# Improved Load Rating Assessment of Princes Bridge through Load Testing

*Aaron Brimfield, BE(Hons) MIEAust CPEng*
*David Coe BSc (Hons) MIEAust CPEng*

## SYNOPSIS

Princes Bridge is Melbourne's grandest bridge linking the southern commercial and art centres to the heart of the city. It is also one of the busiest bridges in Australia servicing vehicular, tram and extensive pedestrian traffic. Located on one of Melbourne's busiest roads there was pressure on Melbourne City Council to assess Princes Bridge for the new higher mass vehicles specified for the Mass Limit Review (MLR). A subsequent desktop analysis suggested the bridge was significantly under strength for the higher loads and extensive strengthening was proposed.

Council originally proposed to design, document and tender the strengthening work based on the desktop analysis. With such a complex structure it was apparent there would be benefits in taking the assessment to an increased level of investigation.

A successful alternative proposal was put forward which included a diagnostic load test on the bridge. The objective of the performance test was to develop a calibrated structural model of the bridge from which strengthening design could be based. This paper will investigate that test and subsequent findings which resulted in significantly reduced strengthening requirements.

## 1 COMMENTRY ON PRINCES BRIDGE

***Figure 1: Princes Bridge, St Kilda Road, Melbourne, Australia***

### 1.1 Structural Form

Princes Bridge, shown in Figure 1, is principally a three span arched wrought iron plate girder bridge with course rock face bluestone piers, abutments and wing walls. The upper sections have dressed granite and sandstone detail. There are distinctive cast iron spandrels fixed to the sides of the external girders, with mouldings and a cast iron balustrade along the top of the bridge.

It is a complex structure consisting of many different structural components including:

- A concrete deck of varying thickness
- Steel arch plates supporting the deck, some of which span transversely and others longitudinally
- Transverse beams supporting the steel arch plates
- Longitudinal beams supporting the transverse beams
- Arch girders spanning between the bluestone piers
- Diagonal lattice members spanning between the longitudinal beam and the arch girder
- Vertical bracing at the ends of the spans
- Spandrel bracing between the bays of structure

Figure 2 shows the concrete deck, arch plates, transverse and longitudinal beams and the diagonal lattice members. Figure 3 shows the underside of Princes bridge including cross and spandrel bracing and main arched plate girders.

