

# Strengthening of the West Gate Bridge Concrete Viaducts

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**Abstract.** The 2.5km long West Gate Bridge comprises an eastern and western concrete approach viaduct, 871m and 670m respectively in length either side of the 850 m long cable stayed steel box girder main span section. The key objective with the West Gate Bridge Strengthening Project was to increase the number of lanes in each carriageway from 4 to 5 to reduce traffic congestion on the M1 Freeway. This paper describes the elements used to strengthen the concrete viaducts including carbon fibre reinforcement and additional post-tensioning. An extensive system of temporary platforms was required for access to the outside of the box girder. Given the weight of these platforms and the limited capacity of the unstrengthened bridge, particular care was required with the staging of the works, traffic controls and platform movements.

## Introduction

The 2.5km long West Gate Bridge spans the Yarra River in Melbourne, Victoria. The bridge is part of the M1 freeway and links Melbourne's CBD with the western suburbs. It comprises eastern and western concrete approach viaducts, 871m and 670m respectively long and a 850 m long cable stayed steel box girder main span section (ref Fig 1).

The typical viaduct span is 67m and the superstructure comprises a three-cell post-tensioned concrete box girder, originally constructed using span-by-span construction. Propped cantilevers at 3.7 m centres support the outer portions of the deck (ref Fig 2). Some strengthening works had been performed on the western viaduct in 2004.

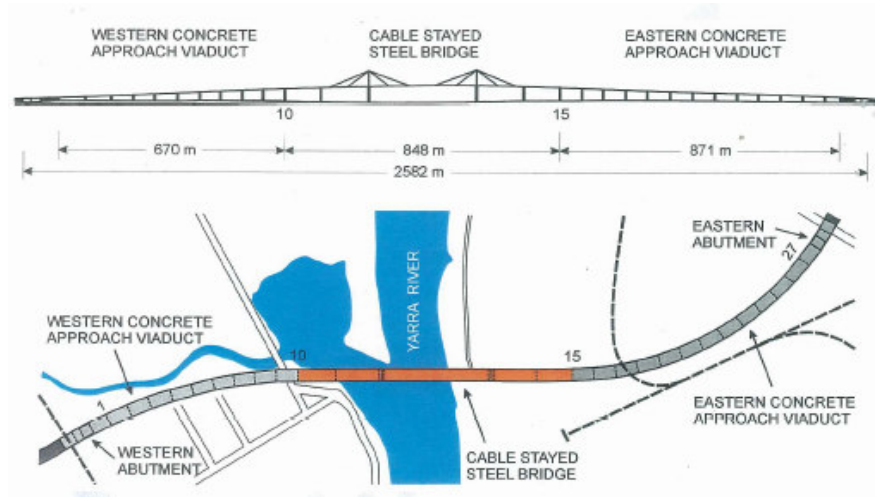


Fig. 1. General arrangement of the West Gate Bridge.

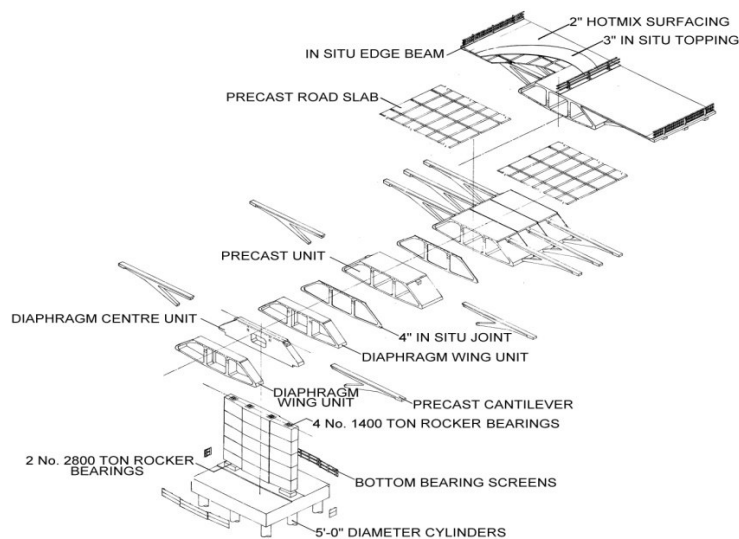


Fig. 2. Concrete viaduct components

The project was delivered by the West Gate Bridge Strengthening Alliance (WGBSA), consisting of VicRoads, SKM, John Holland and Flint and Neill. The strengthening project works were completed in mid-2011.

