Indian J. Innovations Dev., Vol. 1, No. 8 (August 2012) ISSN 2277 - 5390

# Case studies of strengthening and retrofitting of Civil engineering structures – A critical review

**T.S. Thandavamoorthy***

**Professor, Department of Civil Engineering, Adhiparasakthi Engineering College, Kancheepuram District, Melmaruvathur - 603 319, Tamil Nadu.*

***Corresponding author:** *Dr. T.S. Thandavamoorthy, Professor, Department of Civil Engineering, Adhiparasakthi Engineering College, Kancheepuram District, Melmaruvathur - 603 319, Tamil Nadu.Email:drthumati@gmail.com.*

**Abstract**

Civil engineering structures may be damaged due various causes such as earthquakes, cyclones, blasting, etc. This kind of loading collapses the structure prematurely or causes extensive damage to them. When the damage is minor, it is possible to retrofit the structure. A review of the available literature has disclosed that umpteen numbers of retrofitting methodologies are available. Among them, efficient and effective method of repairing damaged structures is the application of Fiber Reinforced Plastics (FRP). In the past, several structures have been rehabilitated using the FRP techniques. This paper presents a critical review of using the FRP techniques, their applications, case studies of repairing civil engineering structures, and appropriate concluding remarks.

***Key Words:*** Civil Engineering Structures, Damages, Repair, Strengthening, FRP

## Introduction

The spectrum of civil engineering structures that are being constructed nowadays is very wide. For example, buildings, bridges, dams, under-ground storage structures, overhead storage structures, high-rise structures, launch pads, airport terminals, stadia, shopping malls, Cineplex's, swimming pools, etc., are some of the structures built for different purposes and to carry out different activities. These structures are built with materials like masonry, concrete, steel and aluminum as per the design requirements and economical considerations. These structures are subjected to geophysical and man-made loads during their service life. When the magnitude of these loads exceed the capacity or strength of the structures, they are likely to be damaged. Considering the economy of constructing another new structure in place of the damaged structures and also the loss of revenue due to interruption in the functioning of the structure and economic an environmental factors, a decision to repair the structure becomes essential.Sometimes the strength of a structure is reduced because of the use of substandard materials in its construction or due to the application of additional load because of change in functioning or due to seismic forces for which the structure had not been designed originally. These situations warrant strengthening or up-gradation of the structure to carry the enhanced loading.

A variety of structural up-gradation and retrofitting techniques has been evolved over the years in respect of different structures and has also been used. Some methods of seismic up-gradation such as addition of new structural frames or shear walls have been proven to be impractical because they have been either too costly or restricted in use to certain types of structures. Other strengthening methods such as grout injection, insertion of reinforcing steel, pre-stressing, jacketing, and different surface treatments have been summarized by Hamid et al. (1994). Each of these methods involves the use of skilled labour and disrupts the normal functions of the building. These well-known techniques may sometimes be inadequate

Indian J. Innovations Dev., Vol. 1, No. 8 (August 2012) ISSN 2277 - 5390

for applications that should preserve architectural heritage with historical value.
FRP composites are now increasingly used in the construction industry and offer considerable potential for greater use in buildings, including large primary structures. In recent years more complex applications have been developed to satisfy the desire for more dramatic features in building design. FRP composites have numerous potential advantages in building construction including the following: Offsite fabrication and modular construction reduced mass, superior durability, ability to mould complex forms, special surface finishes and effects, and improved thermal insulation and lack of cold bridging (Kendall, 2007). As a repair material also confinement with Polymeric Matrix or FRP presents significant advantages over a traditional confinement techniques: the cross sectional dimensions of the column do not increase, which permits compliance with architectural restraints; the mass of the column does not increase, which means that the seismic behavior of the building remains unchanged (Minicelli & Tegola, 2007); the low weight of FRP materials implies that the installation procedure is faster, easier and less dangerous for the operator than implementation of traditional confining techniques, Modern techniques of confinement consist of wrapping with FRP sheets or laminates. They were introduced in engineering practice as an innovative confinement technique during the last decade, as an alternative to wood or steel ties adopted in the past. Therefore the use of FRP laminates for retrofitting and strengthening is a valid alternative because of their small thickness, high strength-to- weight ratio and ease of applications.

The paper presents a few case studies of the application of FRP to strengthen and retrofit masonry both un-reinforced and reinforced structures; concrete structures; pre-stressed concrete structures; masonry arches; underwater piles; bridge piers; monumental structures, etc., by reviewing available literature.