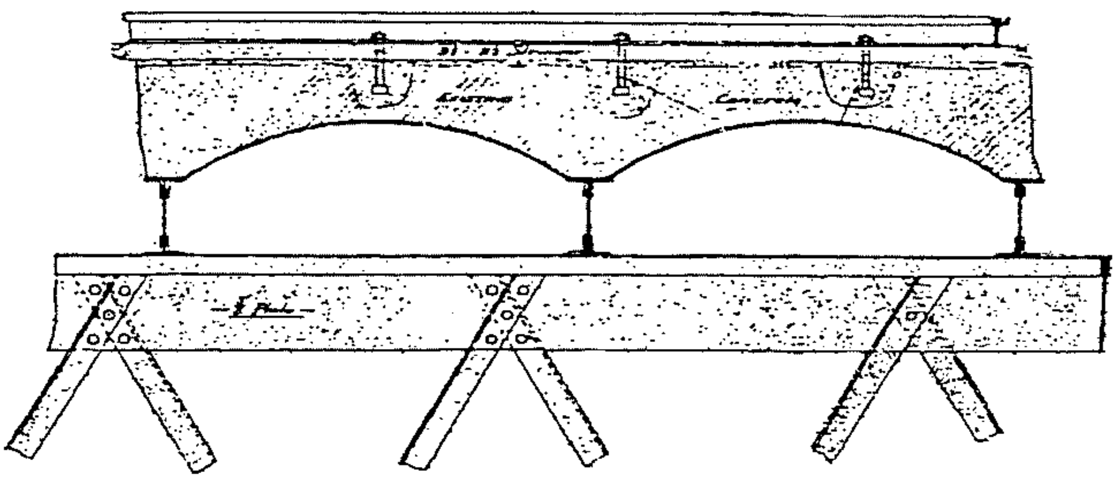

***Figure 2 Typical Section through Deck***

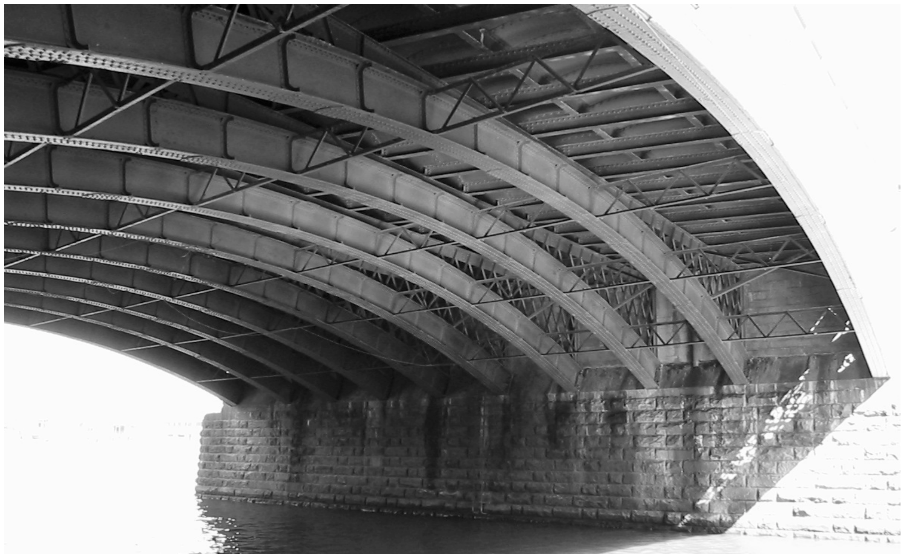

***Figure 3 Underside of Princes Bridge***

### 1.2 Historical Significance

Constructed in 1886-88, Princes Bridge is an important and prominent landmark in the centre of Melbourne with aesthetic and social significance.

The decorative cast-iron spandrels feature the coat of arms of each council that contributed towards the cost of construction. The mouldings and cast-iron balustrade along the top of the bridge and lamp stands crowning the giant half-columns are notable elements.

The bridge has the following significance:

- Its role in the early establishment of main thoroughfares in and around the city.
- Represents a boom period in Melbourne when there was a tremendous increase in traffic.
- Architecturally significant for its substantial size and the skilled stonemasonry demonstrated in the construction of its abutments and piers. The architectural details of the arched girders and cast-iron spandrel panels are worthy of particular note.
- Contributes to the distinct series of bridges which cross the Yarra River within the city vicinity.

## 2 PREVIOUS ASSESSMENT

The results of a desktop review and analysis utilising standard grillage analysis suggested the bridge was significantly under strength for Mass Limits Review (MLR) vehicle and tram loadings. Extensive strengthening was proposed including

- Cover Plates to the Longitudinal Deck Girders
- Cover Plates to the Arch Girders
- Replacement of Rivets at the ends of the Lattice Members
- Replacement of Rivets at the ends of the End Vertical Members.

The strengthening of wrought iron bridges like Princes Bridge is particularly difficult and significant problems were likely to be encountered including:

- High cost – access would be expensive and the strengthening work inherently slow and labour intensive.
- Material compatibility – wrought iron has a laminar structure that means welding additional sections to it will potentially lead to damage.
- Disruption to the community – any extensive strengthening proposals would require prolonged lane closures and possibly closure of the bridge for considerable periods.
- Heritage issues – developing a strengthening solution sympathetic with the heritage values of the bridge would be difficult.

Melbourne City Council originally proposed to design, document and tender the strengthening work based on the desktop analysis. With such a complex structure it was apparent there would be benefits in taking the assessment to an increased level of investigation. An alternative proposal to undertake a diagnostic load test on the bridge with the objective of developing a calibrated structural model with associated strengthening requirements was put forward. The project team was confident the approach would provide valuable outcomes. Council showed faith by funding the alternative proposal to better understand the behaviour of the bridge, even though there could be no guarantee the investment would lead to savings

## 3 LOAD TESTING

A diagnostic load test was carried out on Princes Bridge at 2am on the 20$^{th}$ of February 2003. Diagnostic load testing refers to the use of field measurements to better understand a structure's live load behaviour within its linear elastic range. The test involved

- Carrying out a detailed inspection of the structure
- Setting up instrumentation for the test
- Recording the response of the structure during the passage of a known truck
- Developing a calibrated analytical model
- Undertaking load assessment for MLR vehicle, tram and crowd loading and design of the necessary strengthening of the structure.

The diagram in Figure 4 graphically illustrates the load testing concept adopted at Princes Bridge.

