9. Hammersmith Road Bridge – CFRP CFRP plates bonded to cast iron

Introduction
Hammersmith overbridge carries the A315 Hammersmith Road out of Hammersmith and Fulham and into Kensington and Chelsea Borough Councils. The road is currently 2 No. lanes in breadth, with a bus stop at either side. The lanes have been restricted, a weight limit imposed and bus stops have been suspended from use resulting from an assessment of the bridge as understrength.

Step 1.
Type of structure

The bridge is configured of three spans, two minor side spans of approximately 5m and one major span of 10m. The two side spans cross a disused siding and the London Underground (LUL) DC electrified line from Olympia to Earls Court. The main span crosses a freight line which is also used to take the Eurostar trains to their storage and maintenance depot.

The bridge was constructed in the late 1800s, possibly around 1860-1880, however no accurate date is known, but some cracks in the abutments were repaired in the early 1900's. The bridge is constructed of 13 No. longitudinal cast iron girders in each span (totalling 39 longitudinal girders) with masonry jack arches spanning in 10 of the 12 bays. The beams are 'fish belly' asymmetric 'I' sections, which are deeper at midspan than at the supports (with a flat soffit) and are of larger section in the main span than in the side spans. The edge beams are the same in all spans and are swan neck girders with additional material as aesthetic features. In two of the bays there are cast iron deck plates with vertical stiffeners protruding downwards from the laminates, along each edge and diagonal stiffeners forming a cruciform between the corners of each deck plate. The abutments and pier are constructed of masonry with hard padstones. The parapets are approximately 2m high and constructed of masonry and hard stone. The fill in the jack arch bays is saturated ballast and within the deck plate bays is a lean concrete mix. The lean concrete mix also forms a 200mm slab over the beams and below the running course of the road.

Within the deck of the bridge a large number of services are located, ranging from large diameter (21") water mains to high voltage cables.

Currently, the main span girders are rated as having a capacity of 18 tonnes to BD21/01 in the main span, but the deck plates govern the strength of the bridge as 3 tonnes to BD21/01. The edge beams have been assessed as having a zero live load capacity. This is calculated on the basis of multiple lane loading using BA16/97.

Step 2.
Design conditions

The design conditions were based on the Approval In Principle, which was based on previous feasibility studies looking at a wide range of options, from restricting vehicle lanes to full bridge re-construction.

The design conditions were:

a) Strengthening the cast iron beams to BD 21/01 40 tonne Assessment Live Load (although not for accidental vehicle loading as this was deemed to be acceptable after a risk assessment and provision of high containment kerbs and pedestrian barriers), using FRP laminates bonded to the soffit of the cast iron beams.

b) Strengthening the cast iron deck plates to BD 21/01 40 tonne Assessment Live Load, which for this localised case comprised the single wheel load of 100kN, using FRP laminates bonded to the soffit of the deck laminates.

c) FRP strengthening was to take place within possessions.

The strength criterion for cast iron in BD 21/01 is based on permissible stresses, and therefore the factor on material strength and modulus for cast iron and FRP composite was taken as 1.0.

Step 3.
Initial testing and investigation

A trial trench was excavated across one of the side spans to confirm the type and quality of fill material, and the presence of services. In addition, a road level survey was undertaken to determine the construction depth throughout the bridge. A detailed dimensional and condition survey of the cast iron beam and deck plate soffit levels was also undertaken.

Step 4.
Material selection

To increase the stiffness and flexural strength of the structure, and to minimise the laminate thickness and hence loss in headroom on the operational railway, the stiffest form of carbon fibre system was chosen, ultra high modulus (UHM) carbon fibre. The resin to protect the fibres in transit and use and to transmit the forces from the adhesive bond to the ends of the fibres was chosen to be epoxy or vinylester because it presents a good range of mechanical properties at low cost while being easy to cure and handle. In addition, an insulating layer of glass fibre fabric was chosen to be used between the carbon fibre and cast iron to prevent galvanic corrosion, this being the most cost-effective material with suitable insulating properties. A design was produced allowing the possibility of UHM carbon fibre reinforced polymer (CFRP) laminates manufactured by pultrusion or by pre-formed CFRP laminates manufactured from pre-preg material.