***Retrofitting of a Medieval bell tower***

Retrofitting of existing structures to resist seismic actions that they were not originally designed for is a common practice in structural engineering. Seismic retrofitting of monument structure requires compliance with restrictive constraints related to the preservation of original artistic and structural features. Any conceived intervention must achieve structural performance yet still respect the appearance and structural mechanism of the original and be as minimally invasive as possible. The intervention on the bell tower of Santa Lucias Church in Serra San Quirico, Ancona, Italy is an application of composite materials for the seismic retrofit of historic monuments where traditional retrofit strategies are not suitable. Cosenzo and Iervolino (2007) have presented a case study of retrofitting of the medieval bell tower in Serra San Quirico using the FRP.

Affected by the Umbria-Marche earthquake in 1997, the bell tower of Santa Lucias Church is a multilayered masonry structure built in the XV century. It is located at the centre of the little tower of Serra San Quirico, a medieval suburb near Ancona, and is surrounded by many residential constructions of the same age.

It is a calcareous masonry building, about 30 m in height and 1,200 m in width with a rectangular plan view (Fig. 1). Because of damage and failure of similar structures in the same area, a desire to improve the seismic capacity of the tower was expressed by the local Architectural Heritage Supervision Office. Initially, to fulfill the scope of retrofitting an intervention based on steel reticular system anchored to the inner side of the tower was proposed. The Architectural Heritage Authority recognized that this intervention violates the above described principles and, therefore, rejected it.
Subsequently FRP intervention was proposed, designed, approved and installed. The design also included finite element simulation and a site structural assessment. Effectiveness of the intervention was evaluated by performing nonlinear static analysis, i.e., push over analysis, both on retrofitted and original structures and by comparing


 

Indian J. Innovations Dev., Vol. 1, No. 8 (August 2012) ISSN 2277 - 5390

the results. Pushover curves for the retrofitted and un-retrofitted structures are shown in Fig .2.
The FRP intervention enhances the seismic capacity of the structure and is fully provisional as it may be removed by heating the FRP with a hot

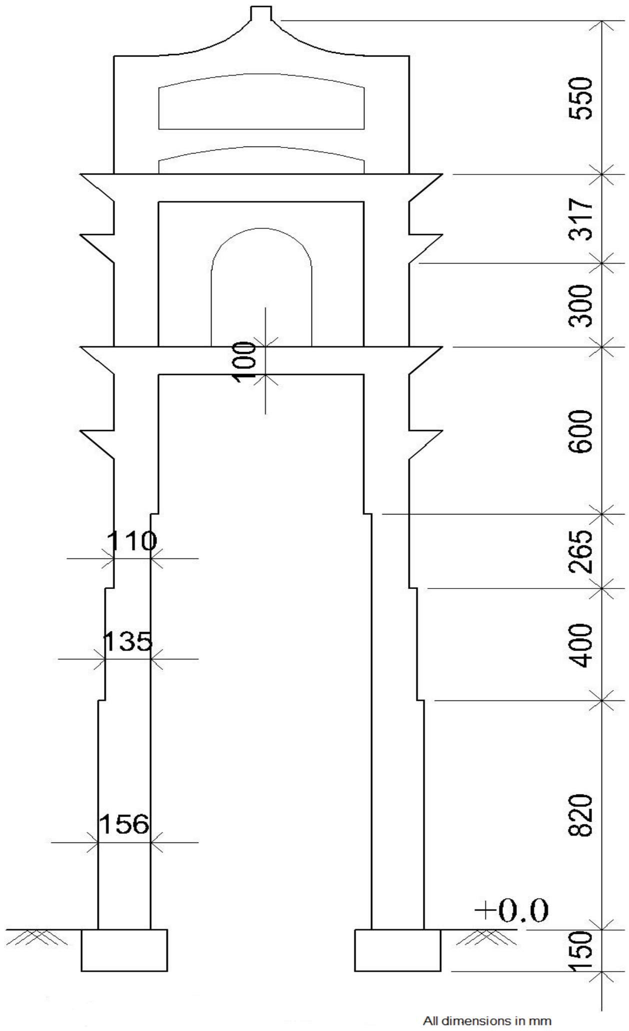


*Fig.1*: Cross section of bell tower

air jet.

