West Gate Bridge Strengthening

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SYNOPSIS

The 2600 m long West Gate Bridge, first opened to traffic in 1978, is one of Australia’s most important transport infrastructure assets. It includes an 850 m long cable stayed steel box girder central portion over the Yarra River and segmental prestressed concrete box girder approach viaducts of 670m and 870m long on the western and eastern sides respectively.

The West Gate Bridge Strengthening Alliance (comprised of VicRoads, Flint & Neill and SKM, with the later addition of John Holland) was formed to undertake all work and improvements relating to a proposed upgrade of the bridge’s capacity. In addition, the bridge’s performance in relation to carrying existing traffic was to be investigated.

This paper presents a summary of the investigation and monitoring work that was conducted in the lead up to the formation of the Alliance and the subsequent detailed assessment work the Alliance has undertaken. An important feature of the assessment is the development of Bridge Specific Assessment Criteria, including specific loading models based on measured data collected using Weigh-in-Motion equipment installed on the bridge.

BACKGROUND

The West Gate Bridge forms an essential part of Melbourne’s M1 transport corridor, by providing a link over the Yarra River and an important connection of Melbourne’s east and western suburbs. The bridge has a mix of commuter, general commercial and container traffic, and carries upwards of 160,000 vehicles per day. As part of the overall widening and upgrade of other parts of the M1, a corresponding increase in the traffic capacity of the West Gate Bridge is required which will take it from its current four lanes plus an emergency lane carriageway arrangement, to a five lane carriageway at peak times. Various options were considered during the assessment, including contraflow, however the preferred solution is to convert the existing emergency lanes into permanent running lanes thus providing five full lanes in each direction. A drawing of the bridge is shown in figure 1.
The bridge is highly complex, not only because of its structural form, but due to the history of the bridge and subsequent strengthening works. The bridge was redesigned in the early 70s as a result of a collapse of a segment of the steel box girder during the construction. More recently the western concrete approach viaduct has been strengthened with additional external prestressing and carbon fibre to allow for the Williamstown Road on-ramp.

As of February 2009, the Alliance is finalising the target out-turn cost (TOC) for the preferred strengthening option. Once this has been approved, final design and construction of the strengthening works will commence. In order to develop the preferred strengthening option, rigorous and progressive analysis was undertaken resulting in a high degree of sophistication in the modelling process. This was enabled by drawing on previous investigations and monitoring of the bridge by VicRoads prior to the formation of the Alliance. These investigations and monitoring programs are listed in the following section of this paper, with reference to how they were utilised by the Alliance. The remainder of the paper details the recent structural assessments undertaken for the steel and concrete sections of the bridge including details of the calibration and verification of the models using data collected from the behaviour of the bridge. Finally this paper details the determination of the Bridge Specific Assessment Live Loading (BSALL) and how data of actual vehicles that travel over the West Gate Bridge was used in its formation.

PREVIOUS INVESTIGATIONS AND MONITORING OF THE WEST GATE BRIDGE

Prior to the formation of the West Gate Bridge Alliance, VicRoads had been entrusted with monitoring and maintenance of the asset. A significant amount of information of the characteristics and behaviour of the bridge had been collected through investigations and monitoring carried out by VicRoads over the years following the construction. Below is a summary of these investigations and monitoring, and how they have been utilised by the Alliance.
• **Original Construction and Administrative Records** – Due to the significance and importance of the bridge to the State of Victoria, all original design calculations, reports, administrative records and drawings have been kept from the original design, Royal Commission, and redesign stages. However, due to the halt in the construction programme, and subsequent redesign, there have been numerous records, calculations and most importantly drawing sets produced. Subsequently there are six main sets of drawings for the steel section of the bridge, the original engineering design drawings, the re-engineered design drawings, and various sets of construction and fabrication drawings based on the two sets of engineering design drawings. Part of the Alliance’s scope of work is to provide a set of ‘as built’ drawings to capture and combine the information from the succession of drawing sets and cross reference them with on site measurements and observations.

• **Photographic Surveys** – In order to assist the Alliance with design and construction of the bridge, in late 2007, a full photographic survey of the inside of the steel bridge was undertaken. The survey involved taking 22 standard photos of each cell. The photos have been a valuable tool for the design team, part of which is based in London.