For the cast iron beams, the survey showed the soffit to be sufficiently flat to allow the use of pultruded or pre-formed CFRP laminates (the classification for the FRP and adhesive in this case would be PBU/T/CI/S). For the deck laminates, the survey and record drawings showed the soffit of the downstand stiffeners to be haunched, and therefore two possible systems were chosen; pre-formed CFRP laminates individually designed to fit each deck plate stiffener, and on-site lay-up and forced heating, vacuum curing of a pre-preg system (the classification for the FRP and adhesive in this case would be PBU/T/CI/S or RW/T/CI/S). The more conventional in-situ laminated system was not used due to the high number of layers required to be installed within the relatively short possessions, and the risk of fibre breakage of the dry UHM carbon fibres. Again, an insulating layer of glass fibre fabric was chosen to be used, between the carbon fibre and cast iron, to prevent galvanic corrosion.

The generic material properties used within the FRP strengthening design on the cast iron beams were:

> Ultimate Tensile Strength = 1000-1500MPa
> Modulus of Elasticity = 320 and 420GPa
> Ultimate Strain > 0.3%
> Dimensions: Width ~ 140mm, Thickness ~ 1mm multiples for pre-formed CFRP laminates, and 2-4mm multiples for pultruded CFRP laminates.

This provided the contractor with two main options for carbon fibre stiffnesses. The selection of the material type was the contractor’s choice and would be approved by the design engineer if it did not match the properties within the specifications and drawings.

The laminates could have been manufactured by the pultrusion process or by factory controlled pre-formed fabric lamination.

The generic material properties used for the FRP strengthening design on the cast iron deck plate stiffeners were:

> Ultimate Tensile Strength = 1000MPa
> Modulus of Elasticity = 320GPa (pre-formed), 420GPa (pultruded)
> Ultimate Strain > 0.3%
> Dimensions: Width ~ 30mm, thickness ~ 1mm multiples.

The laminates can be manufactured by the pultrusion process or by factory controlled lamination to create a pre-formed laminate. The material properties for the on-site pre-preg method are dependent on the final fibre volume fraction of the installed product, typically 30-50%. Therefore, the design was based on the fibre properties and the required effective thickness and width of UHM carbon fibre:

> Ultimate Tensile Strength = 2000MPa
> Modulus of Elasticity = 640GPa

Ultimate Strain > 0.3%
Dimensions: Width ~ 30mm, thickness ~ as required for laminate design, but adjusted for predicted fibre volume fraction.

The adhesive was thixotropic epoxy adhesive recommended by the manufacturer of the FRP laminates. The adhesive must have a 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 adhesive should have the following properties:

Ultimate Tensile Strength > 15MPa
Modulus of Elasticity 3-10GPa
Lap Shear Strength > 12MPa
Adhesive Strength > 15MPa
Moisture Resistance > 0.5% (at 28 days)

In addition, a compatible levelling chemical metal adhesive or epoxy adhesive may be used if required to fill low spots on the cast iron that are outside the specification limits.

Step 5.
Partial factors

The structure to be strengthened is cast iron, thus the partial safety factors are taken from CIRIA Report, C595. These are as follows:

Material	Partial safety factor, γ_{mf}
Carbon FRP	1.4

Type of system (and method of application or manufacture)	**Additional partial safety factor, γ_{mm}**
Laminates **Pultruded**	1.1
Laminates **Preformed**	1.2
Laminates **Pre-preg**	1.1

Material	Partial safety factor, γ_{mf}
Epoxy adhesive, values obtained by tests	1.25

Type of system (and method of application or manufacture)	Additional partial safety factor, γ_{mm}
Manual application, adhesive thickness controlled	1.25

The environmental partial safety factor was based on a maximum operating temperature of approximately 40°C, a reference temperature of 20° C, and glass transition temperature for the adhesive of 60°C.

Cast Iron is assessed to a permissible stress methodology using BD21/01 and thus has a series of stress limits rather than partial factors (see clause 4.10).