Broadly speaking, the strengthening of the concrete viaducts includes:

- Carbon fibre reinforced polymer (CFRP) applied externally to the box girder and the cantilevers;
- Longitudinal external post tensioning installed inside the box girder.

Access to the outside of the box girder was by a combination of platforms suspended from the bridge and scaffold supported off the ground under the bridge.

## Initial Investigations and Studies

With the preparation of the project Business Case it was identified that to maintain the current width of the bridge deck and strengthen the structure to provide for five lanes in each carriageway provided the best value for money (ref Fig 3).

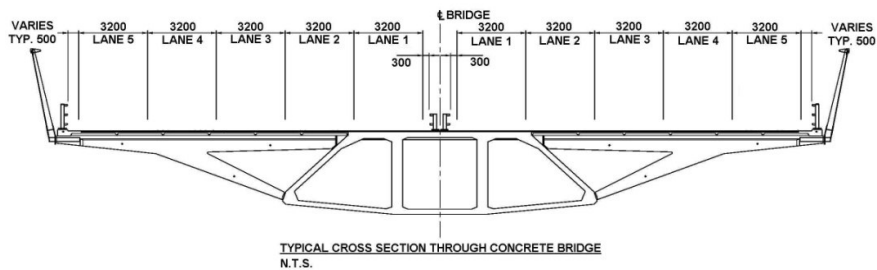


Fig. 3. Cross section of concrete bridge with final lane positions.

## Assessment and Design

### *Bridge Specific Assessment Criteria*

Application of current design standards was deemed inappropriate because of the unique characteristics of the bridge [1]. Bridge specific assessment criteria were developed. The Bridge Specific Assessment Live Loading (BSALL) [2] was, derived from a probabilistic analysis of existing traffic loads. The end result was a design loading that was greater than that for which the bridge was originally designed, but less than the current SM1600 loading.

### ***Structural Modelling***

The structural modelling was carried out using SOFiSTiK, a 3-dimensional finite element structural design package [4]. The full structural model included a global model of the substructure and superstructure with localised sections, such as the section of deck over the piers, modelled in greater detail. The models represented time-dependent effects, including the original construction sequence and creep and shrinkage. The global models utilised predominantly beam elements supplemented with shell elements to examine local effects.

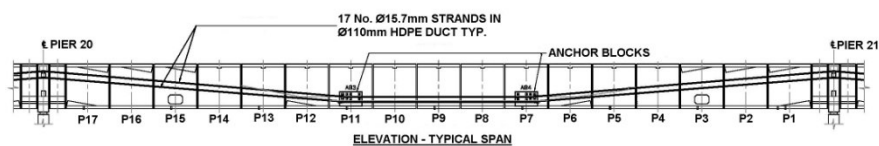
A key lesson learnt with the application of such advanced analysis software was the importance of good back-up either from the software vendor or from others very familiar with the software.

### ***Strengthening Details***

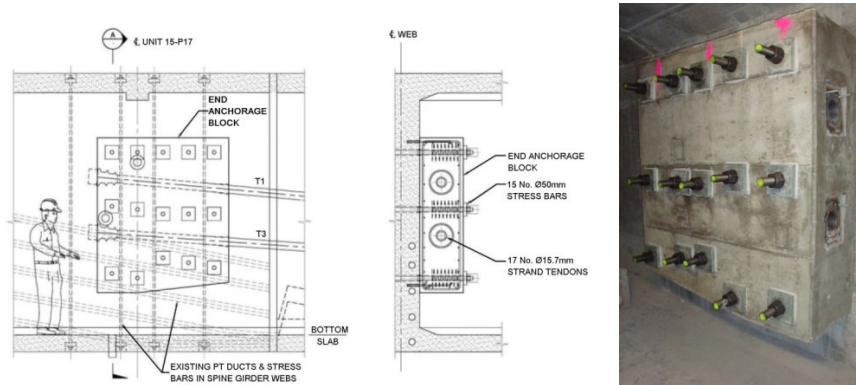
Development of strengthening details was performed generally in accordance with AS5100 [8]. Compression across joints was investigated to satisfy requirements for zero tension. In addition to AS5100, design guidelines were used for the assessment of torsional resistance of the box girder and CFRP design guides such as ACI 440 [5], FIB 14 [6] and TR 55 [7] were used for the CFRP components.

