7. Brockley Slip Road (M1 Junction 4) – CFRP resin wrap and CFRP plates bonded to concrete

Step 1.
Type of structure

The slip road for the A41 onto the M1 at Brockley is a reinforced concrete (RC) deck carrying two lanes of traffic on a tight curve. The structure is supported by RC columns with foundations in the central reservation and verges of the M1 below. The configuration of the structure is of three continuous 30m spans, approximately 14m wide (including edge cantilevers). The deck itself is made up of 14No. prestressed, precast concrete longitudinal beams with concrete infill and a thin concrete slab spanning transversely over the longitudinal beams. The parapet was upgraded to a full containment 'Systema' type parapet, resulting in the deck edge cantilevers (overhanging beyond the 14No. longitudinal beams) becoming insufficient for carrying the hogging moment that is created by the collision load of the Highways Agency DMRB BD37/01.

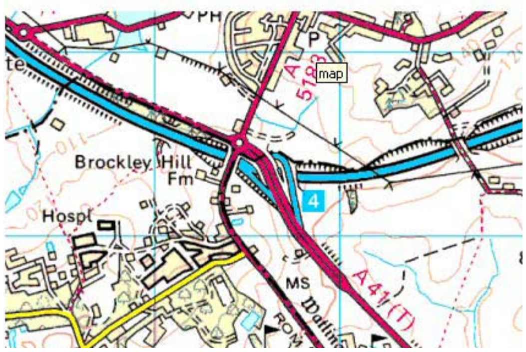

Figure 1. Map showing curved profile of Brockley Slip Roads

Step 2.
Design conditions

The collision load induced by using a full containment parapet is detailed by the Highways Agency DMRB BD37/01, clause 6.7.2. This states that it should contain:

a) A single horizontal transverse load of 500kN applied over a 3m length,
b) A single horizontal longitudinal load of 100kN over a 3m length,
c) A single vertical load of 175kN over a 3m length,
d) Associated primary live load (HA and accidental wheel load).

These local effects are considered in combination 4, with a ULS factor of safety of 1.4 and an SLS factor of safety of 1.15.

The slip road accommodates a large number of vehicles every day and although both deck edge cantilevers had to be strengthened for the structure to remain of use, the road could not be shut off completely for any works to take place.

The additional strengthening reinforcement was to be applied to the top surface of the bridge deck; beneath the running course. On the outside edge of the curve the deck is flat below the running course but on the inside edge the deck is stepped towards the cantilever. Due to overriding factors, the strengthening works took place during the poor weather winter months.

Step 3.
Initial testing and investigation

An initial investigation was carried out which included taking core samples to test the concrete compressive strength, to check for levels of chlorination and carbonation, and pull-off tests to test tensile strength. Following review of the test results, the bridge was deemed appropriate for Carbon Fibre Reinforced Polymer (CFRP) laminates strengthening.

Step 4.
Material selection

To increase the stiffness and flexural strength of the structure, the stiffest fibre system was chosen, carbon. The resin to protect the fibres in transit and use and to transmit the forces from the adhesive bond to the composite strengthening was chosen to be epoxy or vinylester-based because it presents a good range of mechanical properties at low cost while being easy to cure and handle. It was possible to use laminates (classification PBU/1/C/S) on the outer edge cantilever of the slip road because the deck is flat, however, it is impossible to use laminates on the inner edge of the curve because the deck is stepped towards the edge thus a CFRP in-situ laminated fabric system (classification RW/1/C/S) was selected to follow the vertical profile of the deck.

The reinforcement was applied to the top surface of the deck and had to have hot asphalt poured on top; thus the materials must suitable for high temperatures (up to 150°C) were chosen.

Within the design, the approximate characteristic material properties required were assumed as:

Ultimate Tensile Strength = 2800MPa
Modulus of Elasticity = 150GPa
Ultimate Strain > 0.8% (limit from TR55)
Dimensions: Width ~ 120mm, Thickness ~ 1mm multiples

The laminates were manufactured by the pultrusion process.

For the inner edge cantilever, it is necessary to use a in-situ laminated fabric system as the laminates cannot be formed to match the geometry of the deck. As the fibre volume fraction of a wet lay-up system is variable, the effective area of carbon fibre, which is known, was used as the design basis. Within the design, the approximate characteristic material properties required for the fibres were assumed as:

Ultimate Tensile Strength = 3500MPa
Modulus of Elasticity = 230GPa
Ultimate Strain > 0.8%

The adhesive for the carbon fibre pultruded laminates had to be thixotropic epoxy adhesive recommended by the manufacturer of the FRP laminates. The adhesive must have T_g in excess of 60°C and an initial curing time of at least 45 minutes, in addition to being suitable for use in temperatures ranging from –5°C to 35°C. The design assumed that the adhesive had the following properties:

Ultimate Tensile Strength >15MPa
Modulus of Elasticity >9GPa
Lap Shear Strength > 12MPa
Adhesive Strength >4MPa
Moisture Resistance > 0.5% (at 28 days)

Similar properties were required for the laminating resin for the wet lay-up system.

