A future with Advanced Composites in Bridge Engineering

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SYNOPSIS

This paper highlights some of the key contributions that advanced composites have made to bridge strengthening, with some case studies in New Zealand.

1 GENERAL

Advanced composites are used in bridges in three primary areas. These are to strengthen and rehabilitate existing bridges, to substitute steel reinforcement and prestressing strands/bars in concrete decks, and to build bridges entirely made of advanced composites as an alternative to traditional materials. The use of advanced composites in strengthening or repairing existing bridges involves bonding advanced composites as external reinforcement to the substrate made of concrete, steel, cast-iron, or timber. The second area is where it is used as a substitute for steel reinforcement, particularly in corrosive environment. This is attractive in countries where concrete bridge decks are exposed to de-icing salts during winter. The third area of use in the fabrication of bridge decks entirely made of advanced composites is not yet common. The main focus of the paper is on the first area of application, namely the strengthening of existing bridges.

Strengthening bridges with advanced composites as external reinforcement is considered to be an improved and efficient method over steel plate bonding. Although the steel plate bonding technique has been widely used for strengthening bridges since the early 1970s, it has a number of drawbacks such as the difficulty of providing scaffolding due to limited access, the need for joints on site because the steel plates are heavy and need to be made in small and manageable pieces to keep installation simple, the need for costly road closures over long periods, and corrosion of steel plates within aggressive environments.

Advanced composites can overcome the above difficulties as they are lightweight, easy to handle on site, and possibly do not require scaffolding for installation. They do not need joints and can be made of continuous sheets/strips. They normally require a shorter installation time than steel plates, thus minimising costly road closures. There are no corrosion problems, and they have outstanding fatigue performance.

The paper presents an overview of the constituents, properties, products, and installation methods for advanced composites with particular reference to bridge strengthening applications. It describes some of the situations where advanced composites have been successfully used in strengthening existing bridges, with examples from a few projects in New Zealand.

2 CONSTITUENTS AND PROPERTIES

Advanced composites are made of fibres and resin by combining them in such a way as to retain the individual properties of the fibres and resin. To this effect, the fibres and resins are mixed at a specific volume ratio to achieve the desirable properties for individual applications. The fibres are the primary load-carrying component having low-weight, high-strength, and high-stiffness properties. The resin, known as the matrix, provides a continuous medium protecting the fibre reinforcement and transferring the stresses between fibres.

2.1 Fibres

The common fibres used in composites for civil engineering applications are carbon, aramid, and glass. The commonly used resins are polyester, epoxy, and phenol.

Fibres have higher strength and lower weight compared to steel and concrete. The Young's modulus of aramid and glass fibres are lower than that of steel, whereas for carbon it is generally higher than that of steel. Table 1 tabulates some of the characteristics of carbon, aramid, and glass fibres[1]. Figure 1 shows the stress/strain relationship of fibres compared with steel[2].

Fibre	Tensile Strength (MPa)	Youngs Modulus (GPa)	Density (kgm^{-3})	Thermal Expansion ($x10^{-6}/ {}^{o}C$)
Carbon	2,100 – 7,100	220 – 900	1,740 – 2,200	-1 – 0
Aramid	3,150 – 3,600	58 – 160	1,390 – 1,470	-2 – -6
Glass	3,445 – 4,890	72 – 87	2,460 – 2,580	6 – 10
Steel	480 – 700	200	7,850	12

Table 1: Typical properties of fibres

Carbon fibres have the lowest strain to failure among these three fibres as can be seen in Figure 1. The high strength and stiffness coupled with the low density and thermal expansion properties of carbon fibres lend themselves to be suitable for structural requirements that are weight and stiffness sensitive. Carbon fibres are anisotropic and inert to most environmental influences such as alkalinity, moisture, and UV rays. They also have a higher fatigue resistance than aramid and glass fibres. Carbon fibres are made in several grades to suit different applications.

