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Fiber reinforced polymers for structural retrofitting: A review

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Abstract

Many structures located in seismically active zones are not capable of withstanding seismic action according to current codes and provisions. Furthermore, recent earthquakes in urban areas have clearly demonstrated an urgency to upgrade and strengthen these seismic deficient structures. Significant amount of research work has been carried out in recent years to develop various strengthening and rehabilitation techniques to improve the seismic performance of structures. Several strengthening methods like addition of new structural elements; external post tensioning, steel plate bonding etc. has been applied in the past with varying degree of success. Among these methods, seismic retrofit with FRP materials has gained notable acceptance from the civil engineering community in recent years. Retrofitting with FRP materials is a technically sound and cost effective repair technology and is now extensively being used as a seismic retrofitting method all over the world. This paper presents a representative overview of the current state of using FRP materials as a retrofitting technique for the structures not designed to resist seismic action. It summarizes the scopes and uses of FRP materials in seismic strengthening of RC structures and masonry retrofitting as well as the seismic retrofitting schemes for steel structures. The advantages along with the design guidelines and the limitations of FRP applications for seismic retrofit are also included in the paper.

Keywords: FRP, strengthening, rehabilitation

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1. Introduction

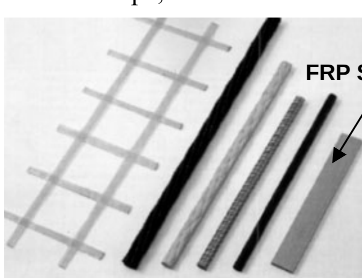
Many existing structures not designed to withstand seismic forces have now become obsolete due to development of more stringent design codes and specifications. Furthermore, recent earthquakes have prompted an urgency to repair and retrofit these seismic deficient structures to reduce the damage and casualties. Though no such thing as fully earthquake proof structure can exist in real, proper retrofitting and rehabilitation method can notably improve the seismic performance of a structure. Mostly column failures, which include shear failure and shear cracking, have been observed in a RC structure during the past earthquakes. Basic methodology of strengthening mechanisms can be classified into two fundamental approaches. They are,

1. Local modification of structural components
2. Global modification of the structural system.

Global modification, also termed as structural-level retrofit includes addition of new structural wall, steel braces, base isolators etc. However, member-level retrofit local modification is a much more cost effective method than the earlier one since it involves selecting and strengthening only the weak and deficient components of the whole structure. It includes addition of steel jackets, FRP materials etc for the confinement of column and joints. Though bonding with steel plate is proved to be successful to some extent, steel as a strengthening material has some certain limitations. Among these are low corrosion resistance, difficulty in handling at construction site because of its excessive size and weight and lack of durability. These problems associated with using steel plates as a retrofit method have led to invent new rehabilitation and strengthening techniques. Among these techniques fiber-reinforced polymer (FRP) composites as retrofit materials has gained much notable success in recent years. This paper focuses on the recent progresses in retrofitting of RC columns, beams, beam-column joints, masonry walls and steel structures using various FRP retrofitting schemes with a view to improve the seismic performance of the deteriorated structure. The main objective is to present a representative overview of the current state of using FRP composite materials as a retrofit technique as well as help the civil engineers consider the recent evaluations while applying this seismic retrofit method.

2. FRP Composites for Structural Rehabilitation

Fiber-reinforced polymer (FRP) composites consist of continuous carbon (c), glass (g) or aramid (a) fibers bonded together in a matrix of epoxy, vinylester or polyester. The fibers are the basic load carrying component in FRP where as the plastic, the matrix material, transfers shear. FRP products commonly used for structural rehabilitation can take the form of strips, sheets and laminates as shown in fig. 1.



(a)

(b)

Figure 1. FRP products for structural rehabilitation, (a) FRP Strips and (b) FRP sheets (Rizkalla et al. 2003).

Use of FRP has now become a common alternative over steel to repair, retrofit and strengthen buildings and bridges. FRP materials may offer a number of advantages over steel plates which include,

1. High specific stiffness (E/ρ)
2. High specific strength (σ_{ult}/ρ)
3. High corrosion resistance
4. Ease of handling and installation

Moreover, its resistance to high temperature and extreme mechanical and environmental conditions has made it a material of choice for seismic rehabilitation. Some of the disadvantages of using FRP materials include their high cost, low impact resistance and high electric conductivity.