In addition, a compatible levelling mortar and crack repair mortar was used prior to the composite strengthening system where required. During the design, generic material properties were assumed, however it was known that several materials were commercially available to provide the assumed characteristic material properties.

Step 5.
Partial factors

The structure to be strengthened is concrete, thus the partial safety factors are taken from The Concrete Society Report, TR55 (2004 Edition). These are as follows:

Material	**Partial safety factor on failure strain, γ_ε**
Carbon FRP	1.25

Type of system (and method of application or manufacture)	**Additional partial safety factor, γ_{mm}**
Laminates **Pultruded**	1.1
Wet Layup	1.4

Material	**Factor of safety on elastic modulus, γ_E**
Carbon FRP	1.1

Factor of safety for steel stress check, γ_{ms} = *1.0* (TR55 recommends $1.0f_y$ for grade 230 steel)

Material safety factors (from BS5400 Part 4) used:

Concrete	γ_c	=	*1.5*
Steel	γ_s	=	*1.15*

The conditions in TR55 clause 5.6.8 Adhesive are satisfied.

Concrete grade: 40 (f_{cu}=40MPa), steel (internal reinforcement) grade 250 (f_y= 250MPa).

Step 6.
Design calculations

The design was performed using TR55 in conjunction with BS5400 Part 4.

For the outside edge of the slip road the design resulted in using individual laminates of 3 No. layers of 120mm wide, 1.4mm thick laminates at 300mm centres running transversely across the deck, over the cantilever (i.e. perpendicular to the edge of the cantilever). In addition to this, 2 No. layers of 1.4mm thick, 4800mm long laminates were required to run longitudinally along the deck, over the transverse laminates in the region of the column crossheads. The whole of the outside of the curve required 1.5km of CFRP laminates. The design of the inside edge of the cantilever required 1300mm^2 of the CFRP in-situ laminated fabric per metre width.

Figure 2. CFRP Laminates Bonding/Strengthen Deck Edge Cantilever (left)
CFRP Wet Lay-up/Strengthen Deck Edge Cantilever (In Polythene Tunnel) (right)

Step 7.
Design conformance check

1. Resin T_g = Not listed, but manufacturer tests show 80°C-100^{o}C
2. Adhesive T_g = Not listed, but manufacturer tests show 60°C

3. The dimensions of the reinforcement are appropriate for the structure as it will not overhang the edge of the soffit.
4. ULS and SLS Stress and Moment Checks
    h. The applied ULS bending moment is 260kNm/m width, the capacity of the strengthened beam is 388kNm/m width, - ok
    i. The concrete stress under serviceability load is 23.4Nmm^{-2}, compared to an allowable of 24.0Nmm^{-2} (0.6f_{cu}), - ok
    j. The stress in the internal reinforcement under serviceability load is 200Nmm^{-2} and the allowable stress is 200Nmm^{-2} (0.8f_y) - ok
    k. The stress in the external reinforcement under serviceability load is 436Nmm^{-2} compared to the allowable of 1400Nmm^{-2} (0.5f_y), - ok
    l. Fatigue check of the FRP ok using 80% of the ultimate design strength, 1454Nmm^{-2} compared to 436Nmm^{-2}, - ok
    m. Stress rupture check of FRP ok, using 65% of the serviceability design strength, 1182Nmm^{-2} compared to 436Nmm^{-2}, - ok
    n. FRP separation failure check ok, factor of safety >1.0 when longitudinal shear stress is limited to 0.8Nmm^{-2}, - ok

Step 8.
Prepare specification

Two specification documents were required for the FRP systems in this project, one for the CFRP laminate system and one for the CFRP in-situ laminated fabric system. The laminate system had a similar specification to that shown in the case study for St Michael's Road Bridge, with further requirements for the contractor to prove – to the Employer's Representative, that the CFRP laminates were able to withstand the high temperature of the hot asphalt pour. The specification for the CFRP in-situ laminated fabric details the methodology for preparation of the materials and detailed testing of the strength of the installed materials, which had to be repeated within the contractor's Method Statement.

Step 9.
Specific materials selection

No requirements in addition to those outlined in Step 4.

Step 10.
Method Statement for application of reinforcement

The method statement detailed the methodology the contractor (Laser Special Projects) intended to use for the installation of the external reinforcement. It also detailed the qualifications of the workers to perform the laminates bonding and various heath and safety and emergency procedures that were required.