Aramid fibres are non-synthetic whereas both carbon and glass fibres are synthetic. They have high tensile strength and behave in a linearly elastic manner until failure. However, they are weak in compression and their behaviour under compression is plastic. Aramid fibres are a thermoplastic type but resistant to combustion up to $200^{o}C$. They are susceptible to moisture absorption, UV rays, and alkalinity. Their important characteristic is their high resistance to impact and abrasion. Consequently, aramid fibres are used in applications that require impact resistance and high tensile strength. They are not suitable for use in applications that require compression or shear strength.

Table 2 illustrates the degradation that occurs in aramid fibres due to exposure to UV rays with time[3]. Surface treatment (e.g., gel coating) could mitigate this at an increased cost.

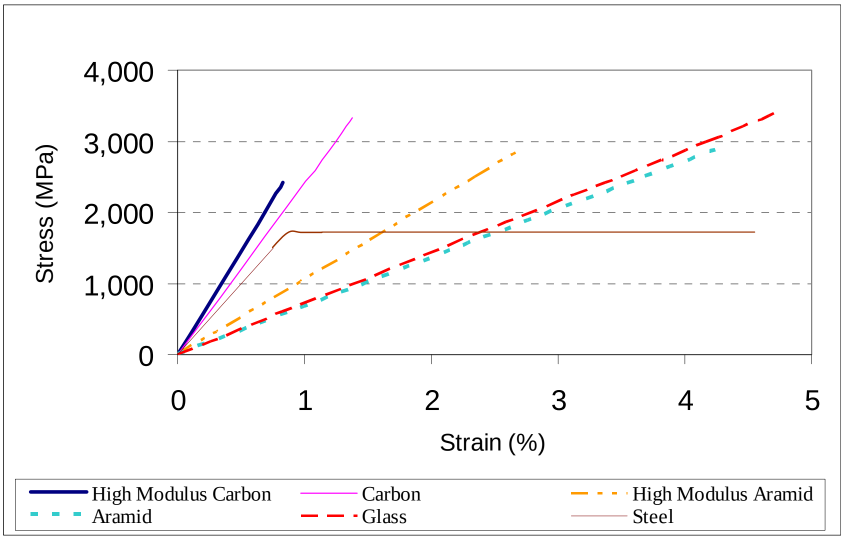


Figure 1: Stress/strain relationship of fibres

Time (months)	Strength Retained (%)
Unexposed	100
6	90
12	81
18	69
24	69

Table 2: Effects of UV rays on aramid fibres

Glass fibres have a high strain to failure (see Figure 1) and a low Young's modulus (see Table 1). They are susceptible to creep or stress rupture and thus their strength is normally limited to 25–35% of their ultimate tensile strength. Like aramid fibres, they are susceptible to damage from moisture absorption and alkalinity, and have a good resistance to impact.

2.2 Resins

The resins are generally synthetic and are divided into two types: thermosets and thermoplastics. Thermosetting is an irreversible process where the resins pass from a liquid state to a permanent solid state in a chemical reaction. Thermosetting resins include unsaturated polyesters, epoxy resins, and phenolic resins. Thermoplastic resins can be heated to an elevated temperature and cooled to the required shape and form.

The properties of commonly used resins are tabulated in Table 3[1].

Type	Tensile Strength (MPa)	Youngs Modulus (GPa)	Strain at Failure (%)	Density (kg/m^3)
Polyester	50 –75	3.1 – 4.6	1.0 – 2.5	1,110 – 1,250
Epoxy	60 – 85	2.6 – 3.8	1.5 – 8.0	1,110 – 1,200
Phenol	60 – 80	3.0 – 4.0	1.0 – 1.8	1,000 – 1,250

Table 3: Typical properties of resins

The main characteristics of polyester resins are that they are easy to process and can cure at atmospheric temperature. The shrinkage after curing can be up to 8%. Polyester resins are relatively inexpensive.

Epoxy resins contain, in addition to the resin, a hardener. Curing should be carried out at an elevated temperature to achieve the best properties. Epoxy resins have good resistance to environmental and chemical influences. Although they are about 1½ to 3 times more expensive than polyester resins, epoxy resins exhibit better mechanical properties and much less shrinkage (2–3%). Their durability characteristics lend them to be the most widely used resins for the high performance composites.

