FRP Strengthening of the West Gate Bridge Concrete Viaducts

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Abstract  At 2582.6 m in length, Melbourne's West Gate Bridge is the second longest bridge in Australia. Completed in 1978, the bridge comprises a cable-stayed steel box girder, with two end concrete sections of similar design. Due to Melbourne’s rapidly growing traffic demand, an increase in the capacity of the bridge was necessary. The winning proposal was to augment the number of traffic lanes by one each way, increasing the total from eight to ten. This additional torsional loading on the bridge added, required large areas of the pre-cast concrete sections to be retrofitted with externally bonded, carbon fibre (Fibre Reinforced Polymer, FRP) strengthening. Whilst ultimately being the largest FRP project in the world, clever early design, detailing & planning decisions, resulted in a number of innovations, which ultimately delivered major savings to the project. This paper highlights the case study of the West Gate Bridge and discusses some of the issues related to optimized design solutions and latest research on anchorage details. It also explores application topics including preparation techniques, environmental conditions and quality assurance issues, dealing with high strength concrete elements, strengthened with FRP systems.

Introduction

For nearly the last 40 years, the West Gate Bridge has been an iconic structure on Melbourne’s landscape. It services the city as the major crossing over the Yarra River, linking the west to the east. Despite the tragic construction collapse in October 1970 which saw 35 workers lose their life, it has served the community well. However, as with many major infrastructure projects around the world, the demands of a growing, modern society, have placed new stresses on the structure.

Nowadays the West Gate Bridge needs to accommodate not only higher traffic loadings, but also increased traffic volumes. The bridge was originally designed
to carry 25 tonne loads, but with increasing truck sizes, transport mass load limits are now up to 68 tonnes for B-Double trucks. It was built to handle 40,000 vehicles per day, but is now required to service in excess of 160,000 vehicles per day. Furthermore, there have been a number of updates to the relevant bridge design standards around the world, including AS 5100-2004 [1], requiring new capacity evaluations.

The 2.6 km bridge comprises three sections; an 850 m long central steel box girder portion with cable stays, and east (870 m long) and west (670 m long) approach viaducts, composed of segmental pre-stressed concrete box girder sections (Fig. 1).

The concrete viaducts consist of 3 cell pre-cast box segments forming the central spine, with pre-cast transverse cantilevers, supporting the outer lanes of the pre-cast deck.

Fig. 1. West Gate Bridge, Melbourne, showing the Eastern Concrete Viaduct (left) and Central Steel Spans

Fig. 2. West Gate Bridge, Melbourne, expanded view showing the structural components and the new traffic loading conditions and lane configuration (on each carriageway)
As part of the M1 freeway upgrade, the Victorian State Government and in particular VicRoads, a statutory Corporation within the Victorian Government Department of Transport, wanted to ease congestion across the bridge and improve traffic flow. As a joint Federal Government funded project, it awarded the project to an Alliance in mid 2008. The West Gate Bridge Strengthening Alliance (WGBSA) partners included VicRoads, UK design specialists Flint & Neill Partnership, local engineers Sinclair Knight Merz and head contractor John Holland.

The resulting solution was to increase the traffic from four to five lanes both ways, without widening the bridge (Fig. 2). The two end concrete viaduct sections of the bridge required upgrades to flexure, shear and torsion. Flexural strengthening was generally achieved by the installation of some complex post-tensioning that was installed longitudinally, along the central spine section of the concrete viaducts, within the cells. Externally, the strengthening involved a carbon fibre solution, which relied heavily on the specialist material supplier advice regarding options for the final choice of materials as well as state-of-the-art research on connection details. This forms the basis of this particular case study.

**Design Development**

The early stages of design development for this project were crucial in setting the stage for the final solutions adopted. Many alternative strengthening schemes were being considered with a variety of methods and materials. These included steel plate bonding, external post-tensioning and vacuum bagged FRP systems, utilized internally within the spine and externally, including on the traffic deck itself.

