EXTENDING THE SERVICE LIFE OF BUILDINGS AND INFRASTRUCTURE WITH FIBRE COMPOSITES

Matthew F Humphreys[1], Queensland University of Technology, Brisbane, Australia

Abstract

New buildings and infrastructure are commonly based on one or more of the three traditional construction materials; timber, masonry and metal. Each of these materials suffers from it's own set of shortfalls and a design option is often chosen which is a compromise between factors such as cost, structural performance, durability and aesthetics. New materials are emerging, however, which allow developers and facility managers to adopt a more suitable choice of material for their structures. One such group of materials is fibre reinforced polymer (FRP) composites. These can be used to construct buildings with greater durability, resulting in less maintenance over the life of the structure. Their potential for modular construction allows standard components to be rapidly assembled in the factory or on site, thereby cutting construction costs. However, the most common use of fibre composites in the construction industry is currently is rehabilitation and retrofit of existing structures rather than provision of new structures. Fibre composites are able to bond to existing structures to restore initial design strength in degraded structures, increase load carrying capacity to satisfy new uses / codes, or extend and modify functionally obsolete structures without excessive additional weight. There are also potentially significant cost and environmental savings which can be realised through the use of fibre composites to rehabilitate rather than reconstruct. This paper examines some of the ways FRP composites are being used to extend the service life of buildings and infrastructure today and their future potential.

Introduction

The deterioration and critical need for renewal of buildings and civil infrastructure has recently been the focus of considerable discussion among researchers in North America, Europe and Japan [1, 2, 3]. In Canada more than 40% of bridges were built over 30 years ago and are in urgent need of replacement or rehabilitation [4], while the condition of the majority of infrastructure assets in Australia are rated as no

[1] Email: m.humphreys@qut.edu.au

higher than adequate - reflecting deficiencies in critical operations such as maintenance [5].

The causes of structural deficiencies include poor design, use of inferior materials during construction, poor construction techniques, wear and tear, insufficient monitoring / maintenance, misuse and severe natural structural actions such as earthquake. Functionally obsolete structures can be brought about through changes in use or changes in building and transport legislation [6, 7]. The pathological study of deteriorated concrete structures shows that damage has resulted from the deterioration of materials, design errors, manufacturing shortfalls or accidents [1]. Karbhari [6] identifies some of the main causes of deterioration of infrastructure as:

- Corrosion of structural steel
- Corrosion of reinforcing steel in concrete
- De-icing salts
- Freeze/thaw cycles
- Vehicle tyre chains
- Scour

A large amount of infrastructure is reaching the end of its design life due to revisions in structural codes and loading codes combined with increased traffic demands causing overloading. In addition to this, earthquakes in Loma Prieta (1989), Northridge (1994), Kobe (1995) and Turkey (1999) have demonstrated the vulnerability of many of the existing concrete structures to the effects of earthquake [6, 8].

Constructed facilities suffering from poor structural performance or those which have become functionally obsolete may need to be repaired, reconstructed, strengthened or reconfigured in order to continue performing as expected. Existing methods often involve the use of steel to strengthen or stiffen concrete and can be extremely expensive and cumbersome. Figure 1 shows an internal concrete span which has been stiffened and strengthened by the addition of a large steel member encased in fire protective vermiculite. The steel universal beam is supported at the ends on new steel columns and fixed to the slab soffit by closely spaced bolts. This method of fixing is expensive and labour intensive while the application of external fire protection involves another step in the installation process.

Figure 1 – Strengthening / stiffening suspended concrete slab with steel beams

The maintenance of structures has become an increasingly serious problem since the cost of new structures is very expensive and repairs often very difficult. Renewal cost is likely to be in the hundreds of billions of dollars and cannot be accomplished with conventional materials and technologies [6]. In Canada, the global market opportunity for infrastructure renewal is estimated to be in the vicinity of $900 billion (Canadian) [4]. The deterioration of infrastructure in countries such as Japan [1], Europe [2], the United States [6] and Canada [4] amongst others, raises the need for inexpensive, unobtrusive and effective methods of rehabilitation. In addition to this, the functional redundancy of some structures coupled with increasing demands for load and traffic capacity and seismic response requires the provision of additional structure and improved strength and ductility [6, 1, 9, 10, 3].