The principal feature of phenolic resins is their high fire resistance characteristics. They also exhibit good resistance to acids. However, the most undesirable property is that they produce water during curing. If they are not cured fully they can produce steam during a fire, which can result in the failure of the laminate.

2.3 Composites

The properties of the advanced composites are derived from both the fibres and the resins and depend on factors such as fibre volume fraction, fibre orientation, type of resin, and degree of curing. The Young's modulus and strength of the composites are lower than that of the fibres alone. The volume fraction of fibres normally ranges between 50% and 65%.

For unidirectional composites, Young's modulus (E_c) in the direction of the fibre is given by

$$E_c = E_f V_f + E_m V_m$$

where E_f and V_f are respectively Young's modulus and volume fraction of the fibre; E_m and V_m are respectively Young's modulus and volume fraction of the resin.

Table 4 compares the properties of composites with steel[3].

Property	Range of Values for Composites	Comparison with Steel Properties
Modulus	20 – 138 GPa	1/10 – 2/3
Strength	340 – 1,700 MPa	1 – 5 times yield
Strain Limits	1 – 3%	1/10 – 1/5
Weight	12 – 19 kN/m^3	4 – 6 times lighter

Table 4: A comparison of composite properties with steel

The distinctive feature of composites is that, unlike steel, concrete, and other conventional isotropic materials, their properties are directional. Based on the fibre orientation, the properties of composites are unidirectional, bi-directional, or quasi-isotropic. The directionality should be taken into account in design. Composites are linearly elastic until failure, which is another deviation from steel and other ductile materials that exhibit plastic behaviour near failure.

When advanced composites are used for flexural strengthening of structural members they reduce the ductility of the original member. However, by ensuring the steel strain at the failure of the member (either failure due to concrete crushing or failure of composites) is sufficiently higher than the steel yield strain, adequate ductility can be achieved.

The durability properties of advanced composites are not yet well established, mainly due to their relatively short existence within the civil and structural engineering community. However, numerous accelerated laboratory experiments have been conducted to study the durability of different advanced composites. Based on these accelerated laboratory experiments, advanced composites have been reported to achieve satisfactory results if properly designed and installed.

3 COMPOSITE PRODUCTS AND INSTALLATION METHODS

There are several forms and shapes of composite products that have been used successfully on bridge engineering applications around the world. These composite products include sheets, pre-impregnated flats, textiles, rods, grids, strands, and pultruded sections as shown in Figure 2.

Figure 2: Advanced Composite Products

Installation of advanced composites for bridge strengthening applications is normally done by the *Wet Layup* method, as illustrated in Figure 3.

The surface is prepared by grinding or sand blasting to remove any loose material, and dirt. A priming coat is then applied to the substrate. Sometimes putty is used to level the surface. This is followed by first coat of resin. The dry fibre sheet is then firmly placed on the resin. Another coat of resin is applied on the fibre sheet and rolled evenly over the surface to remove any excess of resin and air bubbles. The process of resin and dry fibre sheet application is repeated to obtain the required number of layers. It is completed with a protective coating. Sometimes the fibre sheet is pre-wet with resin before laying on the substrate to allow better fibre/resin ratio control.

It is also common to use pre-impregnated flats or laminates bonded to the substrate with an adhesive to improve the quality of composite and reduce the time of installation on site. Pre-impregnated flats are composite products, which have resin added to the fibres and fully cured for application with an adhesive agent.