A key issue was that the client had previous experience with externally bonded FRP technology, in which the composite action is formed on site by applying the dry FRP materials, with epoxy adhesives, onto the concrete surface. It was a combination of these materials that was eventually adopted due to their ease and quickness of application (lightweight), ability to be customized to suit both design and physical requirements and their durability in an external environment, ultimately providing the most cost-effective solution.

VicRoads had successfully trialed and used carbon fibre strengthening before on many infrastructure projects over the last decade. These included the bridges at Little River (and Skeleton Creek) on the Geelong Freeway upgrade in 2001 [2][3]. A relatively small section of the West Gate itself was then strengthened in 2002 during an earlier upgrade to the inbound lanes at the Williamstown Rd on ramp [4]. In 2004, strengthening works to some crossheads on the M1 upgrade at
Warrigal Rd overpass were also completed. In line with the increased use of fibre reinforced polymer solutions worldwide over the last 25 years, these local projects had again demonstrated the clear cost and time advantages of a carbon fibre solution for strengthening of concrete members in major infrastructure projects with minimal traffic disturbance.

Furthermore, the importance of key influencers from industry experts including Universities and other institutions (eg Australian Road Research Board, ARRB) cannot be underestimated. Within Australia in the past 12 years, research work at various leading tertiary institutions has been instrumental in helping to develop the local market for FRP, especially within the civil infrastructure & building construction industries. By supporting key research with institutions like Monash University, leading manufacturers not only helped to demonstrate the performance characteristics of FRP, but helped in the overall acceptance of FRP as a mainstream concrete repair and strengthening strategy. Fundamentally, it gave road authorities the confidence of externally bonded systems, apart from the traditional steel plate alternatives that had been adopted previously. The research also allowed investigation of some innovative applications, some of which were used on the West Gate Bridge project.

Due to the uneven peak traffic loading, the torsional design case on the spine box girder was a key design load case. The use of a continuous closed system to effectively transfer the forces around the precast spine section (Fig. 2) was closely considered. The difficulties arose in trying to detail the materials required for these forces in terms of material type, grade and geometry, whilst considering fundamental design factors of strain compatibility and effective bond strength to the concrete surface.

Importantly, the West Gate project design consultants responsible for the concrete sections, SKM, had some previous experience in the use of FRP materials. In fact early schemes for the current strengthening project, adopted a preliminary design based on the previous 2002 works – it proposed to use “off-the-shelf”, standard section materials. The result was an engineered and technical solution that worked, but involved over 100 km of 1.4 mm thick laminate material, of normal Grade modulus (165 GPa). This is normally supplied in rolls (Fig. 3 left). The cost and time to install this solution sent many “shock waves” through the contracting side of the Alliance team. Early design also included at least two difficult areas of construction: firstly, a detail to strengthen the deck slab from the top to complete the “torsional loop”, with the obvious cost and disruption to the already congested traffic flows and secondly, significant lengths of CF laminate to be installed within the 3-cell boxes that made up the concrete viaducts. This in itself posed numerous application issues within what was arguably a “restricted” space environment. So whilst the design team had produced a technically sound
solution, it did not totally satisfy the construction team’s criteria of “economical buildability” within the budget constraints. There had to be a better way.

Fig. 3. Typical roll of Carbon Fibre laminates with protective peel-ply (left) and thicker, flat “custom-made” sections in special timber packaging (right)

Advancements in carbon fibre design and detailing
- Optimizing the solution

The initial design greatly interested material suppliers around the globe, on the simple basis of the amount alone. However, there was an opportunity to offer an alternative solution; one that was of high value to the WGBSA and VicRoads, not high cost. One that was based on some basic principles of the materials but by using the materials in more efficient ways, one could demonstrate and deliver, an innovative solution to the Alliance.