The costs to facilitate the rehabilitation or retrofit of existing structures can be significantly less than what would be required for demolition and reconstruction. However, existing methods of rehabilitation and retrofit using traditional materials such as steel and concrete are showing signs of inadequacy [4]. Steel plates and jackets fixed to the outside of concrete members can be difficult to attach and are susceptible to corrosion while concrete patching has little structural advantage and is usually used in conjunction with steel to strengthen the structure.

Countries worldwide are looking for a new material which provides better lifetime performance [9]. To date rehabilitation applications using fibre composite materials are showing promising results as long-term solutions [3, 14, 15, 11]. In earthquake prone areas the structural performance of steel reinforced civil structures can be improved by wrapping existing concrete columns in CFRP to increase ductility and improve earthquake response [13, 14]. Studies have shown that CFRP used in some seismic retrofit projects in Japan are less expensive than the traditional steel jackets [1]. In the US, wrapping of freeway supports using robotic tow winders or thin prefabricated sheets bonded to columns is gaining popularity. Carbon fibre sheets are also being used to prevent further cracking in concrete bridges in Switzerland [2].

More general applications are also possible. For example, a number of the infrastructure segments which received poor ratings in the Australia 2000 [15] review potentially suit rehabilitation with composites (Table 1).

Table 1 – Selected Australian Infrastructure Report Card [5]

Segment	Rating
Bridges	D
Railways	D-
Water	C-
Sewage	D-

In addition to prolonging service life of commercial and industrial structures, fibre composites can be used to help preserve culturally or historically significant structures without impacting appearance or utility.

Characteristics

Composite materials combine two or more distinct phases to produce a material which has properties far superior to either of the base materials. *Fibre* composites are a two-phase material in which one phase reinforces the other. High strength fibres are used as the primary means of carrying load and a matrix material binds the fibres into a cohesive structural unit. The combination of fibres and resin produces a bulk material with strength and stiffness approaching that of the fibres and chemical resistance dictated by the resin.

Examples of natural fibre composite materials include wood, bone, muscle tissue and grass. The benefits of natural fibre composite materials have been exploited for centuries and evidence suggests that the Egyptians used the natural fibre composite papyrus to make boats, sails and ropes as early as 4000BC. Straw has been used to reinforce bricks for over 2000 years and this method is still used today.

Synthetic fibre composites originated in the late 19th century when the first man-made polymer, phenol-formaldehyde, was reinforced with linen fibre to make Bakelite, commonly used in early electrical equipment.

In 1936, DuPont patented the first room temperature curing resin, a saturated polyester, which was released in 1942. The first epoxy resin system was produced in 1938 and Ciba introduced the widely recognised Araldite epoxy resin system in 1942. At the same time reinforcing fibres were undergoing rapid development and in 1941 Owens-Corning began production of the world's first woven glass fabric.

In the 1950's vast amounts of money and resources were allocated by the military to developing composite components. Composites tooling technology was developing and the mechanical properties of composites were improving. Thinner and stronger laminates were being produced and the advantages of composites began to include high strength to weight ratios and high stiffness to weight ratios, resistance to fatigue and the ability to retain these properties in extreme environments.

The end of the "Cold War" in the late 1980's produced a glut of fibre composites resources looking for new applications. This has brought about development of reinforcing fibres such as carbon and aramid which offer improved strength and stiffness and better impact performance over glass. Figure 2a shows carbon in the form of a roll of dry woven fibres. Resins have also undergone considerable development, most significantly the introduction of different polyester, vinylester and epoxy formulations. These new resins offer improved performance over the original high temperature curing phenolic resin in areas such as mechanical properties, chemical resistance and bonding. Figure 2b shows a typical two-part epoxy laminating resin.

(a) (b)

Figure 2 – a) Carbon fibre b) Epoxy resin

(Source [16])

The fundamental building block of fibre composites is the *laminate*. The *laminate* consists of a number of layers of reinforcing fibre stacked in a preset pattern and bound by a hardened resin. The strength and stiffness of the laminate depends largely on the amount of fibres and the direction which the fibres are laid. Laminates which are very strong in one direction can be made by aligning the fibres in all layers in the same orientation.

The most common fibre composite materials used for rehabilitation and retrofit projects are epoxy resins and carbon or glass fibres. The epoxy resin system is provided in a two parts which must be combined in exact amounts to ensure correct properties of the hardened resin. Once mixed the resin has around 30 minutes of working time (depending on the constituents) before it begins to harden. Carbon fibres or glass fibres are often used in these projects in the form of strips of either dry cloth or pre-made laminates which can be bonded to the structure after the damaged area has been prepared.