• **Inspections** – At the completion of the bridge construction in 1978, a maintenance manual was written that recommended inspection frequencies of various elements including fatigue critical areas, welds, bolted connections, cables and their supports systems, expansion joints, bearings, general surveys, utilities, paint system and surfacing. To a large degree the inspection schedule has been followed by VicRoads, supplementing additional inspections where necessary. At the beginning of the strengthening project, the Alliance conducted extensive inspections of the entire bridge, identifying and documenting all defects within the bridge. The inspection records are now being used by the maintenance team to develop an updated inspection schedule.

• **Fatigue Studies** – Fatigue monitoring and prevention has been a concern for VicRoads in recent years. VicRoads has taken the approach to fatigue of regular and vigilant monitoring with a focus on critical areas. Fatigue cracking in the cantilever sections of the steel bridge was first identified in the late 1980s. At the time, an investigation into these fatigue cracks recommended a semi-circular cut-out in the web of the cantilever at the high stress locations (Grundy, Burkitt & Stevens, 1994). At other locations where fatigue cracking has been identified, a similar process of modelling and investigating various techniques to impede the advancement of fatigue cracks has been adopted. Modelling techniques in recent years has involved the development of 3-dimensional brick element finite element models of the critical areas backed up by strain gauging of the area to verify the predicted behaviour. The location and behaviour of fatigue critical areas has been recorded by the Alliance team, with the aim of any strengthening options to eliminate or reduce the extent of cracking by reducing peak stresses in critical areas, and provide alternative load paths.
• **Weigh-in-Motion Data** – In 2007 a weigh-in-motion (WIM) system was installed on West Gate Bridge. The system is installed near the east tower and collects data from the four running lanes in each direction by use of piezo tubes. The system has been calibrated at regular intervals and collects axle loads. The data has been used for development of the Bridge Specific Assessment Live Loading (BSALL) mentioned in more detailed in the following sections. The information has also been used to monitor overloaded vehicles and traffic patterns.

• **Cable Accelerometers** – In 2007 the first of four cable damping devices on the outer cables was removed. They were originally installed during the construction phase when a pair of partially stressed outer cables exhibited wind induced dynamic excitation. To assess the natural frequency of the fully stressed cables, accelerometers were attached to the outer cables and an inner cable. The results from the cable accelerometers were also used to verify the cable forces, using a method developed by Geier, De Roeck & Flesch (2006). The calculated cable forces gave good correlation with the documented values.

• **Bridge Deck Accelerometers** – Accelerometers were also placed on the bridge deck to determine the frequency and shape of the first few modes. These values were then used to calibrate the global computer models being developed by the Alliance. A total of 18 accelerometers were placed at critical locations along the steel bridge to measure vertical bending, torsion about the longitudinal axis, and lateral bending. The results confirmed to the design team that the stiffness characteristics of their models closely matched the observed frequencies and mode shapes, but they would also have provided the means to tune the model if necessary.

• **External Prestressing and Carbon Fibre Strengthening of Western Concrete Viaduct** – In 2002 a section of the western concrete viaduct was strengthened using external prestressing and carbon fibre to accommodate the widening of the northern carriageway to five lanes for the Williamstown Road on ramp. Since the strengthening works, the bridge along with the new strengthening works has been visually inspected which included checking for any deterioration of the fibre or its bond to the concrete.

• **Strain Gauging** – A total of four physical load tests have been conducted on the West Gate Bridge in recent years. The test vehicles used have included 45 ton 6-axle semi-trailers, 48 ton 4-axle cranes, and ambient traffic. The strain gauging has been focused around the cross beam and cantilever sections and their associated connections to the steel box girder, primarily to determine loading and fatigue effects on transverse elements of the steel box. Strain gauging in this manner has been used to investigate local effects, and to verify finite element models of a single box section.

• **Barriers** – An extensive inspection programme was undertaken in 2000 to assess the condition of the barriers. Corrosion was identified on some members, that were subsequently replaced and FE modelling was undertaken to assess the consequences of impact of modern vehicles. The Alliance has
made use of this information in developing its approach to strengthening the barriers, as well as conducting an international review of barriers used on similar bridges.

- **Anemometers** – There are anemometers mounted on masts in the centre of the steel bridge. While the primary purpose of the anemometers is to alert the traffic control centre to high winds so that traffic speed restrictions can be imposed, the data has been used by the Alliance in conjunction with the accelerometer readings, survey results and strain gauging.

- **Infra-Red Traffic Logger** – There is a pair of infra-red traffic logger systems on West Gate Bridge used to record the number of vehicles in each lane. Vehicles are classified according to the Austroads vehicle classification system (e.g., passenger cars, single unit trucks, buses, B-doubles etc., cranes). The results have been used to assess traffic flow and behaviour at various times of the day.