Step 6.
Design calculations

The design was performed based on CIRIA Report C595, in conjunction with BD 21/01.

The design resulted in two options for the cast iron beams:

- 3 No. 140mm wide, maximum 20mm thick laminates tapered to 4mm, 420GPa pultruded CFRP laminates on the internal cast iron beams and 2 No. of the same laminates on the external cast iron beams.
- 3 No. 140mm wide, maximum 23mm thick laminates tapered to 1mm, 320GPa pre-formed CFRP laminates on the internal cast iron beams and 2 No. of the same laminates on the external cast iron beams.

In addition, two options were available for the cast iron deck plate stiffeners:

- 1 No. maximum 100mm width tapering to 30mm width, maximum 16mm thick pre-formed CFRP laminates (320GPa) tapered to 1mm, interspersed at the cross-over section on the 'X' deck plate stiffeners, and 1 No. 32mm wide, maximum 21mm thick pre-formed CFRP laminates (320GPa) tapered to 1mm on the edge deck plate stiffeners.
- 1 No. maximum 100mm width tapering to 30mm width, approx. maximum 16mm thick on-site heat and vacuum cured pre-preg CFRP laminates (approx. 320GPa), tapered to 1mm, laid alternately at the cross-over section on the 'X' deck plate stiffeners, and 1 No. 32mm wide, approx. maximum 21mm thick on-site heat and vacuum cured pre-preg CFRP laminates (approx. 320GPa), tapered to 1mm on the edge deck plate stiffeners.
- 1 No. maximum 100mm width tapering to 30mm width, maximum 12mm thick pultruded CFRP laminates (approx. 420GPa), tapered to 1mm, laid alternately at the cross-over section on the 'X' deck plate stiffeners, and 1 No. 32mm wide, approx. maximum 16mm thick pultruded CFRP laminates (approx. 420GPa), tapered to 1mm on the edge deck plate stiffeners.

Step 7.
Design conformance checks

1. Resin T_g = Not listed, but manufacturer tests show 80˚C – 100˚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 or impede on the headroom by an unacceptable amount (after approval by Network Rail gauging engineer).
4. Stress checks:
    a. Strain in FRP at midspan on cast iron beams and deck plate stiffeners = 0.016% compared to allowable of 0.3%.
    b. Live load tensile stress at soffit of cast iron beams (typically 20N/mm^2) and deck plate stiffeners is less than the live load tensile stress limit based on Clause 4.10, BD 21/01 (assuming heavy traffic, poor surface). HB capacity rated at 25 units.
    c. The principal stress in the adhesive bond is less than 25N/mm^2. The design principal stress shall be checked with the peak principal stress back-calculated from the lap-shear tests, using the partial factors from Step 5.
5. Appropriate level of strengthening achieved (~ 30% increase in total bending capacity of cast iron beams). FRP strengthening is specified to take place after dead load reduction by reinstatement of fill with lightweight concrete, to ensure no permanent stresses exist in the adhesive or FRP strengthening.
6. A weight limit of 3 tonnes was enforced during strengthening operations to ensure plant and other equipment would not overload the unstrengthened bridge.

Step 8.
Prepare specification

Extracts from the specification for concrete can be found in the case study 'St Michael's Road'. Extracts of a specification for CFRP materials bonded to cast iron are shown below, however the concrete and cast iron specifications share common clauses of workmanship, FRP laminate, adhesive and independent testing (however the pull-off strength to be achieved on a metallic substrate is 20N/mm^2).

Cast Iron Substrate

1. *The surface of the metal to be bonded shall be dry, sound and uncontaminated. This involves removing any loose paint and corrosion, inspection/repair of any cracks then grit blasting to a level of SA2.5.*

Step 9.
Specific material selection

Two acceptable types of UHM CFRP plates were specified during the design, to allow competitive tendering. The specialist sub-contractor (Concrete Repairs Ltd) selected FRP composite materials that were complied with one of these designs. Therefore, there were no changes to the design due to material selection.