Rehabilitation and retrofit applications

Composites are particularly useful in rehabilitation and retrofit projects due to their strength-to-weight and stiffness-to-weight ratios, chemical resistance, manufacturing versatility and superior adhesion [3]. They can be thought of as akin to the application of a surface layer that either protects and/or improves on the response of the encapsulated element [12]. The materials are usually bonded externally to the structure in the form of tows, fabrics, plates, strips and jackets. To date these materials have been used effectively in the repair, strengthening and seismic retrofit of existing structures and concrete members such as beams, columns, bridge superstructure and substructure and shear walls [6].

The first recorded commercial uses of composites as a method of repair for traditional structures were in Japan in the late 1980's and in Switzerland in 1991. Since that time thousands of composite repairs have been undertaken on structures around the world [2]. Structures that have been repaired using composite materials include bridges [4, 8, 17], parking garages [8], pre-cast pre-stressed curved concrete roof structures [18] and wooden railway sleepers (crossties) [19] amongst others.

Below is a selection of case studies which are intended to demonstrate some relevant applications of fibre composites with particular emphasis on the rehabilitation and retrofit of buildings and infrastructure.

Case Study 1 – Provision of new bridge superstructure [20]

An example of an application which benefited from a temporary solution while sufficient resources were being organised is the Bennetts Creek bridge crossing on New York State route 248. The bridge carries around 300 vehicles per day, 17% of which are trucks consisting of farm vehicles, milk trucks and logging trucks.

The reinforced concrete bridge, constructed in 1926, had undergone significant deterioration from de-icing salts and its capacity had been accordingly reduced to 10 tonne (refer Figure 3). A large proportion of heavy vehicle traffic was required to detour through local roads creating additional transport cost and upset to local residents. A capital construction project being designed would upgrade the crossing in January 2000. This was viewed by local residents as too long to wait and a temporary solution was investigated.

Figure 3 – Existing deteriorated bridge (Source [20])

A partnering agreement was initiated between a number of interested parties including New York State Department of Transport, Federal Hyways Association, Hardcore Composites and a number of consulting engineers.

An on-site detour was constructed to allow passage of light traffic while the bridge was undergoing reconstruction. An FRP structure was chosen primarily due to its resistance to icing salts, light weight and ability to allow the bridge to be made in two lightweight modular components which could be transported to site inexpensively and assembled rapidly on site (refer Figure 4).

Figure 4 – New modular FRP bridge deck
(Source [20])

New bridge abutments were constructed while the deck was being designed and constructed in the factory. The new bridge was delivered to site and installed within six hours. Follow-up work, including railings and approaches were completed within six months. The estimated cost for the project was around US$400,000 compared to an estimated US$1.45M required for the permanent upgrade. However, the cost estimate for construction of the FRP bridge deck omitted a number of costs such as cost of in-house engineers and researchers, overhead charges and manufacturers profit.

Case Study 2 – Rehabilitation of existing bridge structure [21]

The bridge structure carries State Route 378 over Wyantskill Creek, New York State. The simple span T-beam structure with integral deck was built in 1932. The bridge is approximately 12m long and consists of 26 parallel beams spaced at 1.37m centres. The bridge carries five lanes without weight restrictions and is vital link to the city of South Troy, carrying approximately 30000 vehicles per day.

Routine inspection had identified deterioration in the form of salt and moisture attack of the reinforcement, concrete delamination and deterioration due to freeze thaw cycles. Concerns were compounded by the absence of original design documentation which prevented the bridge from being load rated in it's current state. Due to the importance of the bridge authorities elected to rehabilitate the structure rather than reconstruct a new bridge or post load restrictions.

Externally bonded steel plates have been used in applications like this since the early sixties and are a proven method of improvement with little imposition to bridge traffic. However steel plates can be difficult to install and can suffer from corrosion if exposed to the environment. FRP laminates were chosen over traditional steel plates due to their versatility, ease of installation and excellent durability. Figure 5 shows the FRP plates externally bonded to the bridge T-beam.