### *Underwater pre-stressed piles repair*

Mullians et al. (2005) have described a field demonstration study to evaluate the application of FRP for the underwater repair of corroding pre-stressed piles. A total of four full sized 350 mm × 350 mm square pre-stressed piles were wrapped, two with carbon and two with glass. Two of these wrapped piles, i.e., one carbon and one glass, were instrumented to allow evaluation of their post wrap performance. Two other unwrapped piles serve as control. Instrumentation allowed determination of the corrosion potential over the unwrapped surface and the corrosion rate for the wrapped piles.

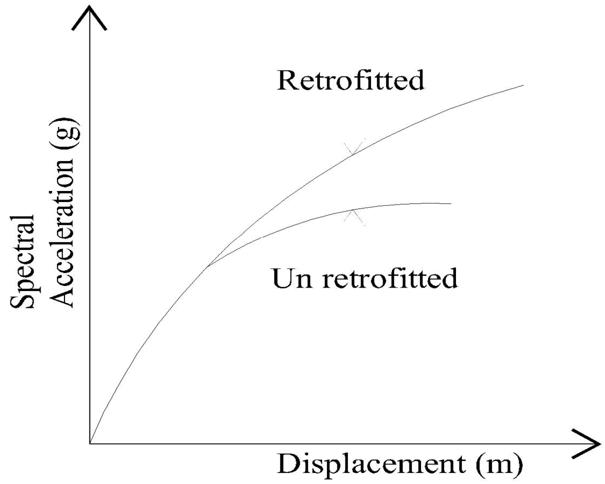


*Fig 2*: Comparision of Push over curves of retrofitted and Un-retrofittes structures

The study showed that underwater wrapping in a visible system. As with most FRP retrofits, surface preparation is of paramount importance. In this case, surface preparation required equipment capable of operation in underwater to grind sharp corners. Although initial field tests on the witness panels indicated that the bond between the wet concrete and the FRP was relatively poor, laboratory tests showed the bond was adequate to restore the full undamaged capacity. Corrosion rate measurements indicate that the performance of the wrapped piles is consistently better than that of the unwrapped controls. The underwater wrap used a unique water activated urethane resin system that eliminated the need for cofferdam construction. The preliminary findings are quite encouraging and suggest that underwater wrapping without cofferdam construction may provide a cost-effective solution for pile repair.

### *Retrofitting of hollow bridge piers*

In order to maximize efficiency in terms of the strength-to-mass and stiffness-to-*mass* ratios

Indian J. Innovations Dev., Vol. 1, No. 8 (August 2012) ISSN 2277 - 5390

and to reduce the mass contribution of the pier-to-seismic response, it has been common engineering practice to use hollow sections for bridge piers, particularly for tall piers. Hollow bridge piers are currently being used in high speed rail and highway projects in Taiwan. Recent earthquakes such as the Northridge earthquakes of 1994, the Kobe earthquake of 1995, and the Taiwan earthquakes of 1999, have respectively demonstrated the vulnerability of older reinforced concrete piers to seismic deformation demands and shear strength. Yeh and Mo (2005), have presented the results of an investigation on hallow piers retrofitted with carbon fiber reinforced polymer (CFRP) sheets. In their investigation the authors have tested circular and rectangular hallow bridge piers retrofitted by CFRP sheets under a constant axial load and a cyclic reversed horizontal load to study their seismic behavior, including flexural ductility, dissipated energy and shear capacity. An analytical model was also developed to predict the moment-curvature relationship of sections and the lateral load displacement relationship of piers. The test results are also compared with the proposed analytical model. It was found that the ductility factor of the tested piers ranged from 3.3 to 5.5 and that the proposed analytical model could predict the lateral load displacement relationship of such piers with reasonable accuracy. All in all, CFRP sheets can effectively improve both the ductility factor and the shear capacity of hollow bridge piers.

***Strengthening of R.C. beam – column joints***

Recent earthquakes worldwide have illustrated the vulnerability of existing reinforced concrete (RC) beam-column joints to seismic loading. Strengthening of R.C. joints is a challenging task that poses major practical difficulties. A variety of techniques applicable to concrete elements have also been applied to joints with the most common ones being the construction of RC or steel jackets. However, these techniques have inherent limitation in the form of intensive labour and artful detailing. In the case of concrete solutions there is a possibility of dimensions and weights of the elements being increased.

Recently, a new techniques based on the FRP for structural elements, has been evolved. This technique involves the use of FRP as externally bonded reinforcement (EBR) in critical regions of RC elements. FRP materials, which are available today in the form of strips or in situ resin impregnated sheets, are used to strengthen a variety of RC elements, including beams, slabs, columns, and shear walls, to enhance the flexural, shear, and axial capacity of such elements.