Key people within the eventual supplier’s company (BASF), were able to contact the design team and offer to work more closely with them. A number of meetings were held to identify key design parameters and whereby the primary material properties of the carbon fibre were discussed. These included the Ultimate Tensile Strength (UTS), the Young’s or Elastic Modulus (E) and the section size (S), which involves the laminate (and fabric) dimensions of width and thickness. After presenting some alternative material options, the design team was then able to produce a design and detailing solution, which was optimized. For a project the size of West Gate, this was of paramount importance.
Customized Sections

The carbon fibre used in the West Gate Bridge project consists of two fundamental types: firstly, carbon fabric (for use where it needs to bend around corners) and secondly, hard, pultruded laminates applied to planar (flat) surfaces. The vast majority of carbon used was of the laminate type. Typical CF laminates are normally supplied in rolls, having either a 1.2 or 1.4 mm thick section (Fig. 3 left) and in E-Modulus grades of 165, 170 and 210 GPa. The eventual material supplier introduced the concept of “custom-made” sections for the carbon laminates, where the designer could consider the possibility of having a more appropriate mix of section size (width x thickness), modulus and strength (Table I).

Table I. Example Comparison of Carbon Laminate properties and custom-made (*) sections, available for design

<table>
<thead>
<tr>
<th>Type</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width b (mm)</td>
<td>120</td>
<td>120</td>
<td>100</td>
<td>100</td>
<td>50</td>
</tr>
<tr>
<td>Thickness t (mm)</td>
<td>1.4</td>
<td>1.4</td>
<td>2*</td>
<td>4*</td>
<td>1.4</td>
</tr>
<tr>
<td>S (b x t) (mm)</td>
<td>168</td>
<td>168</td>
<td>200</td>
<td>400</td>
<td>70</td>
</tr>
<tr>
<td>Tensile Strength UTS (MPa)</td>
<td>2500</td>
<td>3100</td>
<td>3300</td>
<td>2500</td>
<td>1500</td>
</tr>
<tr>
<td>Young’s Modulus E (GPa)</td>
<td>165</td>
<td>170</td>
<td>210</td>
<td>260</td>
<td>460</td>
</tr>
<tr>
<td>UTS x S</td>
<td>420</td>
<td>521</td>
<td>660</td>
<td>1000</td>
<td>105</td>
</tr>
<tr>
<td>Normalized UTS x S (over a Type 1 120 x 1.4 section)</td>
<td>100</td>
<td>81</td>
<td>64</td>
<td>42</td>
<td>400</td>
</tr>
<tr>
<td>E x S (x10³)</td>
<td>27.7</td>
<td>28.6</td>
<td>42</td>
<td>104</td>
<td>32.2</td>
</tr>
<tr>
<td>Normalized E x S (over a Type 1 120 x 1.4 section)</td>
<td>100</td>
<td>97</td>
<td>66</td>
<td>27</td>
<td>86</td>
</tr>
</tbody>
</table>

As indicated in Table I, a discerning designer may choose from a variety of grades of carbon laminate materials. Consideration then needs to be given to whether the design is either majority strength or modulus related, assessing strain compatibility and bond/anchorage issues, for the structural element in question. It can be seen based on normalized values, that the amount of material required can be dramatically affected by the choices available. As a simplistic example, comparing Type 1 to Type 3 materials on and “E x S” basis only, one could theoretically use 34% less material (ie 100 versus 66). Prior to deciding on a section profile however, it is advisable to confirm with material suppliers as to the availability and cost of the non-standard and thicker “custom-made” sections, as they are generally manufactured to order and for large projects only. However, a wide range of standard thickness and widths exist, within the various strength and
modulus grade materials which are available, to allow for optimized engineering
designs, in a majority of cases.

The West Gate Customized Solution

The sheer scale of the West Gate Bridge project demanded the use of a “custom-
made” solution; a solution that would not be considered for “normal” sized
projects. Based on some of these new parameters, various redesigns were
completed, along with the appropriate costing models. This process eventuated in
special sections being specified and subsequently manufactured for the project.
These included a 120 mm wide x 2 mm thick laminate of Grade 210 GPa and a
unique 100 mm wide x 4 mm thick profile of Grade 260 GPa (used on the
cantilevers, Fig. 4).

