Carbon Fibre Fabric Strengthening of Little River Bridge

Bernard SHEPHERD
Project Director
GHD Pty Ltd
Melbourne, Australia

Bernard Shepherd, born 1943, received his civil engineering degree from the Univ. of Canterbury, NZ

Andrew SARKADY
Technical Manager
MBT (Aust) Pty Ltd
Melbourne, Australia

Andrew Sarkady, born 1964, received his civil engineering degree from the Univ. of Melbourne

Summary

The Little River Bridge is an 84 year old, 4 span continuous structure on the Princes Freeway (National Highway 1) between the cities of Melbourne and Geelong in Australia. As part of the upgrading and widening of the road to a 6 lane freeway, the Little River Bridge beams required strengthening for positive moment. The solution selected by the main contractor, Leighton Contractors, was to use MBT MBrace CF130 Carbon Fibre Fabric Composite to strengthen the beams. Alternatives considered were steel plates and external post-tensioning. This paper describes the design and specification process, the implementation and the full scale load testing carried out by the roads authority, VicRoads, which demonstrated the fully composite behaviour of the strengthened beams. Unexpected advantages were also observed which enhanced the value of the Carbon Fibre Fabric Composite system.

Keywords: bridge; carbon fibre fabric; composites; strengthening; reinforced concrete; beams

1. Introduction

The existing structure in reinforced concrete was a three span integral bridge built about 1919, extended to four spans during construction and widened in 1955. In cross-section the bridge has three longitudinal beams and a transversely ribbed deck slab. Over its service life of 83 years the bridge has performed well with virtually no maintenance and only a moderate level of deterioration. The original part of the bridge behaves independently of the widened section and it is only the original part of the bridge that was considered by VicRoads to require strengthening. Figure 1 shows the original bridge in its 3 span configuration.

Fig. 1 Little River Bridge as designed in 1919.

The capacity of the original bridge was no longer adequate to carry the 68 tonne B-Double vehicles using the Geelong Rd on a daily basis. In the project tender, VicRoads called for strengthening of the principal deck beams for positive moment. Figure 2 shows the cross-section of the bridge at the time of strengthening.
2. Carbon fibre systems

Carbon fibre and other high strength materials used in fibre reinforcement polymer matrix composites were initially used in aerospace and high-tech marine applications. They are now being applied with increasing frequency to remedial works and strengthening of civil engineering infrastructure. A number of suppliers of carbon fibre reinforcing products are present in Australia, including MBT, Sika and Freyssinet.

Building structure components such as carpark slabs have been successfully strengthened in Australia using the various types of carbon fibre sheets or fabrics. Up to the present time (Nov. 2001) it is understood that only one other bridge in Australia has been strengthened using a carbon fibre fabric - The Giovanni Brunetti Bridge in Sydney, which was successfully strengthened by Freyssinet in 1999.

3. The design for the Mbrace CF 130 strengthening

The original tender documentation from VicRoads suggested positive moment strengthening of the three longitudinal deck beams using epoxied and bolted steel plates. Leighton Contractors looked for a less onerous solution and a specialist prestressing sub-contractor, Tensacciai, proposed a carbon fibre solution. Alternatives considered were carbon fibre plates and also external post-tensioning. The carbon fibre plates could not develop adequate capacity without unacceptable stacking and the external post-tensioning was significantly more expensive as well as being much more difficult to install.

One of the major difficulties encountered was with the actual profile of the underside of the bridge beams, which included a slight arch in each span. Closer inspection of the width of each beam also indicated that the overall dimensions varied by up to 10% on the nominal 350 mm wide standard beam. A 25 mm chamfer at the soffit edges added to the geometric complexity. Significant positive moment reinforcement congestion at the bottom of the beams, and some concrete repair areas that needed attention, further complicated issues for the design. All options were costed and compared for the installed price. It was apparent which solution was most effective; carbon fibre fabric sheet applied in three layers to the underside of the beams. This solution was easy to apply within the boundaries of the geometric constraints. It had no impact on the bottom layers of reinforcement and did not need to rely on mechanical fixings which were assessed as being a risk to the structure’s integrity if drilled in or near the reinforcement.

After discussions with various suppliers, Tensacciai selected the MBT MBrace system. Tensacciai worked with the material supplier, MBT, to develop the design. As a base hypothesis the carbon fibre composite had to provide the equivalent strengthening to the VicRoads steel plate proposal. The advantage of the carbon fibre composite was that no drilling or destructive techniques would be required. This is an important consideration when dealing with old structures with uncertain reinforcement content and location.

MBT’s specialised software was used to confirm the theoretical behaviour and capacity of the proposed system. A design using 3 layers of CF 130 fabric was prepared by Tensacciai’s engineers and accepted by Leighton Contractors and approved by the Proof Engineers. The system was then ready to be applied. Figure 3 shows an elevation and cross-section of the strengthening for a typical beam.
4. The initial application - a system failure

The first application of the MTB MBrace CF130 carbon fibre strengthening was installed late in August 2000 and initial pull-off testing was carried out from the 7 to 16 September 2000 and on the 4 November 2000. Further tests were completed on the 16 and 18 December 2001.

