

Retrofit of Existing Reinforced Concrete Structures using FRPs: Recent Case Studies

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INTRODUCTION

In recent years, Fibre Reinforced Polymers (FRPs) have become widely accepted as a highly effective means for retrofitting reinforced concrete and masonry structures. They can often be used to achieve a cost-effective retrofit solution that is less intrusive than traditional methods.

This paper presents a number of recent case studies within New Zealand and USA where FRPs have been used, or are in the process of being used, to achieve the optimum retrofit solution. A cross-section of projects is discussed, including gravity load strengthening of floor systems and bridges, rehabilitation of underground pipes, and seismic strengthening of concrete and unreinforced masonry (URM) structures.

FIBRE REINFORCED POLYMERS (FRPs)

FRPs, as referred to in this paper, are composite materials consisting of thin fibres of glass, carbon or kevlar, embedded in a matrix of epoxy resin.

Commonly used in applications such as boat building, these materials have become a very useful tool in the field of structural engineering, particularly for strengthening and repairing existing concrete and masonry structures. This is achieved by bonding a small number of layers of the material to the surface of the member requiring strengthening.

GRAVITY STENGTHENING

FRPs have a proven case history in the area of gravity load strengthening, and the list of projects where they have been used to achieve the optimum retrofit solution is steadily growing. Presented below are two recent case studies.

333 South Beaudry Ave, Los Angeles

This is a 28 storey building with 4 basement levels, located in downtown LA. 20 floors of the building are being strengthened for gravity loads, in two phases. One of the floors was strengthened specifically to house a data storage facility. The other 19 are in the process of being upgraded voluntarily by the building owner, to bring them up to current code levels of live load capacity.

The building was constructed in 1982. It is of reinforced concrete construction, with a gravity system comprising of two-way insitu reinforced concrete floor slabs, supported off concrete columns with capitals. Figure 1 shows a photograph of the building.



Figure 1 – Building at 333 South Beaudry Ave, Los Angeles

A carbon FRP option was chosen as the strengthening solution for the slabs. Alternatives including external post-tensioning were considered, but the FRP solution was preferred because it was far less intrusive, adding only a small thickness to the slab. Additionally, the FRP option offered significant savings in installation time. This is important

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because the work is being done to coincide with a new tenancy fitout. Multiple installation crews are working around the clock to achieve the tight deadlines.

A detailed moment curvature analysis was used to determine the number of layers of carbon laminate required for strengthening. This was based on a combination of the FRP manufacturer's guidelines, and the recommendations of ACI440 [5]. The analysis took account of initial strains in the system at the time of applying the fibre, and used a non-linear concrete stress distribution to ensure an accurate representation of the concrete force component at low concrete strains.

Figure 2 shows the application of carbon FRP strips beneath the slab on one of the completed floors.

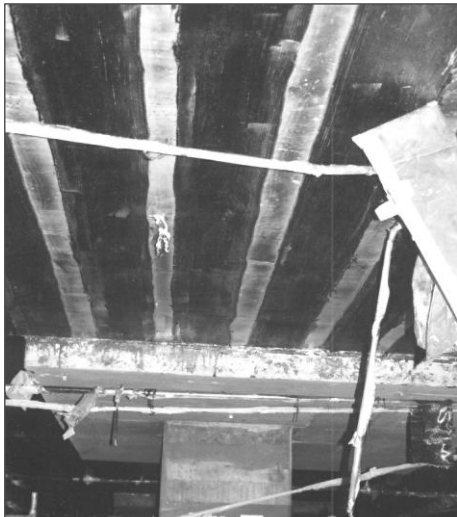


Figure 2 – Carbon FRP to underside of slab

Esmonde Road Bridge

Located on Auckland's North Shore, the Esmonde Road bridge forms part of a connecting road to the Auckland motorway system. The single span bridge is of precast, post-tensioned, single tee beam construction and spans approximately 26m. The bridge was originally constructed as two separate structures, one for each direction of traffic.

Designed in the 1950's, the live load capacity of the existing bridge did not meet current requirements. In addition to this, the bridge was to be widened to allow for a bus priority lane. Significant strengthening work was

required to support this extra lane of traffic, including work to enhance the flexural capacity of the deck, and the flexural and shear capacity of the girders. In addition, a new 'U' beam girder was placed between the two existing bridges, effectively tying the structures together to form one integral bridge structure.