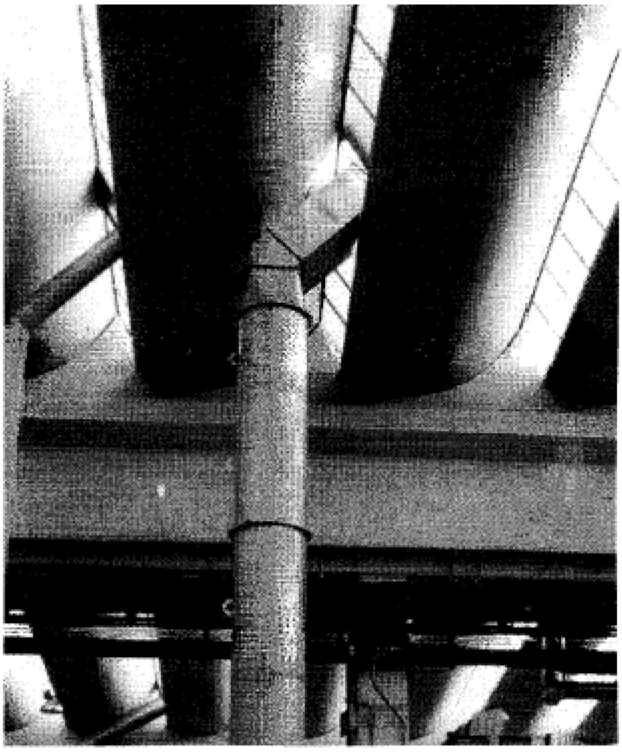
Figure 5 – Externally bonded FRP plates (Source [21])

Subsequent analysis at service live load showed that after the installation of FRP plates stresses in the main reinforcing steel were moderately reduced, concrete stresses were moderately increased and transverse live load distribution to the beams was slightly increased. It was also noted that the neutral axis shifted slightly towards the bottom of the beam.

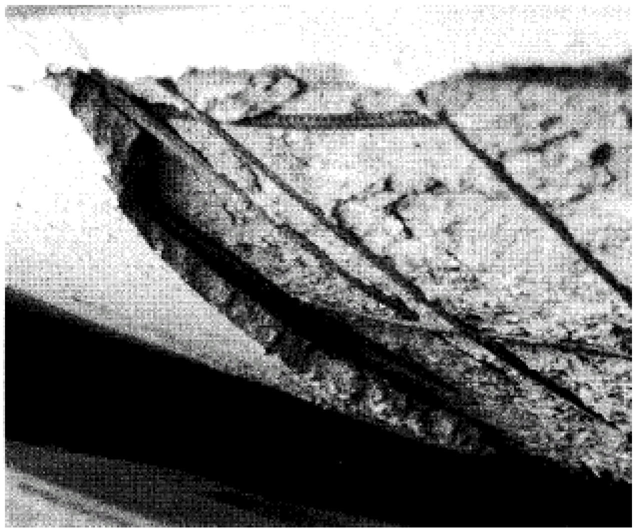
The analysis indicated that the potential of FRP plates was not fully realised within the load range studied. However, this application demonstrated that FRP laminates could be installed with minimal disruption to traffic. This project also showed a total rehabilitation cost of US$300,000 compared to a replacement cost of approximately US$1.2M.

Case Study 3 – Rehabilitation of existing compound curved prestressed / precast roof structure [18]

Precast prestressed concrete (PC) shells have been used since the 1960's. Their shape and construction allows very thin sections which makes them well suited as roof elements covering large clear spans required by industrial buildings. However, their thin profile produces poor fire performance and provides little cover to the reinforcing steel. One such application of these structures, in Italy, suffered deterioration due to the thermal effects of a chimney located near one of the roofs PC elements. Figure 6a show the proximity of a flue to the roof elements and Figure 6b shows the damaged caused by the heat from the flue.



(a)



(b)

Figure 6 – a) Location of flue to PC roof elements b) Damaged portion of roof element
(Source [18])

Assessment of the damaged roof section identified the need for strengthening or replacement of the shell. The option of replacement of the shell externally was eliminated due to the size of the roof element, its location in the building (unable to be accessed externally by crane) and the potential disruption to plant production.

Similarly, access from the inside via scaffolding or trussed support structures was impossible due to the location of machinery.