Not surprisingly, the construction team of the WGBSA immediately saw the
advantages of these sections. The total length of laminate reduced from the
proposed 100 km of 120 x 1.4 mm “thin” laminate to around 42 km of an
optimized combination of “thick and thin” laminate. This resulted in a significant
reduction in application time and therefore cost savings. The use of larger section
sized FRP materials on the underside of the bridge, not only resulted in a
reduction of the total square meters of FRP used, but encouraged the designers to
redistribute the materials away from the deck and inside the cells. Significant
benefits were achieved in the following areas:

- No top deck strengthening was eventually required, due to the sufficient
capacity of the existing deck reinforcement, to take the additional torsional
forces, thus eliminating major traffic disruptions
- Almost no FRP needed to be applied inside the problematic 3 cell pre-cast box,
spine sections
- Lower preparation costs (approx 50% the surface area of substrate concrete
needed preparation)
- Reduced labour required for installation
- A reduction of approx 50% in the amount of adhesive resins required
- Reduced time and cost required for the complicated access systems involved
- Overall reduction in program for full installation.

Due to the thickness and stiffness of these particular laminates, transport needed to
be via pre-cut sections, loaded into timber crates (Fig. 3, right). This method of
delivery was ultimately seen as a major advantage to the quality systems adopted
on the project due to the ability to individually number each piece (via bar coding)
and thereby have full traceability for a total quality approach.
So despite an overall increase in cost of carbon fibre materials, the reduction in installation time and overall project cost was very attractive to the WGBSA.

The West Gate Detailing - Connections

In parallel with customizing of FRP sections, some interesting research was being completed at Monash University, regarding a couple of key connection details (Fig. 5). The first involved the lapping of the laminates with the fabric at the lower corners of the spine (corner splice detail) and the second concerned the detailing of the laminate into the underside of the deck (outer web/deck soffit anchorage detail).
Careful consideration of the flow of forces around the section was required, due to the torsional load case caused by uneven peak hour traffic flows, on either side of the bridge and this resulted in some innovative detailing.

At the lower corner detail (Fig. 6), a combination of two layers of uni-directional carbon fabric, lapped with the (uni-directional) spine carbon laminates was initially installed. The research then determined that by applying a layer of bi-diagonal (+/- 45 deg) carbon fabric, over the splice zone, made a huge improvement in distributing the forces over a larger concrete area, in the zone from where the lower laminates lap with the carbon fabric, around the corner of the spine [5]. This resulted in an overall reduction of materials required and shorter installation time as well.

![Fig. 6. Corner Splice Detail showing the extent of bi-diagonal carbon fibre, lapping the spine laminates with the uni-directional carbon fabric, wrapped around the lower spine corner](image)

The outer web/deck soffit anchorage detail (Fig. 7) required anchorage of the inclined laminates into the underside of the deck. This was achieved in critical areas by an embedded steel reinforcing bar, inserted and epoxy bonded into a cored hole into the corner of the spine girder. The bar was also chased into the outside face of the web, then lapped with the carbon laminates and fully bonded with epoxy adhesive. To prevent premature corrosion, a layer of glass fabric was introduced between the steel and carbon fibre. This detail provided higher strain transfer from the CF laminates into the concrete and better longitudinal shear resistance [6] [7].
Preparation Techniques

The concrete substrate on West Gate was generally a high strength (>60MPa), very dense and smooth, pre cast surface. In order to fully reap the benefits of the optimizations discussed earlier, the bond to the substrate needed to be maximized. This was done on two fronts: firstly with the preparation using a dry, grit-blast and secondly, adopting a low viscosity primer under all FRP materials.