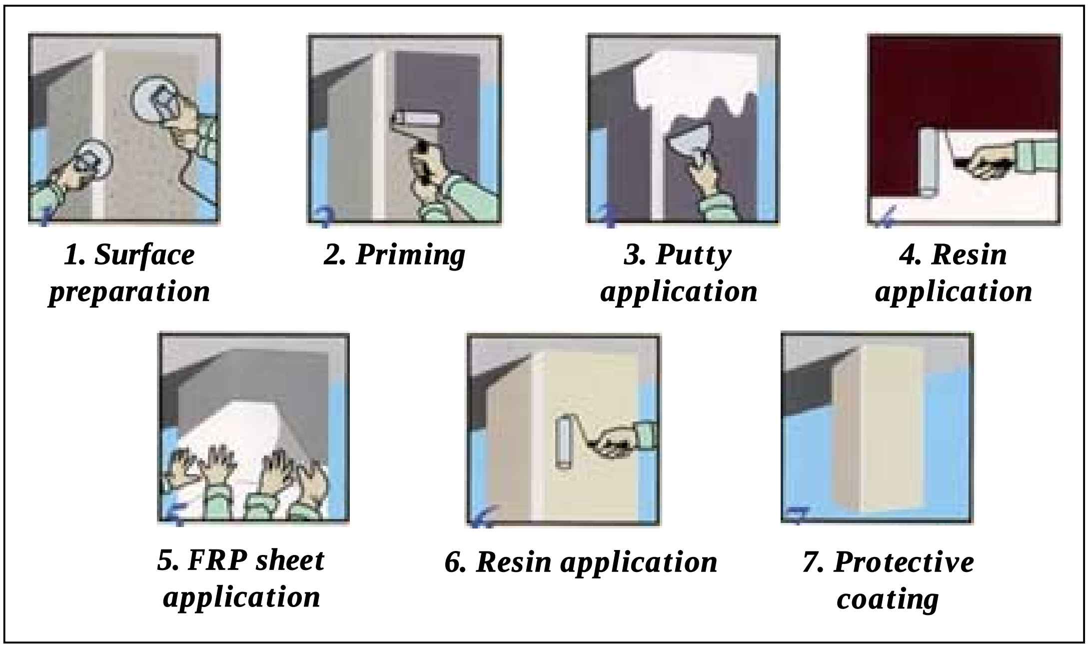


Figure 3: Wet Layup Method

4 APPLICATIONS IN STRENGTHENING EXISTING STRUCTURES

There are several situations in which a structure would require strengthening or rehabilitation due to lack of strength (flexure, shear etc), stiffness, ductility, and durability. Some of the common situations where a structure needs strengthening during its lifespan are seismic retrofit to satisfy current code requirements, upgraded loading requirements, damage caused by accidents and environmental conditions, initial design flaws, and change of use.

Following are a few example projects in New Zealand, which highlights the range of situations where advanced composites can be used in strengthening existing bridges.

4.1 Makarau Bridge

Makarau bridge is on SH16, located about 20km north of Helensville town. The bridge is made of two simply supported end spans of 9.14m and main arch span of 25m (Figure 4). The bridge was constructed in 1934 and did not have adequate capacity to allow Class I traffic. Additionally, the bridge is on the Overweight Vehicle Route and thus it was decided in 1999 to upgrade the bridge for 85% HN-HO-72 loading[†].

Figure 4: Makarau Bridge

[†] The strengthening works were carried out as a design and build contract. Opus International Consultants were the Principal Consultant. The contractor was Conspec, who appointed Michael Newby & Associates for the design of composites.

The critical structural elements were the longitudinal reinforced concrete beams in the two end spans, which lacked flexural and shear capacity[4]. Traditional strengthening methods such as steel plate bonding was not favoured due to their known problems and it was decided to use advanced composites to strengthen the longitudinal beams.

Fosroc Towsheet (Carbon fibre composites) was used for both flexural and shear strengthening of the beams as carbon fibres have better stiffness and environmental resistance than that of glass fibres. For flexural strengthening, one sheet on the outer beams (30% increase from their original capacity) and three sheets on the centre beam (70% increase from its original capacity) were applied to the beam soffit in the longitudinal direction. Shear strengthening of the beam (25% increase from its original capacity) was done by wrapping the sheets around the beam in the transverse direction at the beam end regions.

Figure 5(a) shows one of the strengthened outer beams prior to applying the protective coating. All surfaces of the beams received coating *Deckguard* as protection against environmental effects and accidental damages to the composites. Additionally it provided an effective barrier against moisture for remaining, exposed concrete surfaces.