### **Post Tensioning**

Additional post tensioning was provided to limit the tensile stress in the spine girder at SLS, as well as increasing the ULS capacity. Draped tendons were used for the Eastern Viaduct (ref Fig 4). Cast in-situ concrete was used for the anchorage blocks, including both end anchorages and deflector blocks. The anchorage blocks were stressed onto the box girder webs using 50mm diameter stress bars (ref Fig 5).



**Fig. 4.** Typical additional tendon profile on Eastern viaduct

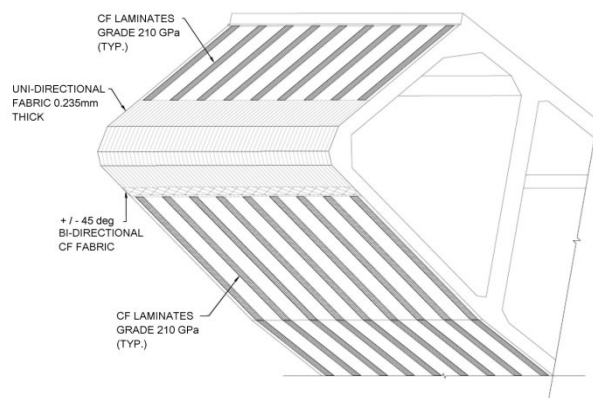


**Fig. 5.** Typical end block tendon anchorage

The Western viaduct had been strengthened in 2002. This strengthening was found to be insufficient for the BSALL, and additional straight tendons were provided.

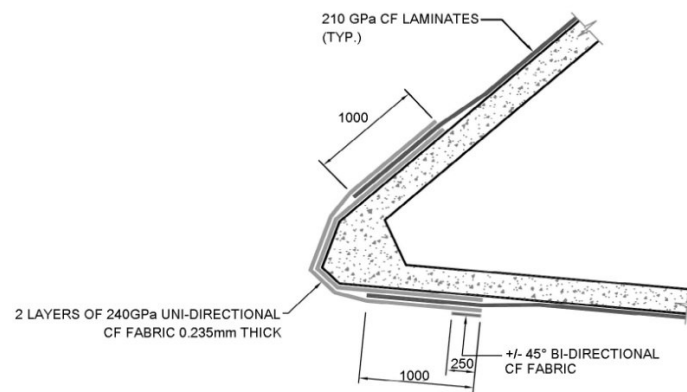
### Shear and Torsion

CFRP laminates were applied transversely and continuously around the outside perimeter of the box girder from the top of the outer face of the web on one side, down the face of the web, across the soffit and up the face of the web on the other side (ref Fig 6). Care was required with the interpretation of Section 8.3 of AS5100, which was found to be somewhat ambiguous when applied to the shear flow in the box girder. This was resolved by considering the box girder walls as elements in shear rather than applying the specific torsion provisions of AS5100.



**Fig. 6.** External laminate layout, Eastern viaduct

Unidirectional carbon fibre fabric was applied at the corners, with the laminates applied between two layers of fabric. An additional layer of  $\pm 45^\circ$  bidirectional fabric was applied on the soffit near the termination of the unidirectional fabric to assist with spreading the laminate force. The use of the  $\pm 45^\circ$  bidirectional fabric together with the unidirectional fabric provided an efficient means of anchorage and increased the ultimate laminate strain [5] by up to 195% (ref Fig 7). The performance of this arrangement was verified by extensive laboratory testing.