Step 10.
Method Statement for application of reinforcement

The Method Statement for general works was prepared by Edmund Nuttalls. This document details:

- The scope of works, identification of hazards
- Railway interface arrangements (e.g. possession types etc.)
- Protection from railway infrastructure
- Environmental protection
- Required plant and equipment
- The bonding methodology
- The materials to be used
- Emergency arrangements
- Contractor qualifications.

The document was checked, commented on and then approved by the Employer's Representative.

Concrete Repairs Ltd was the sub-contractor who prepared the Method Statement and carried out the works for the CFRP strengthening. This document details:

- Surface preparation
- Environmental control
- CFRP laminate and adhesive preparation and installation
- Temporary clamping arrangements
- Test samples to be made on site
- Finishes to bonded CFRP laminate
- Procedures for remedial work (e.g. injection of adhesive if voids present after tap-testing).

Step 11.
Site activities prior to installation

These processes are detailed within the pre-approved Method Statement:

1. Arrive at site
2. Set up lights, heating and enclosure

3. Await ES/COSS permission to begin
4. Check cast iron surface and prepare
5. Apply adhesive to laminates, cast iron and concrete
6. Apply laminates to bridge soffit, install temporary clamps, and check minimum headroom
7. Clear site and hand back possession.

These activities took place over both a single long possession and a series of shorter possessions over a number of weeks, so the setting up of site and other related activities were repeated more than once. During bonding works, an Employer's Representative was present on site to maintain and confirm the bonding record and approve 'check points'.

Step 12.
Surface preparation

Prior to bonding the surface was prepared to be clean and free from contaminants. The cast iron was vacuum blast cleaned to SA2.5. It was then repaired if required using an appropriate, compatible repair material that was approved prior to commencement of activities. Steel dollies were then bonded onto the primed and un-primed substrate for subsequent pull-off tests, which were performed after a cure of at least 24 hours, but prior to application of the composite materials system.

10 No. pull-off test dollies were bonded during possessions prior to the main installation possession. A number of these pull-off tests failed due to the uncontrolled environment (particularly cold temperatures of approximately 5°C) outside the main installation possession. A further 30 No. pull-off test dollies were installed on primed and unprimed surfaces at the beginning of the main installation possession, and were found to provide adequate pull-off strengths (generally varying from $20N/mm^2$ to $40N/mm^2$).

These steps are detailed within the method statement and had prior approval of the Employer's Representative.

Step 13.
Application of composite materials system

The peel ply was first removed from the laminate and the surface was 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. The laminates are then clamped into position with the temporary support device. Simultaneously, the testing samples are prepared. These steps are detailed within the method statement and had prior approval of the Employer's Representative.

Step 14.
Final QA checks, inspection and approval

The laminates were tap tested after cure to ensure the entrapped air is within the limits within the specification. However, the tap testing found that there were a small number of voids bigger than those allowed by the specification. The contractor had to inject a low viscosity resin to fill the voids and then bond a plate over the injected area. The Employer's Representative was consulted on this and approval was given to proceed. Off-site testing by Oxford Brookes University on dumb bell samples of adhesive (for tensile modulus and strength), adhesive T_g, single lap shear for different batches. The results were all within the specification and are as follows:

T_g	=	62.6°C	Pass
Ultimate tensile strength	=	32.5MPa	Pass
Tensile modulus	=	7.7GPa	Pass
Lap shear strength	=	15.1MPa	Pass

Inspection / maintenance / monitoring regime
A maintenance manual was produced, with inspections scheduled at regular intervals after the installation of the laminates to ensure:

- There is no visible evidence of cracks developing in the cast iron;
- There is no visible evidence of the laminates becoming debonded, determined by visual inspection of the edges of the laminates, with no attempt to pry the laminates from the flanges/deck soffit;
- By tapping the laminates with a light metallic object (e.g. a light metal hammer), there is no audible evidence of the laminates having become debonded;
- There is no evidence of mechanical damage to the laminates, from accidental impact or vandal attack.

This system of inspection will be at three monthly intervals for the first six months, then yearly until year three and then finally at five yearly intervals for the remaining life of the bridge.