The site works were planned to begin in October 2001 and end in January 2002. The process followed the following steps:

- The deck surfacing was to be planed off to reveal the structural concrete beneath.
- The deck cantilever area was then to be surface-prepared by grit-blasting.
- Any substandard surface areas were to be repaired with an epoxy mortar compatible with the CFRP strengthening system.
- The East Cantilever (outside edge) was programmed to be strengthened first, using high-strength pultruded multiple CFRP composite laminates.
- The rate of strengthening work during inclement weather was to be maintained by erecting a polythene tunnel. It was planned to take 6 weeks to strengthen a 90m length of the deck.
- During work on one side of the deck, the other side was open to traffic. Therefore, the East side of the deck was reinstated and opened prior to works on the West (inside edge) cantilever.
- The West cantilever was programmed to be strengthened in the winter months, using a polythene tunnel to allow continual installation to take place. This section of the work took about 4 weeks.
- The West side of the deck was then reinstated and the bridge opened to traffic.

Within this activity stage, the designer was able to check that the contractor-selected material system for the strengthening is appropriate to project requirements. It is possible that the contractor may suggest materials different to those referenced in Step 4 which must then be confirmed to match the specified properties and design criteria.

Step 11.
Site activities prior to installation

This step involved detailed planning and implementation of traffic management and taking possession of the site.

Step 12.
Surface preparation

Following the Method Statement, the asphalt running course was removed and then the concrete surface was prepared by grit blasting. Damaged areas of the deck surface were then repaired (e.g. any cracks greater than 0.3mm wide) with a compatible resin. Steel dollies were then bonded on for subsequent pull-off tests which were performed after a cure of at least 24 hours, but prior to application of composite system. Once the deck was deemed to be suitably prepared and free from dust, bonding works could commence.

Step 13.
Application of composite materials system

Due to the winter weather a long polythene 'tunnel' was erected first over the bonding area. The peel ply was then removed from the laminate and the surface degreased. A thin layer of adhesive was applied to the laminate and the laminate was then applied to the bridge soffit in the correct position, under pressure to remove air voids. Simultaneously, the testing samples are prepared. These steps are detailed within the method statement and had prior approval of the Employers Representative.

The same procedure was applied to the CFRP in-situ laminated fabric, except the material had to undergo more site based preparation, including:

- The fabric sheets were cut to an appropriate size, the maximum length of any sheet cut was 2 metres to allow a wrinkle-free application and to minimise entrapped air,
- The resin was then applied to the surface of the reinforcement system,
- The resin saturated fibre reinforcement system was then applied by hand to the primed substrate, avoiding the inclusion of air and wrinkles,
- After application by hand any paper backing material was removed from visible surface of the saturated fibre reinforcement system,
- The saturated fibre reinforcement system was then consolidated in the longitudinal direction,
- The saturated fibre reinforcement sheets were joined by a 15cm overlap with additional resin on the surface of the fibres to overlap,
- The saturated fibre reinforcement system was then left to stand for a period in accordance with the manufacturers recommendations,
- The second coat of resin was then applied onto the surface of the saturated fibre reinforcement system and further layers of fibre reinforcement installed using the same procedure.

Step 14.
Final QA checks, inspection and approval

The laminates and fabrics were tap tested after cure to ensure the entrapped air is within the limits within the specification. The pull off test results showed that of the 8 No. tests performed, none failed the $1N/mm^2$ concrete tensile strength limit, and approval was given to proceed with the composite strengthening installation.

Off site testing by RMCS (Cranfield University) and Oxford Brookes University on dumb bell samples of adhesive (for tensile modulus and strength), adhesive T_g, the tensile strength and modulus of the CFRP wrap and single lap shear for different batches. The results were as follows:

In-situ laminated fabric tensile strength	>710MPa (fibre volume fraction ~ 30%)
In-situ laminated fabric tensile modulus	>60GPa (fibre volume fraction ~ 30%)
Adhesive T_g	>50^{o}C

Characteristic tensile modulus of laminates =148GPa
Characteristic tensile strength of laminates =2928MPa
Lap shear strength >10MPa

These results show that the in-situ laminated fabric (CFRP wraps) did not meet the specified values of UTS (1800N/mm^2) and tensile modulus (120GPa) in the specification, which were based on a fibre volume fraction of 50%. After these results were received, the design calculations were revised using the actual test values. Further analysis of the test results showed that the fibre volume fraction was approximately 30%, and that the product of the tensile modulus and area (E x A), was therefore sufficient to provide the stiffness and strength required. This revision resulted in a reduced, but still acceptable, factor of safety.

Inspection/Maintenance/Monitoring Regime

CFRP laminates and in-situ laminated fabric samples from the materials used in the strengthening were bonded to the deck of the bridge in an easily accessible location. This was to allow an opportunity to test the integrity and condition of the CFRP strengthening system under the actual environmental conditions at the bridge site.

Typically, visual inspections are required annually for the first three years and then at greater intervals ad infinitum. The visual inspections shall include looking for signs of de-bonding or cracking in the adhesive bond and damage to the concrete substrate and CFRP laminates.