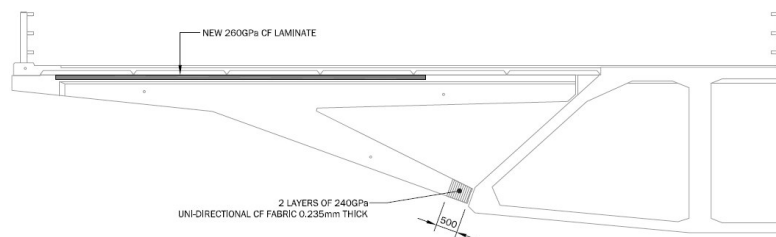


**Fig. 7.** Corner splice details

The internal webs required strengthening in discrete locations near the piers. Because of the difficulty of effectively anchoring the laminates in this region, confined space requirements and other practical difficulties applying CFRP inside the box girder for the internal webs was kept to a minimum.

### Cantilevers

The prestressed concrete cantilevers had adequate flexural capacity for SLS loading but not for ULS. CFRP was applied to the cantilevers as shown in Fig 8.



**Fig 8.** Typical Cantilever Strengthening Layout

### ***Public Safety Barrier***

Public safety barriers (PSBs) were installed along the length of the bridge (Fig 9). The PSB's posts were aligned with barrier posts and connected to end of cantilevers with a bolted bracket connection. The brackets had to be fixed without damaging the existing prestress and reinforcement in the cantilever and were detailed with a number of redundant bolt locations to provide the flexibility to satisfy this requirement.

A special detail was developed at the bridge expansion joint to accommodate movements of the bridge. It involved two interconnected cantilevered panels that slide past each other.

Details of the design and development of the barriers is provided in a paper by Juno & Percy [3].



**Fig. 9.** Architectural images of the PSB (left) and final installed system (right).

### ***Freeway Management System Gantries***

Being part of the M1 Freeway Management System (FMS), four gantries were required on the bridge viaduct, as well as gantries just off the bridge for mounting variable Lane Use Management Signs. Arriving at a concept for the gantries and accommodation of the loads they applied to a structure not designed originally for such loads presented both a design and constructability challenge.

The adopted concept includes cantilever arms that extend under the bridge to the concrete cantilever ribs (Fig 10) and a central vertical prop between the median barriers. The structure was modelled to confirm its dynamic behaviour and the implications for fatigue. Having a prop within the median is clearly undesirable

from the road safety perspective, but was regarded as providing a reasonable compromise in this instance.



**Fig. 10.** FMS gantry

## **Construction**

### ***Access***

#### **Internal Works**

Some access holes were enlarged and additional access holes provided in the soffit of the concrete box girder. Monorails and material hoists were installed above the openings. The materials were moved inside the box girder by means of electric tugs.

#### **External Works**

The access system comprised large platforms suspended from the bridge as well as birdcage scaffolding built from the ground.

A modular steel space truss external access platform with a structural plywood deck was adopted. The platforms were suspended by chain assemblies from the



existing viaduct cantilevers. Entrance to the platforms was via the construction lane and an aluminium stair tower. Static scaffolding and mobile aluminium scaffold towers were provided on top of the access platforms. All of the platforms were fully serviced with potable water, toilets, power and extensive lighting.

The limited capacity of the unstrengthened viaduct required strict control measures to limit the platform loads. A tagging system was adopted to ensure that the maximum allowed number of personnel was not exceeded.

The bulkier materials and equipment was lifted with the platform during its erection while the more manageable items were lifted by cranes or by a davit mounted onto the bridge barrier.

Two platform types were used (ref Fig 11):

- A spine platform was used to access the box girder central spine. Four 20m x 20m ‘Spine platforms’ were commissioned with each platform providing access for up to 26 personnel. The spine platforms were adjustable to fit the geometry of the underside of the viaduct spine.
- A wing platform was used to access the cantilevers and the Public Safety Barrier. Four 35m x 15m “Wing platforms” provided access for up to 27 personnel.

Spine platforms were relocated by lowering segments onto truck trailers using ‘man riding’ hoists and then moving them and hoisting them in the next position.