- **Thermocouples** – Recently, as a result of the Assessment and Criteria developed for the strengthening works, thermocouples were installed on each of the two towers. The thermocouples were installed inside the north and south faces of each tower at three locations (i) deck height, (ii) mid-height, and (iii) at the top. The bridge also contains thermocouples to measure ambient and bridge deck temperatures.

- **Routine Maintenance** – Over the thirty odd years the bridge has been in-service, various elements of the bridge have required routine inspection and maintenance. These have been carried out by VicRoads as the need arises. On top of those elements described in this section, maintenance has also been required for the asphalt surface, bearings, expansion joints, concrete pier cracking repair and touch up of external paint to name a few.

- **Risk Review** – VicRoads has been continuously assessing and mitigating potential risks that could influence the behaviour of the bridge. Risk reviews undertaken include, impact, blast, fire, earthquake, and damaged utilities. The Alliance has utilised these reviews to develop a risk register.

### RECENT DETAILED STRUCTURAL ASSESSMENT

In order to first evaluate the current capacity of the bridge and subsequent degree of strengthening required to achieve the desired loading criteria, models were developed for both the steel and concrete sections of the West Gate Bridge. The following sections detail the range of models developed and the calibration and verification methods.

1) **STEEL BRIDGE**

Both global and local models have been developed for assessment of the steel bridge, as well as wind tunnel testing of the cross-sectional profile. These models, and their calibration and verification are detailed in the following sections.
i) Global Models

Two independent global analysis models were formulated for use in the assessment. The first was a relatively straightforward line element model. This model provided the ability to model the bridge and interpret the results rapidly and directly. It was therefore used for early preliminary assessment, calibration against the observed behaviour of the West Gate Bridge, seismic behaviour, and verification of the later more sophisticated models.

The bulk of the detailed structural assessment was undertaken with a full LUSAS shell finite element model (as shown in figure 2). This model included the full deck cross section of inner and outer webs, top and bottom flanges and cross beams and cantilevers. This enabled shear lag, torsional and distorsional effects to be modelled with greater accuracy. This model was used for the majority of the assessment work including modelling of the original construction sequence. The model was calibrated both against the observed behaviour of West Gate Bridge and verified against the earlier line model.

A strong benefit of the global finite element model is that specific areas of the model can be worked up in much greater detail. This means that with today’s computing power, the analysis of areas which would formally have been undertaken by a separate area finite element model can now be undertaken as part of the global model analysis, thus avoiding the need to balance local and global effects and apply boundary conditions and restraints to a separate area model.

In order to calibrate the global model, the dynamic mode shapes and frequencies from the global analysis model were compared against those obtained from studies based upon deck box accelerometer gauge readings recorded between December...
2007 and January 2008 Jan 08, and those contained in the “West Gate Bridge, Wind Tunnel Tests,” by Melbourne (1973). Close agreement was found.

The cable tensions were similarly compared with those from the “Redesign of West Gate Bridge” Report (Toakley, 1986), FFP Drawings, and from studies based upon cable accelerometer gauge readings recorded during 2007. Again satisfactory agreement was found.

Calibration of global analysis models by comparison of modes and frequencies to those measured from the actual bridge is considered a highly suitable model verification method for the following reasons:

- Frequencies and modes derived from a series of accelerometers measuring ambient vibrations of the bridge over a period of time are clear and unambiguous.

- The bridge does not have to be shut to traffic as it would for a load test.

- The results are not dependant on local structural load paths, or exact distributions of axles and weights, and are not prone to experimental scatter.

- Matching across a range of mode shapes and frequencies provides a high degree of confidence that the mass, mass distribution and stiffness of the analysis model matches that of the bridge very well.

- The derived model shapes account for all structural load paths, including for instance, contributions from composite action from orthotropic deck surfacing.

An example of the comparison of the analysis model and measured bridge frequencies is shown in Table 1 and Table 2.

<table>
<thead>
<tr>
<th>Vertical Mode Number</th>
<th>Line Analysis model frequency (Hz)</th>
<th>Measured West Gate Bridge frequency (Hz)</th>
<th>Percentage difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.340</td>
<td>0.348</td>
<td>2%</td>
</tr>
<tr>
<td>6</td>
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<td>18</td>
<td>1.532</td>
<td>1.570</td>
<td>2%</td>
</tr>
</tbody>
</table>

*Table 1: Comparison of the analysis model and measured bridge frequencies for vertical modes.*
<table>
<thead>
<tr>
<th>Lateral/ Torsional Mode Number</th>
<th>Line Analysis model frequency (Hz)</th>
<th>Measured West Gate Bridge frequency (Hz)</th>
<th>Percentage difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
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<tr>
<td>5</td>
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<td>8</td>
<td>0.841</td>
<td>0.859</td>
<td>2%</td>
</tr>
</tbody>
</table>

*Table 2: Comparison of the analysis model and measured bridge frequencies for lateral and torsional modes.*

**ii) Area and Local Modelling**

Although local area modelling was predominantly conducted within the global model, some separate area models were produced along with local models of elements such as tower saddles and splay clamps.