Because the bridge had to remain operational during the strengthening work, a non-intrusive solution incorporating FRPs was preferred. Carbon FRP overlays were used to strengthen the deck and existing girders. The completed job is depicted in Figure 3.

To determine the flexural strengthening requirements, software was developed to carry out a full moment curvature analysis of the prestressed section, including the effects of the FRP.



Figure 3 – Esmonde Rd bridge girders after wrapping with FRP

UNDERGROUND PIPE STRENGTHENING

Another application where FRPs have been used recently is for strengthening underground prestressed concrete cylinder pipes. Over time, the integrity of these pipes can suffer due to environmental effects such as corrosion and hydrogen embrittlement. This has led to instances of pipes rupturing under water hammer effects.

Calleguas Pipe Project

The Calleguas Pipe project in California involved strengthening several lengths of 1.7m

diameter, potable water pipes for the reasons discussed above.

Alternatives to strengthening with FRPs were considered, including the provision of a new steel liner within the pipe, and also complete replacement of damaged lengths of pipes. Although these two options can prove to be more cost effective in some cases, the FRP solution was the only practical option in this case because there were severe restrictions on how long the pipes could be taken out of action. With the FRP solution the repairs were completed in a four day window.

A detailed finite element analysis of the pipe was carried out using specifically developed software, to determine the number of layers of FRP required to effectively replace the corroded prestressing wire. The analysis accounted for loading effects including lateral earth pressure, internal water pressure and overburden pressure due to fill and traffic loads. Figure 4 shows a photograph of the repaired pipe.



Figure 4 – Internal view of repaired pipe.

SEISMIC APPLICATIONS

FRPs have been widely used in the past to enhance the seismic resistance of reinforced concrete structures. The most common applications, for which design procedures are well defined, include concrete column and pier confinement, and shear strengthening of columns and beams [2,4,5].

Where, for the action being considered, the element is expected to behave in a ductile manner under seismic loads, FRPs are not generally considered appropriate because of

cyclic effects and strain compatibility issues. The latter issue is illustrated in Figure 5, which compares the moment-curvature response of a bare reinforced concrete beam section. With that of the same section, enhanced with 3 layers of carbon FRP.

This shows that if the section is required to behave in a ductile manner, the FRP will rupture prematurely and will be rendered ineffective.

The conventional approach for designing FRP solutions is to first determine design loads on members using an elastic analysis and secondly design the FRP to make up the deficit between the original strength and required strength of the member. The problem with this approach is that the performance of the final retrofit solution is never verified and issues with strain compatibility as described above can remain undetected.

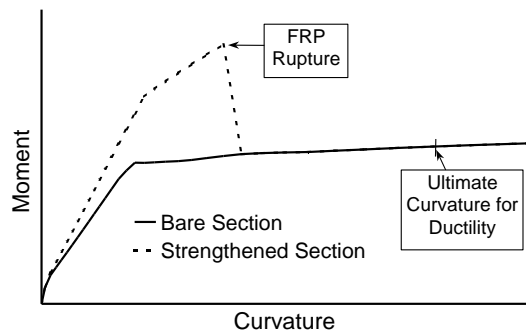


Figure 5 – Moment curvature response of concrete beam with and without FRP strengthening

Performance Based Design

A more desirable approach is to include the FRPs directly in an analysis model which explicitly represents the effects of non-linear behaviour of the structural elements. In doing so, the performance of the final design is verified to ensure it meets the required performance objectives. This is known as Performance Based Design [7,8]. With this approach, there is scope for using FRPs in a wider range of applications.

There are two analysis methods that are consistent with the intent of Performance Based Design for buildings, each with a different degree of sophistication. These are

the Non-linear Static Procedure (NSP), or Pushover Analysis, and the Non-linear Dynamic Procedure (NDP), or Inelastic Time History Analysis.

Both these procedures are capable of explicitly representing material non-linearity and the strength and stiffness degradation characteristics of structural elements. In addition, the NDP subjects the analysis model to real earthquake records, and explicitly models dynamic and cyclic effects. The outcome is that the behaviour of the building is more accurately modelled, and that more efficient, less intrusive, more effective retrofit solutions can be devised.