A number of options were assessed to strengthen the roof panel in place. Externally retrofitting steel prestressing cables was not possible due to the close spacing of the existing cables did not allow installation of anchorage points for the new cables. Strengthening by bonded steel plates was also not possible because of the roof's compound curve. Bonded CFRP laminates were chosen as the most suitable option as they could be installed with minimal interruption to plant production, their pliable nature allows them to follow compound curves and they have been shown to provide an adequate and durable method of strengthening.

The damaged area was prepared, patched and primed to provide adequate bonding of the carbon fibre strips. The ability to install the strips using hand techniques suited the difficult in-situ location. The strips were applied in a number of layers and sealed with a brush painted epoxy film (refer Figure 7).

Figure 7 – CFRP strips located on PC shell
(Source [18])

An investigation of the effectiveness of the repair was undertaken and consisted of load deflection measurements taken before and after the repair. It was found that the roof structure deflected at midspan approximately 16% less after the CFRP laminates were installed. It was also concluded that the repair method corrected the loss of flexure / shear stiffness. This was the first commercial application of CFRP flexible sheets for repair in Italy.

Case Study 4 – Rehabilitation of deteriorated prestressed concrete bridge piles [22, 23]

The Houghton Highway is a dual carriageway bridge in Australia linking Queensland's capital Brisbane with the northern shire of Redcliffe. The bridge crosses open water at close to sea level and consists of a number of short spans. The structure consists of an integral concrete overlay tied to prestressed concrete T-beams. The beams are used in simple spans between concrete headstocks connecting five prestressed concrete piles at each support (refer Figure 8).

Figure 8 – Houghton Highway substructure
Source [23])

In 1991 routine inspection identified deterioration of the prestressed concrete piles caused by alkali-silica reaction. The result of this reaction was internal cracking of the concrete with crumbling and spalling of the concrete leaving the reinforcing steel exposed to the marine environment. Figure 9 shows a typical longitudinal crack.

Figure 9 – Typical longitudinal crack in concrete due to alkali / silica reaction (Source [23])

The concrete and steel degradation was too advanced for concrete repair alone and a strengthening system was required to reinstate the columns original capacity and to cover the existing cracks. Due to the octagonal shape of the prestressed columns and proximity of the columns to seawater, the traditional method using steel jackets was eliminated. The upper section of the piles suffering longitudinal cracking is able to be seen by the public and a repair system was required which could cover the damage and contain the existing cracks. Concrete was considered but avoided due to the tendency for cracks to migrate through the concrete encasement. Externally bonded fibre composite materials were identified as potential candidates as they can be applied on site in a pliable form which can easily follow the shape of the column. Fibre composites had also been demonstrated to conceal repaired areas without reflecting previous cracks. Externally bonded fibre composites were also believed to offer adequate re-strengthening as well providing protection of the concrete piles from the environment through resin encapsulation during laminating (refer Figure 10).

Figure 10 – Externally bonded CFRP
(Source [23])

In total 500 piles were repaired and the rehabilitation project was completed in the year 2000. Fibre composites were not used below the water surface due to concerns relating to installation and replacement should long-term durability become an issue. The repairs are continuously monitored for in-service performance.

Summary

Buildings and infrastructure deteriorate or become functionally obsolete for a number of reasons. Potentially significant financial and environmental savings can be realised through the use of fibre composite materials to repair and rehabilitate structures rather than demolishing and reconstructing them.

As the case studies show, fibre composite materials offer a number of benefits over traditional materials for the repair and rehabilitation of structures. Benefits include versatile on site installation, ability to follow complex shapes, ability to bond well to traditional construction materials, excellent durability, non-obtrusive nature and they often require little or no interruption to traffic or downtime of machinery.

Fibre composites are demonstrating the potential to save owners significant amounts of money in the maintenance and repair of buildings and infrastructure with potential savings of between 30 and 40 percent expected over traditional materials. Worldwide the potential savings through the use of fibre composites for rehabilitation and retrofit is estimated at between US $10B and $20B annually [24].

However, two issues often emerge when designers and owners consider the use of fibre composite materials which prevent their adoption; cost and long-term durability. The cost associated with using composite materials to extend the service life of structures is continually reducing and composites are beginning to compete on cost with traditional materials. While demonstration projects are an important part of building confidence in the material, research is required to provide cost / benefit evaluation of real world applications. Further research is also required into the long-term durability of the material to provide designers and consultants with confidence when recommending fibre composites as a viable option.

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