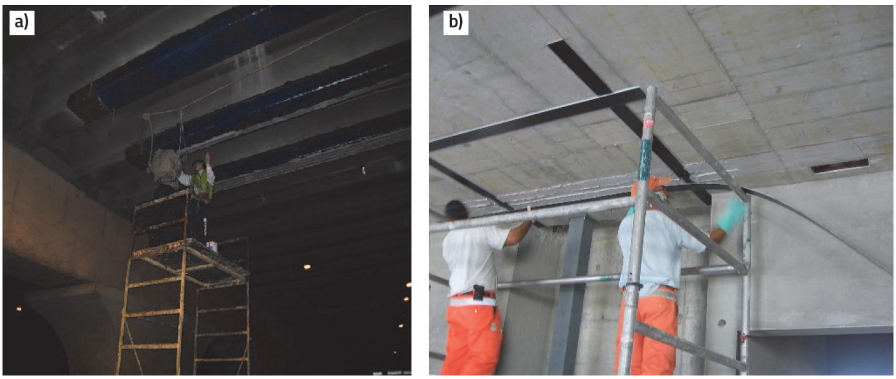

Figure 3. a) Strengthening of RC beam with CFRP plates; b) Strengthening of RC slab with CFRP plates.

4.2 Strengthening of infill walls

Although the interior walls of the RC structures are not designed as load bearing elements and thus not considered as a part of structural system, it has been experienced during the earthquakes that these walls can contribute to the lateral load bearing capacity and reduce damage by limiting interstory drift deformations when they are strengthened. The use of diagonal CFRP fabrics to integrate the existing infill walls with the surrounding reinforced concrete columns and beams as shown in the Fig. 4 has been proved to be a practical and effective solution for retrofitting seismically deficient RC frames.

Figure 4. Strengthening of infill walls by using diagonal CFRP fabrics

5 Retrofitting masonry structures

Masonry structures are more prone to extensive damage followed by failure and collapse than reinforced concrete structures when subjected to seismic motions. There are several reasons leading to this result and the lack of tensile reinforcement can be noted on top of the list.

FRP composite materials have become popular recently in retrofitting of masonry structures especially after the increase in the number of researches supporting the effectiveness of these systems. Available literature on masonry proves the efficiency of FRP systems based on their advantages related to easiness of application, relatively lower installation costs, less disturbance to occupants, improved durability when compared to steel, flexibility of use, and minimum changes in the member size after retrofit. Moreover, when the earthquake forces are considered as they are created by the mass of the structure, the impact of the FRP composites used for retrofitting on the dynamic properties of the structure remain unchanged because the addition of weight is almost negligible.

FRP fabrics are widely used for flexural and shear strengthening of the masonry walls. In this way, not only the lateral load capacity of the masonry structure is increased, but also walls can be strengthened against out of plane loads which can commonly cause casualties even during moderate earthquakes. Besides, the minimized change in the retrofitted member size is a significant benefit for historic structures. A practical example can be seen in Fig. 5 before and after retrofitting an old museum building with CFRP fabrics.

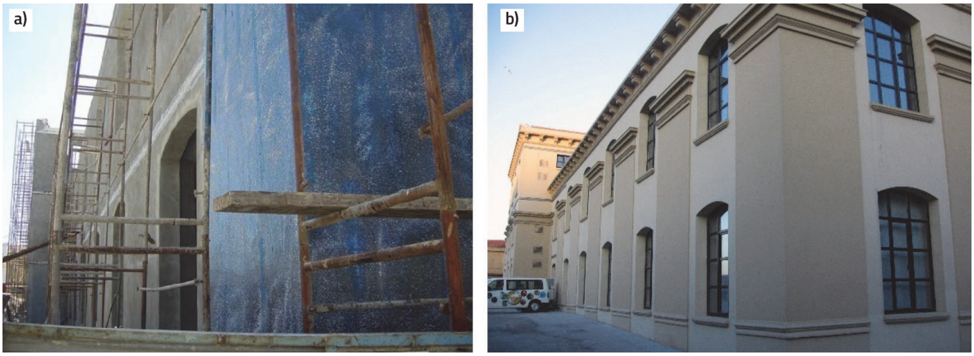

Figure 5. a) Retrofitting masonry walls with externally bonded CFRP fabrics; b) Final look of the building

Similar to the masonry walls, arches, domes and vaults can be also retrofitted effectively by using FRP composites. Externally applied FRP fabrics and plates, or near surface mounted FRP strips and bars are the most common methods to retrofit the circular shaped masonry members. With these techniques it is also possible to keep the impact on the architectural design minimized which is very crucial for preserving cultural heritage. A clear example for protecting cultural heritage by using FRP composites can be seen in Fig. 6.

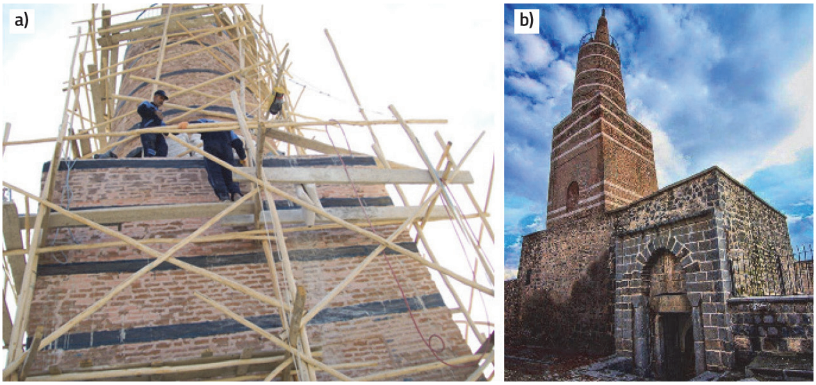

Figure 6. a) Retrofitting a minaret of 12th century mosque by using CFRP fabrics; b) Finished work.

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