There are some disadvantages with these more sophisticated analysis techniques. These include the significant computational time required, and the level of detail required to define the model, including non-linear material behaviour characteristics, and appropriate seismic loads.

When it comes to using FRPs with these procedures, there are further complications because there is a lack of test data available. Existing building details vary greatly and different details can have a marked effect on the behaviour of the building. In addition to this, there are complex failure mechanisms at play. In masonry piers wrapped with FRP for example, failure can be instigated by toe crushing of the piers, localised delamination of the FRP and rupture of the FRP to name a few.

Because of these complications, a reasonable level of conservatism must be adopted, and significant care is required when it comes to detailing the retrofit solution.

Despite these issues, Performance Based Design using the NSP and NDP has proven to be capable of determining very efficient design solutions, and has enabled the use of FRPs in situations where it would have otherwise not been possible to use them [1]. Three recent case studies are discussed below.

Hamilton Post Office

As part of the Riverside Casino development in Hamilton, significant alterations to the existing Hamilton Post Office building were proposed. These included the removal of a number of

structural elements, infill of a number of openings and the potential future addition of two levels of structure above the roof level to house apartments.

In addition, the building was to undergo a change of use. For these reasons, an assessment of the lateral load resistance of the building was required in order to satisfy the requirements of the Building Act.

The post office building is a 1920's reinforced concrete structure, three storeys high with a partial basement. In situ reinforced concrete slabs are supported off a grillage of reinforced concrete beams and columns. The façade of the building consists of pierced walls. Although not specifically detailed for this, the reinforced concrete gravity frames and perimeter walls contribute to the seismic resistance of the structure.

The NDP in conjunction with a US guideline on Performance Based Design, FEMA 273 [9,10], and the NZSEE Green Book [13] were used to evaluate the seismic resistance of the existing building. The structural model is depicted in Figure 6. It was found that work was required to confine the hinge regions of many of the reinforced concrete beams and to strengthen a number of the wall and column elements in shear. FRP overlays were used in the latter two instances. FRP for the wall shear strengthening was included directly in the analysis model, and the extent of non-linear behaviour in the underlying concrete elements was tracked to ensure it met required performance objectives specified in FEMA 273.

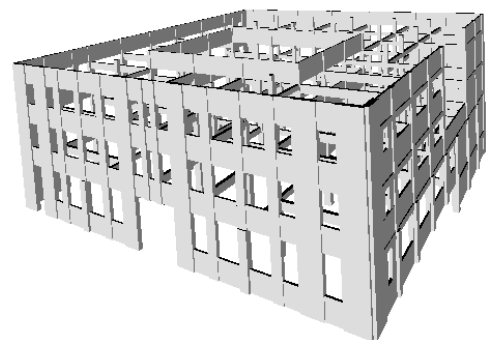


Figure 6 – Structural model of Hamilton Post Office building

San Francisco Piers 1½, 3 & 5

Constructed in the late 1910's, the San Francisco Piers structure consists of a concrete deck with a grillage of concrete beams supported off precast concrete driven piles. The Piers support a series of buildings of significant historic value. These buildings are to be refurbished, and some new buildings are to be constructed as part of a redevelopment of the San Francisco waterfront.

Due to its age and the aggressive environment, the Piers substructure is in poor condition and requires significant repair work to bring it up to the standard required by the 1998 San Francisco Building Code. Strengthening for both gravity and seismic loads is required.

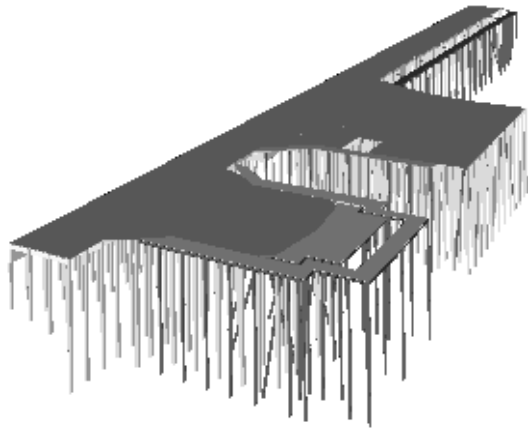


Figure 7: Structural model of San Francisco Piers

A retrofit solution incorporating significant use of both glass and carbon FRP has been chosen for a number of reasons. These include the stability of the system in corrosive environments, its cost-effectiveness, and the non-intrusive nature of the solution.