Figure 5(a): Strengthened Outer Beam showing Fosroc Towsheet at the end regions and beam soffit

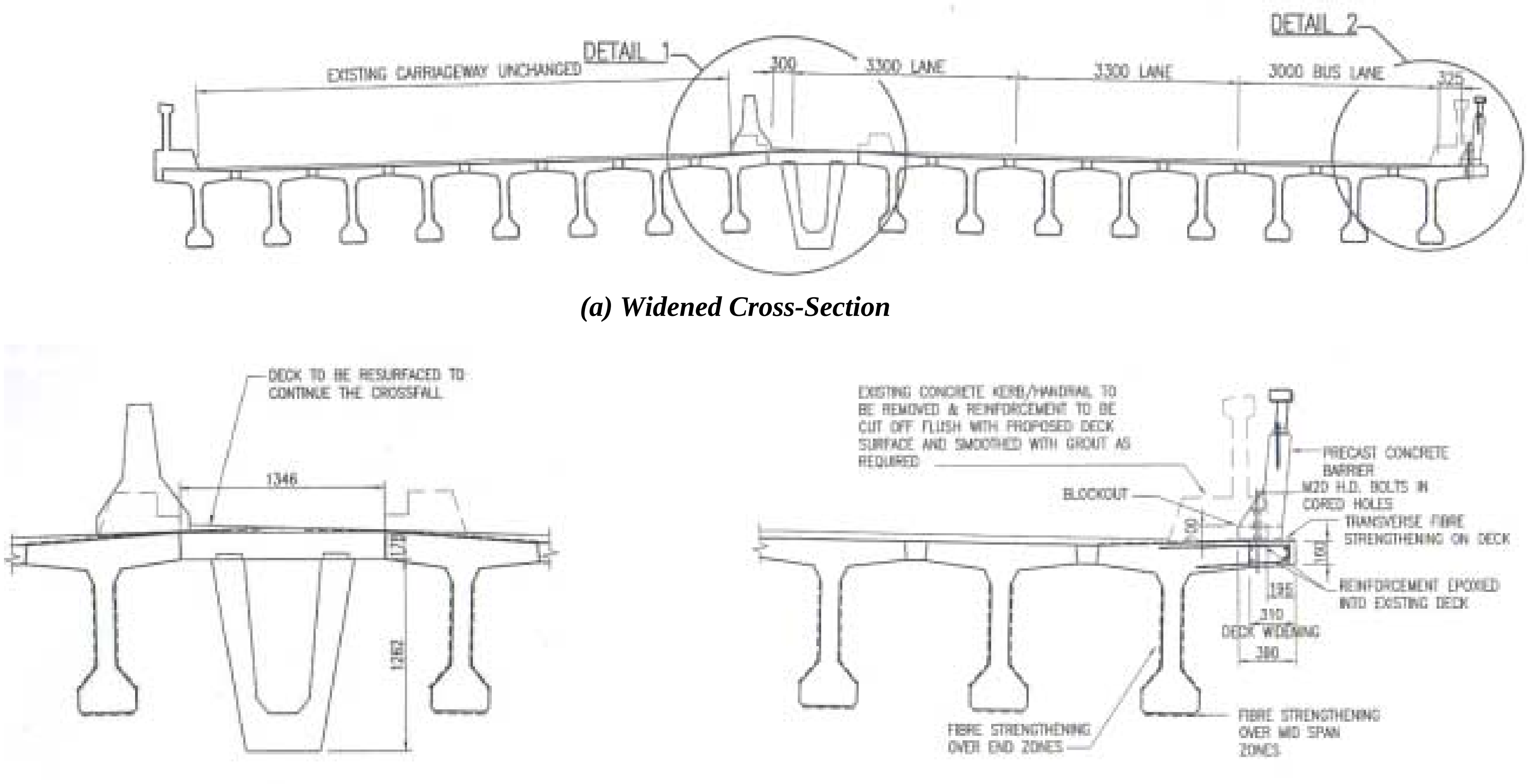
Figure 5(b): Strengthened Outer Beam after receiving the protective coating

The installation of Fosroc Towsheet took place in the winter period. Curing of epoxy resins thus took longer than expected and caused delays. Otherwise the strengthening of the beams was carried out without any problems. Makarau Bridge is one of the first few bridges in New Zealand to be strengthened with advanced composites and the strengthening is found to be satisfactory.