The results of the assessment were broadly in line with what was expected and with what had been found during the assessment and strengthening of other bridges in the West Gate family such as Wye, Erskine and Cleddau (Milford Haven) bridges in the United Kingdom. Deficiencies were found with stiffener and panel buckling capacity with some local yield capacity problems extending in varying extent throughout the deck. In addition, the provision of an additional running lane where the current emergency lane is residing on the outer edges of the bridge will necessitate strengthening of the cantilevers underneath. This will be undertaken by propping of the cantilevers which is also expected to reduce the stresses in fatigue critical cross girder connections. Calibration and verification of the local models was conducted by comparing results to strain gauge testing undertaken on the cantilevers and cross beams.

An additional but vital part of the early assessment work was to make provision for improved access into the box girder, which was previously only possible through manholes in the central reserve necessitating lane closures. New soffit openings have been provided and designed at the end piers of the bridge, and access internally in the bridge vastly improved by strengthening webs and diaphragms to permit much larger access openings to be installed. This ensures that the main box strengthening can be undertaken as a more efficient, safe and productive operation.

**iii) Wind Tunnel Testing**

Models of West Gate Bridge were wind tunnel tested at the time of its design in 1973, however since some of the strengthening options and proposed upgrades will alter the cross sectional profile of the bridge it was considered essential to re-evaluate the bridge’s aerodynamic stability. Of primary interest were the effects of a new security fence outside of the existing parapet, the new cantilever props and the relocated gantry rails. It is the nature of long span bridges with aerodynamic sections that relatively small changes in certain sensitive locations can have a pronounced effect on the bridge’ behaviour. At the time of writing the tests had not yet commenced.
2) CONCRETE VIADUCTS

Independent longitudinal analysis models were developed for assessment of the Eastern and Western Concrete Viaducts. Transverse models were also developed for assessment of local effects. These models and their verification are detailed in the following sections.

i) Longitudinal Models

The original construction process consisted of a span by span sequence. This sequence typically began with the erection of the first span of precast spine segments followed by the stressing of the web and bottom slab tendons. Further spans were then progressively erected with a similar stressing order. After the fourth span in the sequence was erected, the final top prestress along with the installation of the precast cantilevers and composite precast deck slab of the first span in the sequence was carried out.

Detailed three-dimensional line models were developed for the assessment of the longitudinal behaviour of the Western and Eastern (as shown in figure 3). Concrete Viaducts. These models included the original construction staging and the time dependent effects due to creep and shrinkage. The model for the Western viaduct also included the recent external prestressing strengthening works along with the corresponding time dependent effects. This modelling process provided the ability to not only compare the Eastern and Western Viaduct analyses, but also provide the ability to assess the effect of the recent strengthening.

![Figure 3: Longitudinal Sofistik model.](image)

This advanced modelling was undertaken using Sofistik. Sofistik is a finite element analysis and design package which allows for the integration of construction stage analysis, full 3D prestressed geometry definition including un-bonded tendons and
time dependent effects due to creep and shrinkage. Influence lines evaluation is also a feature that was used for live load application and super-positioning. The analysis results were verified against simplified SpaceGass models and close agreement was found.

Pertinent results included extreme fibre tensile and compressive stress evaluations considering shear lag effects. Checks of the ultimate flexural, shear and torsional resistance were also obtained.

**ii) Transverse Models**

Complex transverse analysis models were also developed in order to adequately assess the Concrete Viaducts (see figure 4 below). These models consist of a combination of plate and beam elements. Typically plate elements were used to model the spine while beam elements were used to model the cantilever beams. These models typically replicated the original construction sequence and included the time dependent effects due to creep and shrinkage.

This modelling was also undertaken using Sofistik. It allowed for the combining of beam and plate elements with the integration of construction stage analysis, the 3D prestressed geometry and including the time dependent behaviour of concrete as well.