The test method was chosen after a review of the available literature and discussions with the specialist supplier. The recognised acceptance criterion was for a basic pull-off test result to be greater than 3 kN for a 50 mm dia section - i.e. a tensile stress not less than 1.5 MPa on the bond line at any interface in the reinforcement materials or within the concrete. The ideal result is to have 100% failure in the concrete or, for high concrete strengths, on the testing dolly epoxy interface with the material.

Results from the tests were generally unsatisfactory and a final series of pull-off tests on the composite material on all beams in December 2000 confirmed that the material had not bonded to the concrete nor had the 3 fabric layers bonded between themselves in all locations. Figure 4 shows the pull-off tests in progress.

At this stage the entire operation was reviewed from design through to specification of the implementation methodology. This review involved the contractor, Leighton Contractors, VicRoads, the specialist supplier, MBT, and the specialist sub-contractor, Tensacciai, plus GHD working on behalf of Tensacciai. VicRoads also obtained expert input from Vistasp Karbhari of the University of California, San Diego.

4.1 Review Findings

Inappropriate substrate surface preparation, unsatisfactory and undisciplined installation procedures and inadequate equipment had been used in the application of the composite material. One beam showed evidence of graffiti still on the substrate after removal of the defective composite.

There were only two beams that met the acceptance criteria - beam 2 on span 1 and beam 1 on span 2.
The remaining 10 beams needed to be completely stripped. Surface preparation and reinstallation was not to be carried out until the preparation and application procedures had been site-specifically documented and approved by the relevant parties.

The reinstallation process would need to be carried out under direct engineering supervision.

4.2 Recommendations For Remedial Works

The following sequence was to be followed in the reinstallation process.

1. Removal of all composite material and examination of the stripped surfaces to note any defects or evidence of inadequate preparation such as smooth or non-abraded surfaces.

2. Implementation of an agreed substrate preparation and installation procedure. A particular point was to be an upper limit of ambient temperature for the installation of the system.

3. Testing of the new procedure on site by using a short section of soffit on one of the beams on the adjacent widening. Three pull-off tests on a 1 m section were to demonstrate that the 3 layers of CF130 fabric would retain their integrity and full composite action with the concrete - ie no failure “ at the bond line at a tensile stress less than 1.5 MPa ”. The term “ bond line ” refers to the interface between the primer and the concrete.

4. If the test in 3. above was satisfactory then the new specification incorporating the MBT Application Guide was to be reissued for full implementation.

5. Full preparation and re-installation would then be able to proceed under the following general principles
   a. Repair of any defects using a high strength repair mortar (Concreacive 1446) leaving adequate time for curing and strength gain.
   b. Preparation of surfaces using blast cleaning or a suitable scarifying system that does not produce smooth surfaces nor damage the concrete
   c. Have the surface preparation inspected and approved in writing by the supervising engineers from GHD and MBT.

6. Two weeks after the completion of the reinstallation, one pull-off test per beam – ie one test per 3 m² of carbon fibre fabric - was to be carried out to confirm the behaviour of the system.

7. If all test results were satisfactory, then the test holes were to be repaired and the soffit coated with the Barracryl D protective coating.

5. The Second Application - Design and Specification

After agreement on the overall remedial process a clearer framework of design and specification responsibilities was established.

- GHD assumed the role of “designer” on behalf of Tensacciai and repeated the design process.
- A detailed specification was finalised jointly by GHD and MBT following review and input by VicRoads and Vistasp Karbahari.
- The Tensacciai Quality Control (not Quality Assurance) methodology and documentation was upgraded and extended.
- A joint supervision by GHD and MBT was to provide a permanent site presence during application.

5.1 Design

The design exercise of the carbon fibre composite was repeated to confirm the original evaluation. This was carried out on a first principles basis and the results agreed closely with those given by the MBT customised analytical software.
Material properties for the unidirectional CF130 sheets are:

- Modulus of elasticity: 240 000 MPa
- Tensile strength: 3 900 MPa

Ultimate tensile force for a 300 mm width of sheet: 133.5 kN
Ultimate elongation: 1.5%

For the purposes of the design and analysis, the steel reinforcement was assumed to have a yield strength of 250 MPa and the 28 day concrete cylinder strength was taken as 25 MPa.

Figure 5 shows the strain diagram over the depth of a beam at mid-span, for the ultimate load analysis. Beam height is approximately 1100 mm.

\[
\begin{align*}
\epsilon_{cu} &= 0.0008 \quad \text{Maximum strain in the concrete} \\
\epsilon_{s1}(\epsilon_{cu}, \epsilon_{cu}) &= 0 \quad \text{Strain in the mild compression steel} \\
\epsilon_{s}(\epsilon_{cu}, \epsilon_{cu}) &= 0.013 \quad \text{Strain in the mild tension steel} \\
\epsilon_{ps}(\epsilon_{cu}, \epsilon_{cu}) &= 0 \quad \text{Strain in the prestressing steel} \\
\epsilon_{f}(\epsilon_{cu}, \epsilon_{cu}) &= 0.014 \quad \text{Strain in the carbon fibre composite}
\end{align*}
\]

![Fig. 5 Ultimate strain diagram for a beam section at mid-span](image)

5.2 Specification

The purpose of the specification and its accompanying documentation - i.e., the MBT Application Guide - was to prescribe in detail the procedures to be followed in the application of the composite material.