4.2 Shoal Bay Bridges 4 and 4A

Shoal Bay Bridges were twin, single span structures located on the on-ramp and off-ramp to the Auckland Motorway at Esmonde Road. Each superstructure comprised of eight, 26m long precast prestressed concrete T-beams. As part of the Esmonde / Akoranga Drive Traffic Link Scheme, these bridges were widened and strengthened to allow an additional bus lane in 2001[‡][5].

[‡] The strengthening works were carried out as a design and build contract. Opus International Consultants were the Principal Consultant. The contractor was Construction Techniques, who appointed Holmes Consulting for the design of composites.



(a) Widened Cross-Section

(b) Detail 1 - Median Widening

(c) Detail 2 - Edge Widening

Figure 6: Shoal Bay Bridges Widening and Strengthening

These bridges were constructed in 1958 as part of the Auckland harbour Bridge Project and were designed to a relatively low traffic loading. Widening only one structure by extending its outer edge or replacing its superstructure would have required new foundations. Any work within the inter-tidal zone needed coastal permit, which could result in delays in obtaining the necessary Resource Consent. Therefore, it was preferred to avoid any construction work in the inter-tidal zone but to join the two structures and strengthen the superstructure. This option also had reduced traffic disruption, as only lane closures were required compared to full traffic diversion required in other options.

The final option (Figure 6) involved infilling the median gap between the two superstructures and extending the outer deck edge of one of the structures to gain the remaining deck width required. This resulted in extensive strengthening work to the superstructure.

Advanced composites were chosen for strengthening the beams and outer deck edge as it has the advantages of being lightweight, good environmental resistance, and easy to install on site with minimum scaffolding.

The new median deck was supported by a standard precast, prestressed U-beam. As shown in Figure 6, carbon fibre composites were used to strengthen the mid-span and end-span regions of all beams for enhanced flexural and shear capacity respectively. Additionally, carbon fibre composites were bonded to the top surface of the extended outer edge deck in the transverse direction to improve the flexural capacity of the cantilevered deck. The strengthening was completed with the application of protective coating. Figure 7 shows the strengthened beams and new U-beam at the median.

Figure 7: Shoal Bay Bridges after Widening and Strengthening

4.3 Newmarket Viaduct

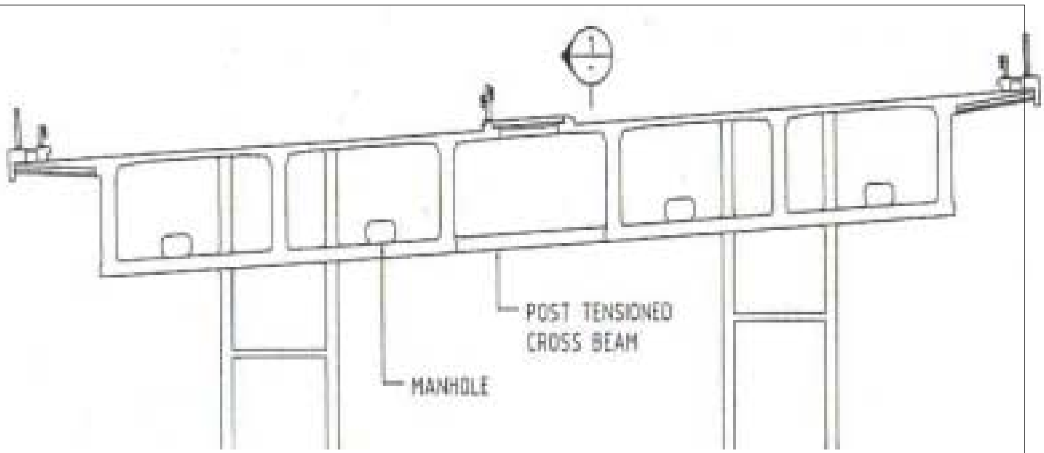
Newmarket Viaduct is a cast in-situ post tensioned box girder bridge constructed in the late 1960s. It is 690m long with 16 spans. The standard span is 42m while the maximum span is 60m. The bridge is part of a motorway and is built over three main roads and a railway line. Figure 8 shows a part of the bridge over Broadway, a main highway in the busy Newmarket area.