![Figure 4: Local Sofistik model](image)

The intent of these analyses was to assess the transverse flexure of the spine and the capacity of the precast cantilever. Pertinent results other than forces and moments included extreme fibre tensile and compressive stress evaluations and checks of the ultimate flexural capacity of the precast cantilever beam.

The analysis results were verified against simplified hand calculations and SpaceGass models and close agreement was found. The results of the assessment were generally in line with what was expected.
BRIDGE SPECIFIC ASSESSMENT CRITERIA

The goal of the West Gate Bridge assessment and strengthening is to provide economic, safe and appropriate structural strengthening solutions for the proposed capacity upgrade. For the following reasons the application of current design codes by rote does not provide the best basis for this:

- The codes in general and the traffic loading models in particular are not intended for longspan bridges. Traffic models intended for shorter spans are overly conservative when applied to long ones.

- The codes often do not cover the full range of load effects or methods of application of loads appropriate to cable supported bridge structures. For example the full range of differential temperature cases (eg between cables and deck, across a steel tower, or for AS5100 even the steel box girders themselves are not covered). Similarly, dynamic and patch wind loading is often not dealt with.

- There are specific assessment codes available which deal with the strength assessment, these are also supplemented by further research into the behaviour of stiffened steel panels. Not all of this is captured in the design codes because in some cases they are not relevant to new build bridges. For example, such codes assume certain and not overly onerous levels of imperfection in the structure. If the actual level of imperfection is less, the structure will possess extra reserves of strength that will not be predicted by the code. For this reason, use of the UK assessment code BD 56/96 (with accompanying advice note BA 56/96), which allows strength predictions based on measured levels of imperfection is preferred, and indeed the stiffener imperfections were surveyed to provide this information. The design codes are also from necessity a simplification meaning that benefit is often obtained by referring back to the research or drafts that formed the basis of the code including IDWR and the Merrison Rules.

A bridge specific assessment document was therefore developed to cover both the loading and capacity sides of the assessment.

Of particular importance was development of a Bridge Specific Assessment Live Loading (BSALL). This is a technique used to probabilistically derive design loading from the actual current traffic using the bridge. The process, in simple terms, is summarised as follows.

Weigh-in-Motion installed within the asphalt surfacing on the bridge in early 2007 was used to measure axle weights and spacings over a six month period. This data provides individual vehicle characteristics which can then be assembled into theoretical traffic jams that could actually occur on the bridge if an incident were to arise. The worst jams in terms of loading are collected and then an extrapolation made to generate the worst conceivable jams in a suitable return period. This worst conceivable event is then translated into a load model which can be used in the
analysis. The resulting BSALL represents the extreme loading condition that provides the same level of safeguard or reliability against bridge overload as the standard code model loads.

The BSALL is a robust load model because it caters for increased traffic, so long as the traffic mix between different categories of vehicles does not change significantly. Historically this has proven to be the case; as the number of heavy goods vehicles has increased so has the numbers of cars and light trucks. Weights per unit length of individual classes of vehicles has also historically been stable, governed to a large extent by existing road network and vehicle manufacturer constraints. It is interesting to note that the BSALL for West Gate Bridge closely matches the T44/L44 code loading contained in AUSTROADS 92 as indicated in the figure below.

![Figure 5: BSALL loading compared with the SM1600 and T44 loading.](image)

One of the established principles of adopting a BSALL approach is that the WIM data should be collected and analysed roughly every two years to confirm the continued applicability of the live load model used in the assessment and design.

**SUMMARY**

Due to strengthening nature of the works (rather than a green field site), a significant body of information on the West Gate Bridge already exists, which can be utilised to the benefit of the project. As custodian of the bridge, VicRoads has undertaken numerous investigations and is constantly monitoring critical elements. The data available to the Alliance varies from the original documentation and drawings, to recent fatigue studies and traffic monitoring equipment.

A variety of global and local models were developed for both the steel and concrete sections of the West Gate Bridge. The global steel models were calibrated and verified using frequencies and mode shapes collected from accelerometers, while the
local models used strain gauging of the cantilevers with known applied vehicles loads. The concrete viaducts modelling incorporated the original construction sequence, and both longitudinal and transverse models were developed to assess the behaviour of the viaducts.

Finally, a Bridge Specific Assessment Live Loading (BSALL) was developed for West Gate Bridge, as the length of the bridge, load effects, and assessment of an existing structure, rather than design of a new one, resulted in a specific bridge assessment criteria being more suitable than simply applying current design codes. The BSALL was developed using weigh-in-motion data from the bridge, and correspondingly resulted in a close match with T44/L44 loading.

REFERENCES