As a “wet-on-wet” process, the CF130 installation calls for meticulous preparation and a high level of discipline. The specification has to reflect these imperatives. Personnel must be trained and certain parameters - such as ambient temperature and wind speed - must be set in the specification as “go” or “no go” situations. In his paper on materials considerations [1], Vistasp Karbhari indicates some of the difficulties of the “wet-on-wet” process, many of which were observed on the Little River Bridge project.

6. The second application - installation and system success

After a series of successful procedural tests and under tight supervision, the second application commenced with thorough preparation and repair of all the beam soffits. Vacuuming of soffits was carried out to remove dust and loose particles immediately before applying the primer, the first part of the “wet-on-wet” system.
6.1 Placing of the carbon fibre composite

No work was permitted at temperatures higher than 25ºC or lower than 5ºC. Wind speed was to be minimal and there was to be no risk of rain.

The system layers were built up as follows in a continuous process (5. to 11. without interruption):

1. Preparation and repair (if necessary) of soffit
2. Vacuum clean
3. Apply primer
4. Place levelling layer, Concresive 1446 (if necessary)
5. First layer of saturant
6. First layer of carbon fibre
7. Second layer of saturant
8. Second layer of carbon fibre
9. Third layer of saturant
10. Third layer of carbon fibre
11. Final layer of saturant
12. Barracryl D protective coating (applied after testing)

Special tools were used for the working of the saturant through the carbon fibre to create a homogeneous and wrinkle-free composite. Figure 6 shows the first layer - a levelling layer of Concresive 1446 - being placed on the first beam in span 1.

6.2 Testing

A critical component to the success of the project was on-site testing and verification. On-site testing consisted of two basic parts: Quality Control testing of the applied materials and load testing of the structure in order to prove that the carbon fibre composite was acting compositely and was increasing the load carrying capacity of the bridge.

In this case, the load testing carried out by VicRoads came before the testing of the composite material in situ.

6.2.1 VicRoads testing

The VicRoads testing was implemented in two parts - Part 1 before application of the carbon fibre and Part 2 after completion of the carbon fibre installation.

The testing consisted of loading using a 5 axle 60 tonne mobile crane placed at predetermined locations on the bridge. Strain gauges were placed on the beam reinforcement and on the carbon fibre composite. Test loading operations were carried out in the early hours of the morning to minimise disruption to traffic.
Results from the test confirmed that the carbon fibre material was acting compositely with the concrete and that the strain profile was in agreement with predicted behaviour.

A detailed study and comparison of the results with a finite element analysis has been performed by Riad Al-Mahaidi at Monash University [2]. The conclusion from this study give a load factor increase of the order of 50% for the load cases of 45.5 tonne semi-trailers and 68 tonne B-Doubles.

6.2.2 Pull-off testing

After completion of the VicRoads load testing, the pull-off testing programme was completed. One test was carried out on each beam in the extended end zones so as not to damage the load carrying areas of the composite. The results summary for the 12 beams is given below.

- Average failure load  = 4.39 kN
- Average failure stress  = 2.24 MPa
- Failure mode  = concrete x 11
  = test dolly x 1

These values were comfortably in excess of the 3 kN (=1.5 MPa) acceptance value and confirmed the behaviour assessment from the VicRoads load testing.

6.3 An unexpected benefit

Earlier substrate testing had shown pull-off test values for the concrete not much greater than 3 kN. After completion of the strengthening the pull-off value averaged 4.39 kN - ie a 46% increase. One possible explanation is a strengthening of the substrate by capillary action from the epoxy resin primer. Whatever the reason, the result is beneficial and vindicated the earlier decision not to drill into the existing concrete substrate.

7. Conclusions

There are several important conclusions to be drawn from the initial failure and ultimate success of this project:

- The carbon fibre fabric composite system is an effective and practical method of strengthening concrete beams.
- Substrate preparation and material application procedures are critical and must be tightly specified and closely supervised to obtain the necessary quality of work.
- The specialist sub-contractor needs to closely involve the material supplier so that procedures (and training) for correct application are clearly understood. The material supplier should be involved with the design consultant and a documented system must exist on-site to monitor that the correct procedures are being followed.
- The three parties, material supplier, specialist sub-contractor and design consultant, need to work very closely together to give the best chance of a successful project.

Figure 7 shows the Little River Bridge in service in February 2002.

Fig. 7 The strengthened Little River Bridge in service
8. Acknowledgments

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9. References