3. Retrofitting of Reinforced Concrete Structures

3.1 Column strengthening

When an earthquake hits, reinforced concrete columns are considered to be the most vulnerable part of a typical RC structure as they are the major load carrying element of the building. Minimum cross section size and lack of steel reinforcement in under designed columns leads to a weak column—strong beam construction. It is very important to strengthen the columns so that the plastic hinges are formed in the beams since it allows more effective energy dissipation. Moreover, columns should be adequately designed to avoid a soft story collapse of a building due to seismic action.

Figure 2. Application of FRP for seismic retrofitting of RC columns

During an earthquake, three modes of RC column failures that can take place due to cyclic axial and lateral loads are – shear failure; flexural plastic hinge failure and lap splice failure. Lack of transverse reinforcement can result in shear failure, which is both brittle and catastrophic in nature. Shear capacity of deficient columns can be significantly enhanced by providing externally bonded FRP laminates with fibers in the hoop direction as shown in Fig. 2. Researches have shown that an increase in the thickness of CFRP and AFRP jacket proportionally increases the shear strength of the upgraded column or pier. (Fujisaki et al. 1997; Masukawa et al. 1997). Experimental studies (Kobatake et al., 1993; Saadatmanesh et al. 1996; and Ehsani and Jin, 1996) have shown that properly designed composite wrap for reinforced concrete column can increase shear strength to the extent that brittle shear failure mode is converted to inelastic flexural deformation mode and enhances flexural ductility.

Lap splice failures in reinforced concrete columns occur when the length of lap splice in the column is so small that the bond breaks during seismic action. According to a research conducted by Seible et al. (1997), the required FRP wrapping thickness to fasten the lap splice region is directly proportional to the effective column diameter and inversely proportional to the modulus of elasticity of the laminate.

Several investigations (Benzoni et al., 1996; Masukawa et al., 1997; Seible et al., 1997; Lavergne and Labossiere, 1997; Saadatmanesh et al., 1997; Seible et al., 1999; Mirmiran and Shahawy 1997; Fukuyama et al., 1999; Pantelides et al. 2000b; Bousias et al. 2004 and Harajli et al. 2006) have been conducted to study the effectiveness of FRP in restrenghtening of circular, square and rectangular reinforced concrete columns. Haralji et al. (2006) reported that confining rectangular columns with FRP, results in significant improvement in axial strength and ductility. For square column sections without longitudinal reinforcement (plain concrete) the increase in axial strength was found to be 154, 213, and 230% for one, two, or three layers of CFRP wraps, respectively. However, this increase in strength due to FRP confinement becomes less significant as the aspect ratio of the column section increases. For square steel reinforced concrete columns, the increase in axial strength resulting from FRP retrofitting scheme is 188, 255 and 310% with one, two or three layers of CFRP wraps, respectively (Haralji et al. 2006). Moreover, in reinforced concrete columns, FRP strengthening prevents premature compression failure of the concrete cover and buckling of the longitudinal steel bars leading to improved performance of the column under seismic loading. This improvement is due to increased strain capacity of the confined concrete, to enhanced restraint of bar buckling, as well as to suppression of the effects of shear on deformation capacity (Bousias et al. 2004).

3.2 Retrofitting of beam-column joints

Beam-column joint retrofitting is an important aspect of improving the seismic performance of a structure. Confinement and wrapping of reinforced concrete columns with FRP materials will help the plastic hinges form in the beam region which will promote a more acceptable ductile and energy dissipating failure mechanism during an earthquake. Strengthening of columns usually results in better structural performance in terms of global behavior since the objective of local upgrade of a single element is to get better and more ductile global behavior. Full-scale experimental studies have also shown that FRP laminates can significantly strengthen exterior beam-column joints with deficiency in shear strength (Pantelides et al. 2000a; and Ghobarah and Said, 2001). Figure 3 shows examples of RC column beam joints retrofitted with FRP.