Wing platforms were advanced whilst suspended from the bridge. The travelling was facilitated by rail beams fixed to the platform deck, chain assemblies and girder trolleys. As the platform progressed forward using tirlors, a new chain assembly was installed at the leading edge of the platform and the redundant chain assembly was removed at the trailing edge of the platform.



**Fig. 11.** Spine and wing platforms

The unstrengthened viaduct capacity required the wing platforms to be operated in pairs to minimise the eccentric loading. A procedure was established for the efficient sequencing of the platform works taking into consideration the bridge loading constraints, space and time constraints to provide continuous access for up to 100 personal and all relevant resources.

A portion of the spine CF works was undertaken from large birdcage scaffolds up to 20m x 20m in plan and up to 50m above the ground.

### ***Staging and Sequencing***

The construction phase of the project was complicated by the requirement to minimize lane closures. Typically, during peak times no lane closures were allowed, while at night and on weekends up to 3 of the 4 lanes in each carriageway could be closed without a significant impact on traffic flow. Some flexibility was provided by the fact that during peak hour, there is an increased percentage of commuter vehicles, which leads to a reduction in the loadings for the traffic jam situation.

To facilitate access for the works the original emergency lane that was ultimately being converted into the fifth operating lane, was converted to a 2.5 m wide construction lane for the duration of the project.

### ***Carbon Fibre***

The West gate Bridge Strengthening Project is the largest carbon fibre (CF) civil structure strengthening project ever undertaken in the world by a factor of four. The extensive CF materials, including sections up to 14m long were sourced from France and transported by ship or air depending on the size and program demands. All of the components were pre-cut to length to a tolerance of -0mm to +10mm. . CF laminate sections were also custom made to maximise design efficiency, reducing waste and eliminating the need for multi layered laminates. All of the CF laminate sections were fabricated with a protective 'peel ply' on both sides. The peel ply was only removed just prior to installation or painting and significantly reduced the amount of thinners required on site for cleaning and the safety risks associated with handling thinners.

The Quality Assurance (QA) system included hammer testing to detect de-bonded areas, destructive tensile pull-off testing, compressive testing of epoxy materials

as well as strict control over the thickness of the epoxy layer to ensure strain compatibility.

Installation of the 14m long CF laminate sections to the underside of the viaduct soffit was particularly challenging. These sections were temporarily supported during the curing period by a strapping system which ensured that the stiff CF sections would follow the bridge soffit profile (Fig 12).



**Fig. 12.** Installation of 14m long carbon fibre laminate

### ***East Viaduct Jacking***

The piers on the viaducts are effectively pinned and have rocker bearings at the top and bottom and the viaduct is anchored to the abutments. Longitudinal movement is accommodated by a roller bearing at the expansion joint.

The additional post-tensioning strengthening caused shortening of the Eastern viaduct, which created a potential problem with the functioning of the roller bearing at times of extreme cold weather. The jacking relocated the 51,000 tonne viaduct 80mm towards the west to offset the effect of the shortening.

## **Legacy and Maintenance Documentation**

The last stage of the project included the production of as-built drawings, preparation of a report that captured, for posterity, the essence of the design and recorded important issues that arose during construction and preparation of a maintenance manual for the bridge. The maintenance manual will provide the basis for the development of a comprehensive Bridge Maintenance System.

## **Conclusion**

The strengthening of the concrete viaducts of the West Gate Bridge presented major challenges and this paper describes the work and how it was approached. In addition, the following provides key conclusions that can be drawn from this experience:

- A careful balance is required between programme, design, constructability, site access, delivery, resources, etc. The Alliance delivery model was a very effective mechanism for achieving this balance and effective cooperation between the design teams and the construction teams.
- Comprehensive analyses, in the early stages of the project, and an innovative approach led to a thorough understanding of the structure and the development of an efficient design solution.
- Constant liaison between the construction and design teams allowed for the early identification of innovative, practical and constructible design solutions developed in parallel with access requirements, construction processes and procedures.
- The use of unidirectional and bidirectional fabric as a means of creating a greater bond area with the concrete substrate enabled substantially higher utilisation of carbon fibre laminates.

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