The results of a comprehensive experimental programme aimed at providing a basic understanding of the behaviour of shear-critical RC joints strengthened with FRP under simulated seismic load have been presented by Antonopoulos and Triantafillou (2003). The role of various parameters such as area fraction of FRP; distribution of FRP between the beam and the columns; axial load of column; steel reinforcement in internal joint; initial damage; carbon versus glass fibres; sheet versus strips; and effect of transverse beams, on the effective FRP has been examined through 2/3 scale testing of 18 exterior RC joints.

The tests performance in this study demonstrated that externally bonded FRP reinforcement is a viable solution towards enhancing the strength, energy dissipation, and stiffness characteristics of poorly detailed RC

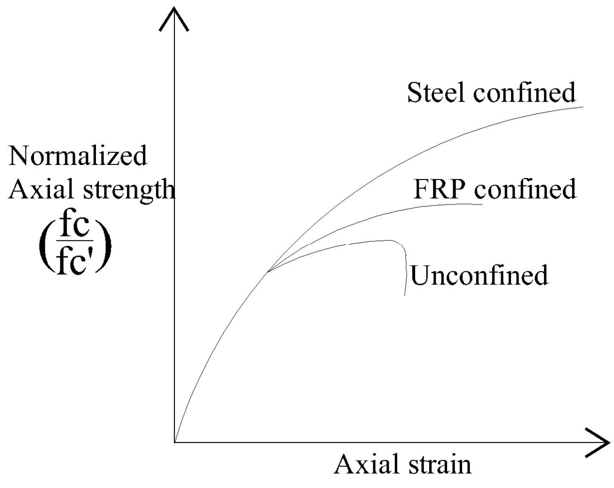


*Fig.3*: Typical effect of confinement of column

Joints in shear that are subjected to simulated seismic loads. Relatively low fraction of FRP area enhanced both in the peak lateral load capacity and the cumulative dissipated energy up to about 70 to 80 percent. The increase in stiffness varied with the imposed displacement level reached values in the order of 100 percent. The results demonstrate the important role of mechanical anchorages in limiting premature de-bonding.

***Concrete confined with FRP tubes***

Axial load on concrete causes the concrete to expand laterally. In an encased concrete column, this lateral expansion is resisted by the hoop action of the shell that surrounds the concrete. Such confinement changes the stress-strain behaviour of concrete and also increases its compressive strength as shown in (Fig. 3)**,** which depicts the typical stress-strain relationship of un-confined concrete, confined by FRP tube and by a steel tube respectively.

The advantage of improved performance of concrete encased in steel tubes has been well recognized for a long time and is used in structural applications (Choi and Xiao, 2010). However, the use of FRP tubes to encase concrete columns instead of steel is a more recent development that offers certain advantages, such as elimination of corrosion of the confining tube. FRP tubes are also light-weight and easy to handle. They act as an ideal formwork that eventually remains in place as permanent part of the structure. The confining pressure of an FRP shell subjects the core concrete to a tri-axial state of stress. Concrete itself prevents the shell from buckling inward. The shell protects the concrete surface from physical damage and environmental effects such as carbonation and chloride penetration. The shell acts as a uniform longitudinal reinforcement located at the most advantages position to resist moments. Therefore, concrete confined with FRP is currently considered a technically attractive system for piles, highway overhead signs, and other compression members that can be subjected to moments.

Bacque *et al.*, (2003) have developed analytical models for prediction of stress-strain curves for concrete confined with FRP. The predicted stress-strain curves for confined concrete using the proposed models were compared with those of tests on concrete specimens confined with FRP. The agreement was found to be good. The proposed model was also able to predict the well-known behaviour that concrete confined with a GFRP exhibits better ductility as compared with concrete confined with CFRP.

***Heritage university building***

Nanda and Sahoo (2010) have presented the factors influencing the damages and repairing methodology adopted in the restoration work of a heritage Ravenshaw University situated on Orissa and constructed in 1868. Fine cracks in the walls were sealed with epoxy putty instead of wall stitching. For grouting port holes were provided along the cracks. Nozzles were fixed, and grouting was done with water-insensitive high-bond-strength epoxy of density 1.1 kg/L, compressive strength 75 MPa, tensile strength 34 MPa, and bond strength 3.5 MPa. Styrene Butadiene rubber emulsion based latex modified concrete was used to apply a ferrocement treatment for repairing leaking roof of the building.