3.3 Retrofitting of RC beams

Flexural strengthening of reinforced concrete beams can be done either by external bonding of FRP composites [external bonding (EB) system] or by insertion of FRP strips or bars into grooves cut into the concrete [near surface mounted (NSM) system]. In both methods, bond between FRP and concrete surface must be ensured to attain improvement in flexural strength and stiffness and to avoid premature debonding failure. Flexural strengthening of reinforced concrete beams by bonding FRP laminates at the tension face of the beam was first introduced by Meier's group (Meier 1997) at the Swiss Federal

Laboratories for Materials Testing and Research. Since then, extensive experimental and analytical studies (Colalillo and Sheikh 2009; Saxena et al. 2008; Choi et al. 2008; Nitereka and Neal 1999; Brena et al. 2003; Bonacci, and Maalej 2000) have been carried out all over the world on flexural strengthening of concrete beams. The objectives of these studies were either to evaluate the effectiveness of FRP on flexural performance of concrete beams or to investigate the effect of various parameters on possible failure modes. Early research has demonstrated an increase in ultimate strength of concrete beams by 22% due to FRP strengthening. In some cases strength increases up to 245% have been achieved through the use of external clamps to prevent debonding of FRP (Saadatmanesh and Ehsani 1990). In addition to the strength enhancement the FRP strengthening scheme with anchoring system improves the ductility of the retrofitted beam by confining the concrete. This in turn improves the seismic performance of the retrofitted beams. It has been reported in the literature that the shear strength of CFRP retrofitted beams under simulated earthquake loads were enhanced by up to 114% as compared to a similar RC beam without FRP (Colalillo and Sheikh 2009). Prior to shear failure, FRP material stiffened the beams and allowed for relatively elastic behavior. While it is possible to increase the flexural strength of concrete beams and girders by plate bonding FRP sheets to the tension face, care must be taken not to introduce new failure modes into these beams. These failures, which are often brittle in nature, limit the strength of the retrofitted beam and occur at loads that are much lower than the theoretical failure load. In order to use FRP sheets effectively an improved understanding of the failure modes through experimentation and model-based simulation is necessary.

Figure 3. Retrofitting of RC beam-column joints with FRP (Tsionis et al. 2001 and Motavalli and Czaderski 2007).

The FRP strengthening system for RC beams can be made more effective by prestressing the fibers. The most beneficial effects of the prestressing method are delaying the crack formation, filling the cracks in structure with existing cracks and enhancement of the members shear capacity due to the action of confinement and reduction of FRP associated costs, because the same strength levels reached with nonprestressed composites can be reached with pretensioned sheets of reduced area (Triantafillou et al. 1992; El-Hacha 2003; and Millar et al. 2004). Thus, the serviceability of beams strengthened with FRPs is improved when the sheets or laminates are prestressed. However, codes and guidelines of applying pre-stressed FRP are not yet fully established. The prestressing techniques and installation methods need to be further modified and simplified before prestressed FRP can be used more frequently for practical applications.

The bond behavior and load transfer behavior between concrete beam and FRP laminates has significant impact on the failure behaviour and stress distribution of retrofitted beams. Experimental studies (Brena et al. 2003; Hamad et al. 2004; Saxena et al. 2008; and Choi et al. 2008) indicated that debonding of the bottom strip from the concrete surface is the most common mode of failure for concrete beams strengthened by externally bonded FRP sheets. The debonding results in the loss of the composite action between the concrete and FRP laminates. The local debonding initiates when high interfacial shear and normal stresses exceed the concrete strength (Kotynia et al. 2008). Additional U-jacket strips or sheets can be provided in the debonding initiation region to delay the FRP debonding resulting in increased efficiency of the FRP retrofitting scheme. More experimental and analytical studies should be carried out to find a more reliable relation between bond behavior of FRP laminates and concrete to make sure that the FRP fitted structure does not fail prematurely.