Removing contaminants and cement laitance from the surface of 30 year old concrete is a key step in any externally bonded system. Various forms of preparation were considered, trialed and rejected on West Gate including grinding and wet-blast systems. Ideally, the hard surface needed to have an “open, dry structure” and have a slight texture similar to 60-grit sand-paper (Fig. 8). Preparation techniques using water should generally be avoided, as water tends to inhibit maximum bond. The best option of achieving the required outcomes was a dry, garnet blast. This was a process which could be concentrated to the areas that required it and was easy to handle in an overhead application.
Furthermore, WGBSA and VicRoads decided to adopt the use of a low viscosity epoxy primer, which was used under all carbon fibre materials (Fig. 8). This was utilized to maximize adhesion to the dense, high strength pre-cast substrate, minimizing the risk of any “defects” in the surface preparation. Initial FRP research and trialing of early FRP systems during the 1990’s with CALTRANS, the Department of Transport in California, indicated the benefits and ultimate requirement of a low viscosity primer used in their bridge retrofit program [8]. The West Gate team was also well aware of ongoing durability studies at Monash University, which have indicated a significant increase in the long term performance of adhesion to the concrete surface, by the use of such primers, resulting in VicRoads adopting the use of a primer as standard practice. This is particularly important in areas that are subject to wet-dry cycles or fatigue loading, such as on a bridge structure.

Application of the FRP system continued in the normal way, with a combination of laminates on the flat surfaces and fabric around the corner sections (Fig. 9).
Once the FRP system was installed, a series of destructive tensile adhesion tests was used, as the best test of preparation and application techniques. These involve “pulling” a 50 mm diameter aluminum disk (dolly) attached to a sample of installed FRP, directly off the concrete substrate. This measures where the location and magnitude of the weakest bond line in tension is, through the whole system. On West Gate, a multitude of on-site QC tensile adhesion tests were performed, demonstrating outstanding performance and adhesion (Fig. 10). Tensile bond results of up to 6 MPa, with failure in the concrete substrate were regularly achieved. These were well in excess of the 3 MPa VicRoads specification requirement.
Fig. 10. Tensile adhesion testing of the applied FRP systems, showed consistent failure in the concrete substrate of in excess of 6 MPa.

A Demanding Construction Program

Program and Planning

One of the key considerations for success of this project, was the ability to deliver the massive amount of materials (carbon fibre, epoxy resins and other supplies) to a strict and tight construction schedule. To give an indication of what lay ahead, the final material quantities eventually supplied included:

- Carbon Fabric – 16,000 m²
- Carbon Laminate – 42,000 m (over 6,100 individual pieces)
- Epoxy Primer ~ 7,000 lt, Epoxy Adhesive ~ 40,000 lt, Epoxy Saturant ~ 29,000 lt.

Program and planning were critical issues to the Alliance. Assurances were required regarding production capacity and consistent supply to accommodate the tight time frame for construction and associated liquidated damages. The carbon and resin volumes were massive by any previous project standards, not only placing pressure on manufacturing facilities, but equally placing pressure on the entire supply chain, from raw material suppliers to transport operators. The first order was received in late July 2009, with a start in application of early September 2009. All CF material was to be fully manufactured and supplied by mid January 2010. The production capacity and flexibility of the supply team ensured that the ambitious program could be met. The eventual supplier of the FRP system has the largest capacity in the world to produce carbon fibre pultrusions, combined with
the locally manufactured resins in Australia, meant that lead times were kept to a bare minimum.

Moreover, production forecasting and transport co-ordination were crucial, with both international and local freight required. In total for the CF materials, there was a combination of 4 air-freight deliveries (for early works) and 4 sea-freight deliveries, with the 6,100 individual laminate pieces, packed into robust timber crates (Fig. 3, right). After confirmation from site regarding the as-built dimensions of the bridge, the laminate pieces were manufactured in pre-cut lengths, with extremely tight tolerances of -0+10 mm. The individual laminate lengths ranged from 3 m (the short inclined web laminates) to 14.315 m (the longest laminates on the underside of the spine).