***Arresting leakage in Muran dam***

The step by step approach in arresting water leakage in the inspection gallery of Muran dam using Polyurethane (PU) injection system has been described by Mishra (2010). The Muran Dam is located on Muran River in Khatiguda in Orissa. The walls of the inspection gallery of this dam were made of concrete and were of old construction pattern. Keeping in view the age, the thickness, the strength and other physical conditions PU injection system was considered for arresting leakages. After some time after repair it was ascertained from the engineer in-charge that the system was completely successfully as the affected area was intact even after the rise of water level in the upstream side.

**Conclusion**

FRP as strengthening and retrofitting material has several advantages over conventional materials. Its thickness is small and hence its application does

Indian J. Innovations Dev., Vol. 1, No. 8 (August 2012) ISSN 2277 - 5390

not add weight to existing structures. It helps to preserve the cultural heritage of monumental structures. It is not corrodable.

In a case study of bell tower it has been shown that FRP intervention enhanced its seismic capacity and such a solution was acceptable to local Architectural Heritage Authorities.
Underwater FRP wrappings without cofferdam construction could provide a cost effective solution for pile repair.

CFRP sheets can effectively improve the ductility factor and the shear capacity of hollow bridge piers. It was found that the ductility factor of tested piers ranged from 3.3 to 5.5.
It has been demonstrated by experiment that externally bonded FRP reinforcement is a viable solution towards enhancing the strength, energy absorption and stiffness characteristics of poorly detailed RC joints in shear.

The use of FRP tubes to encase concrete columns instead of steel is a more recent development that offers certain advantages, such as elimination of corrosion of the confining tube. FRP tubes are also light-weight and easy to handle. Analytical prediction of stress-strain curves for concrete confined with FRP was found to be in good agreement with those obtained from testing.

A heritage university building was repaired and restored by repairing the fine cracks of the walls by epoxy injection and with ferrocement treatment using latex modified concrete to repair the leaking roof.

The leakage in the walls of the inspection gallery in a dam was arrested by Polyurethane (PU) injection system.

**References**

1. Antonopoulos, CP and Triantafillou, TC (2003) Experimental Investigation of FRP-Strengthened R.C. Beam-Column Joints. *J. Composites and Construction*, ASCE, 7(1), pp. 39.
2. Bacque, J Patnaik, AK and Rizkalla, SH (2003) Analytical Models for Concrete Confined with FRP Tubes. J. Composites and Construction, ASCE, 7(1), pp. 31-38.
3. Choi, KK and Xiao, Y (2010) Analytical Studies of Concrete-Filled Circular Steel Tubes under Axial Compression. J. Structural Engineering, ASCE, 136(5), pp. 565-578.
4. Cosenzo, E and Ivervolino, I (2007) Case Study Seismic Retrofitting of a Medieval Bell Tower with FRP," Journal of Composites for Construction, ASCE, 11(3), pp. 319-327.
5. Hamid. AA Mohmond, ADS and El Magal, SA (1994) Strengthening and Repair of Un-reinforced Masonry Structures: State-of-the-art, Proceedings of the 10th International Brick and Block Masonry Conference, Vol. 2, Elsevier Applied Science, London, pp. 485-497.
6. Kendall, D (2007) Building the Future with FRP Composites.Reinforced Plastics, May, pp. 26-33.
7. Minicelli, F and Tegola, LA (2007), Strengthening Masonry Columns: Steel Strands Versus FRP, Proceedings of the Institution of Civil Engineers Construction Materials Vol. 160, Issue CM2, May, pp. 47-55.
8. Mishra, A (2010) Arresting Leakges on the Inside Walls of Inspection Gallery (Muran Dam) of Upper Indravathi Hydro Electric Project, Orissa, India – A Case Study, Int. J 3 R's, (1)2, pp. 87 – 89.
9. Mullians, G Sen, R Suh, K and Winters, D (2005) Underwater Failure-Reinforced Polymers Repair of Prestressed Piles in the Allen Creek Bridges, J. Composites and Construction, ASCE, 9(2), pp.136-146.
10. Nanda, R and Sahoo, DK (2010) Restoration of a Heritage University Building – A Case Study, Int. J.of 3 R's, 1(2), pp. 84 – 86.
11. Yeh, YK and Mo YL (2005) Shear Retrofit of Hollow Bridge Piers with Carbon Fibers-Reinforced Polymers Sheets, J. Composites and Construction, ASCE, 9(4), pp.327-336.