4. Seismic retrofit of masonry structures

Many of existing unreinforced masonry (URM) buildings are seismically vulnerable and need to be retrofitted. FRP application is mostly limited to RC structures, however, a few experimental and numerical studies have been carried out on masonry structures (Triantafillou and Fardis 1997; Ehsani et al. 1997). These studies have focussed on both FRP tendons and laminates and showed that FRP has a great potential to enhance the strength and ductility of masonry structures. For masonry walls strengthened with FRP laminates, research results have shown that debonding of the FRP laminate from the masonry substrate is the controlling mechanism of failure. This has been evident in masonry walls strengthened to resist either in-plane or out-of-plane loads. For clay units, debonding may have a direct relationship with the porosity of the masonry itself. Investigations should be carried out on different walls built with different and representative types of masonry units. The interaction of strengthened walls with the surrounding structural elements (i.e. beams and columns) is of also important since the effectiveness of the strengthening may be dangerously overestimated due to premature failures (e.g. crushing of masonry units at the boundary regions).

The flexural strength of URM walls is basically limited by the tensile strength of the mortar. But FRP bonded wall can resist large moments as it provides a large tensile component. It has also been shown that the lateral strength and stiffness of the URM walls can be improved by providing proper FRP retrofitting schemes. A typical seismic retrofitting scheme for masonry wall is shown in Fig. 4.

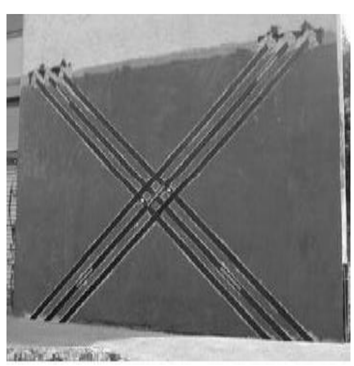


Figure 4. Seismic retrofitting of masonry shear wall with GFRP sheets
(Motavalli and Czaderski 2007)

5. Seismic Retrofit of Steel Structures

Though FRP materials have gained much acceptance from the research community as a retrofit method of RC structures, retrofit of steel structures using FRP materials have not received the same attention yet. However, seismic retrofit of steel structures using FRP materials is gradually gaining popularity.

A few researches have been conducted to find out the potential of FRP materials to repair and retrofit steel structures. The majority of the past research work done on the strengthening of steel structures using FRP materials have mainly focused on the following areas,

1. Strengthening of steel girders which are not welded.
2. Repair of corroded steel girders and
3. Rehabilitation of fatigue damaged riveted connections

These researches have shown that FRP retrofit can increase the elastic stiffness of damaged steel girders from 10 to 37 percent (Gillespie et al, 1996). Literature to date shows that as a repair technique, FRP sheets and strips are capable of restoring the lost capacity of a steel section as well as can effectively strengthen steel structures to resist higher loads. Fatigue life of steel structures can also be extended by using epoxy bonded FRP sheets and laminates. Moreover, FRP has a considerable effect on reducing the crack propagation. Application of FRP to steel structures leads to an increased yield strength of the steel section, which is followed by an increased service load.

6. Conclusions

Seismic retrofitting has now become a crucial issue. Recent occurrences of earthquakes in different parts of the world have clearly demonstrated the urgency of repairing seismic deficient structures. Design guidelines and recommendations should be made more readily available to ensure more rapid and effective applications of FRP as a seismic material. In spite of the significant research being reported on their structural mechanism and performance, there are still great deal of concerns regarding possible premature failure due to debonding, especially in zones of combined flexural and shear stresses. More research needs to be conducted addressing issues related to mechanics, design, and durability of FRP retrofitted concrete and steel systems to ensure a proper use of FRP composites in seismic retrofitting applications. An improved understanding of the structural behavior of FRP fitted structures along with their failure mechanisms, which are often brittle in nature through experimental and numerical simulation, is necessary. Influence of cyclic and fatigue loading on the FRP strengthened member performance must be characterized and accounted for in the design process. Design manuals and codes of practice should be updated to take these issues into consideration. Related personnel should be trained properly to ensure an effective seismic application of FRP materials for retrofitting and rehabilitation purpose. However, before applying any seismic retrofit method to a damaged or deficient structure, a proper and accurate assessment of the seismic performance and current state of the structure is essential.

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