The NSP formed the basis of the design procedure for the retrofit scheme, which includes wrapping the top of all the existing piers with carbon FRP to enhance their plastic rotation capacity and increase the system ductility. This effectively reduces the magnitude of seismic load that the system is required to sustain. The predicted behaviour of a typical pier bent is illustrated in Figure 8.

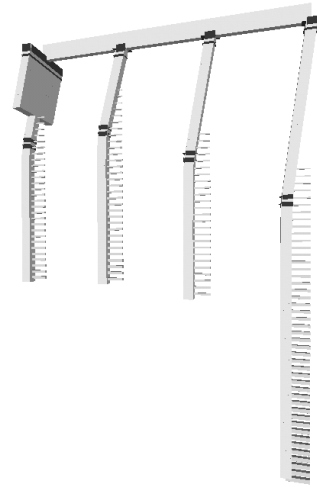


Figure 8 – Typical Marginal Wharf bent showing failure mechanism predicted by NSP.

Gateway Building, Utah

This early 1900s building in Salt Lake City, Utah was to become a focal point for the development for the 2002 Winter Olympics.

The existing building, shown in Figure 9, was constructed largely of unreinforced masonry and as a result, it did not have sufficient inherent seismic resistance. Using conventional design techniques, a retrofit scheme had been developed that required the construction of an entirely new seismic resisting system for the building.



Figure 9 – Entrance to the Gateway building, Salt Lake City

As an alternative, a scheme was developed using the principals of Performance Based Design. This involved enhancing the existing unreinforced masonry using FRPs, and providing a limited number of additional

elements to enhance its seismic resistance, rather than providing an entirely new system.

Compared to modern construction materials, unreinforced masonry is characterised by a relatively low strength [3, 6] and a brittle failure mechanism, with rapid strength degradation. URM buildings can sustain only very low levels of drift before collapse. This is a very significant issue because relatively stiff structures attract larger seismic loads.

When enhanced with FRP overlays however, URM can exhibit a much improved behaviour [11]. Significant shear strength increases occur, but perhaps more importantly, the inelastic behaviour of URM is improved so that it can sustain larger drifts without failing. In essence, FRP can be used to provide ductility to URM. This can eliminate the need for providing additional seismic resisting structure.

This approach was used to develop an alternative scheme for strengthening the Gateway building, using the NSP and NDP analysis procedures. In the longitudinal direction of the building, FRP wrapping of the piers, and some strengthening of the spandrel beams was found to give sufficient seismic resistance. The structural model, with predicted crack patterns in the masonry, is depicted in Figure 10.

The overall cost of the alternative solution was less than the original scheme. In addition, the scheme was far less intrusive, which was important because of the heritage nature of the building.

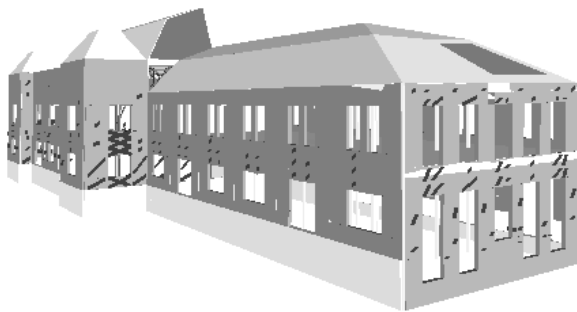


Figure 10 – Structural model of the Gateway showing predicted crack patterns.

CONCLUSIONS

FRPs have matured as a product over the past few years. Many of the design issues that have lead to problems in the past have been resolved and a number of international guidelines are now available to assist in designing a range of FRP retrofit solutions.

The list of projects where FRPs have been used to provide a cost-effective, efficient, non-intrusive retrofit solution is steadily growing. The breadth of possible applications for FRP is also growing, with the assistance of the techniques of Performance Based Design.

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