### Environmental Conditions

When applying any FRP material, there are certain environmental conditions that need to be met – temperature, humidity, wind, sun and dust, to name a few. During the 16 month FRP application on the West Gate Bridge, the site was subjected to the weather extremes of (almost) two Melbourne summers and a winter, with seasonal daily maximum temperature variations from 5 to 40 deg C. One of the challenges facing the WGBSA was to maintain the construction schedule and productivity, as much as possible, all year round. Considering the work area was between 30-50 m above the ground, this created a series of significant issues within itself. However, there were a number of means by which environmental conditions were overcome, including:

- The material supplier also had the ability to supply resins in special large kit sizes which enabled the contractor to choose mixing volumes. By choosing appropriate kit sizes to suit daily temperatures, the applicators could more easily cope with the extremes of weather conditions (winter vs summer), and this lead to minimized product wastage and overall reduced rubbish to landfill
- The contractor allowed for air-conditioned containers for storage of epoxy materials, to condition the products for optimal usage in all conditions (hot and cold)
- Shade cloth was erected around the perimeter of the access platforms, to help shield the wind and sun
- QC testing of local weather conditions including dew-point, prior to and during application was completed. If conditions did not suit a particular application, then the workers were directed to do alternative tasks which were not weather dependant. Alternatively, shift work was scheduled to apply early in the morning or late at night, during warm weather.
**The Value of Quality Assurance**

Quality Assurance was of paramount importance on this project and systems were implemented well above current industry practice. The client retained the use of a Construction Verifier to review site application in detail, and oversee quality controls on site, such as the extensive adhesion testing. Some of the material and service related QA issues delivered to the project include:

- Supplier QA/QC systems were the strictest ever seen. Apart from ISO 9001 accreditation, all materials were required to have comprehensive (internal) batch records maintained, along with full third party testing of carbon fibre components.
- Expert, local technical support was provided by experienced personnel from the supplier. This was a major benefit for the head contractor, whether it was for initial project start-up trials, comprehensive theory and practical application training as well as inspections and “heat of the moment” advice during full construction.
- The use of a carbon fibre laminate with a protective, removable “peel-ply” on both sides (Fig. 3, left), was a huge advantage to the applicators. The “peel-ply” negated the requirement for a “traditional” solvent clean prior to application. Minimizing the use of solvents on construction sites is now an important EHS issue. This plastic layer not only provided protection during transport and handling, but also permitted labeling (QC identification via a digital barcode and safety information). Once it was removed, the surface of the laminate reveals a slightly textured surface, further maximizing adhesion. Time, safety and quality considerations were satisfied with the use of “peel-ply” laminates and should no doubt become the preferred choice for this market in the future.
- Each of the 6,100 individual pieces of laminate was given a unique digital barcode number able to be scanned, for total traceability. This feature had never been required, nor included previously, but given the enormous challenges with logistics on site, this became an important aspect of QC on the project.
- The ability for one supplier to offer a complete product range, with full compatibility of materials including associated concrete repair and crack injection products, assisted greatly where required.
- Long term monitoring of the FRP system has been made possible by installation of test panels, which are included in a maintenance schedule for the overall structure.
Conclusions

The now completed West Gate Bridge strengthening project stands as a landmark project. Having been constructed in 1978, the demands of a growing, modern city have meant that it needed a new lease on life. After many years of considering all types of strengthening techniques, fibre reinforced polymer (FRP) strengthening formed an integral part of the solution in making this bridge sustainable.

In terms of the volume of FRP used, the West Gate bridge is now the largest bridge strengthening project in the world to date, utilizing over 42 km of carbon laminate (comprising 6100 individual pieces), 16,000 m² of carbon fabric and 76,000 lt of epoxy resins. By incorporating the latest material properties combining the appropriate choice of section size, modulus and strength into “custom-made” solutions, the design consultants skillfully designed and detailed the final configuration accordingly. The WGBSA team was also able to incorporate the latest research knowledge available for connections and anchorage of FRP systems. Special detailing at critical locations ensured that the flow of forces was optimized, to compliment the choice of materials. In combination, they were then able to fully utilize the high strength concrete substrate of the bridge to their advantage.

The significant results were major time and cost savings for the project, whilst being able to maintain the tight construction schedule, in extremes of weather. Quality assurance requirements demanded new world class standards in many areas. Overall, the project stands as a shining example of best practice in the carbon fibre strengthening industry.

References