Figure 8: Newmarket Viaduct over Broadway

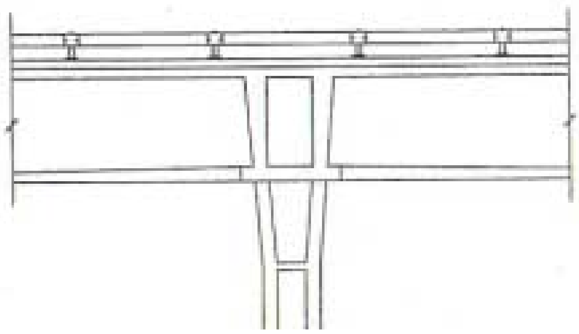
The bridge consists of two, 2.4m deep reinforced concrete box girders connected by diaphragms at piers. Each girder has twin cells and diaphragms connecting these cells at mid-spans.

This bridge received extensive staged strengthening work between 1970 and 2000, as the initial design overlooked the differential temperature effects and resulted in tensile stresses developing at certain locations of the bridge soffit.

In 2000-2001, cracks were observed in the diaphragms of piers 10 and 11 during routine inspections. The piers 10 and 11 support the longest span of 60m over Broadway. Assessments indicated that these pier cap cross beams were deficient in shear and torsion[6]. A cross section at a typical pier is shown in Figure 9. The discontinuity in the force path due to manholes and drainage pipes was critical that it significantly reduced the capacity of the diaphragms. It was found that the outer cell diaphragms were more stressed than inner cell diaphragms, especially near the manholes.



(a) Cross-section



(b) Section at 1-1

Figure 9: Typical sections at a pier
(Courtesy of Beca Carter Hollings and Ferner)

Various options were considered to improve the capacity of these diaphragms, including infilling the cells within the pier cap cross beams with reinforced concrete and post-tensioning. However, the strengthening method should retain the existing manholes through the pier caps for future inspections and maintenance. Additionally, traffic disruption to users should be minimal during strengthening works. It was also important that this interim strengthening work should not impair any future seismic retrofit or widening of the bridge.

Considering all these constraints, it was decided to strengthen the critical, outer cell diaphragms of pier cap cross beams at piers 10 and 11 with advanced composites, which is less intrusive than other strengthening options[§]. Shear capacity increases by 10% when strengthened. Figure 10 shows the strengthening with glass fibre composites on the outer cell diaphragm of pier cap cross beam at pier 10. Glass fibre composites was chosen for this application as it was required for shear enhancement and the strengthening was within the cells and not affected by the outside environment. Additionally, glass fibre composites are several times cheaper than carbon fibre composites.

Figure 10: Strengthened Diaphragm of the Outer cell of Pier Cap 10

5 CONCLUSIONS

The use of advanced composites in bridge engineering has steadily increased over the past few years. A number of bridge decks and piers have successfully been strengthened or retrofitted with advanced composites in many countries. Concrete bridge decks have been reinforced and pre-stressed with FRP rebars and cables. A few entirely composite bridges have been built in the UK, Europe, and US.

Currently, advanced composites are proposed in a few bridge live load upgrade and seismic retrofit projects in New Zealand (Newmarket Viaduct and old Grafton Bridge). Advanced composites are readily used for bridge strengthening applications mainly due to the relative ease of installation. The schemes developed for strengthening with advanced composites have mostly been either the lowest cost or the only plausible solution available. The material costs of the advanced composites are several times more than that of conventional materials (e.g., steel and concrete). However, the life-cycle cost, including fabrication, construction, protection, and

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[§] Beca Carter Hollings and Ferner (BCHF) designed the advanced composites and Construction Techniques carried out the installation on the bridge.

projected maintenance costs, is comparable and can be less than that of conventional materials.

There is an element of reservation on the use of advanced composites because it has been in use within the construction industry for a relatively short period. Therefore, the long-term behaviour of FRP composites have been studied from accelerated laboratory experiments. Numerous R&D works are focused on durability issues, improved installation techniques and improvement of design methods, aiming at producing cost-efficient designs.

6 REFERENCES & NOTES

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