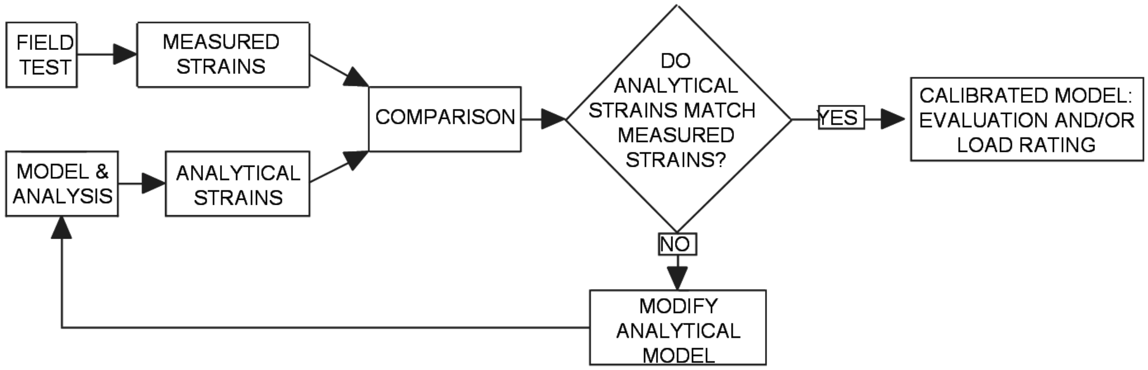


***Figure 4 Illustration of the Diagnostic Testing Process adopted at Princes Bridge***

## 3.1 Detailed Inspection

An inspection of the bridge was undertaken to check for any fatigue related problems and to verify the bridge was constructed in accordance with the drawings. During the inspection sections of the bracing were removed for testing and replaced with equivalent steel sections to determine:

- The composition and microscopic structure of the material
- Relevant engineering properties of the material to enable the calculation of section and member capacities.

Further small samples of wrought iron material were taken to verify the consistency of material throughout the bridge.

## 3.2 Instrumentation

The Diagnostic Load Test was carried out to gain a better understanding of the response of the structure under actual live load by measuring the strain at key locations in the structure. A total of 40 strain transducers measuring both the flexural and axial responses were applied to the structure. As all three spans were of similar construction one span only was instrumented.

As the data from the diagnostic load test was intended to help define an accurate analysis rather than measure critical responses it was not necessary to take measurements at the most critical location or maximum strain locations on the bridge. Measurements were taken at convenient locations near to critical areas.

The testing equipment, including strain transducers and the data acquisition system, has been specifically designed for bridge load testing to ensure the greatest efficiency onsite without any reduction in accuracy. Complete instrumentation was installed within 12 hours and removed in 7 hours.

### *3.2.1 Strain Transducers*

The testing process uses reusable, high output aluminium strain transducers containing a full Wheatstone bridge with a total of four active foil gauges. All transducers were mounted on tabs and attached to the cleaned wrought iron members with a quick setting adhesive.

A special feature of the transducers adopted for the testing of Princes Bridge is the inclusion of a microchip which identifies the transducer number thereby allowing automatic application of calibration factors and simplification of field procedures by eliminating the need to track channel numbers.

Figure 5 and Figure 6 show the gauges used and their attachment to a longitudinal T-beam member to measure both axial and flexural responses.


***Figure 5 Strain Transducer used for Diagnostic Bridge Testing***

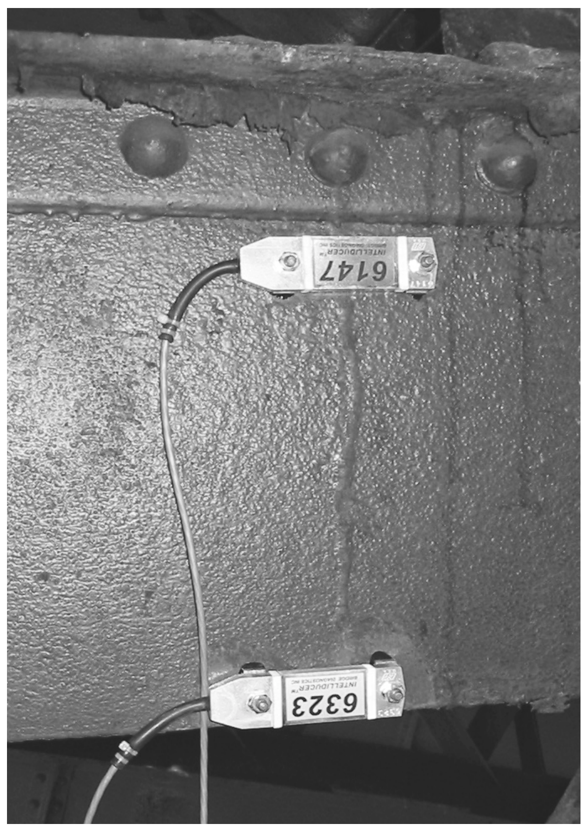


***Figure 6 Transducer Attachment to Longitudinal T Beam***

### *3.2.2 Data acquisition system.*

A series of 4 strain transducers were connected to a local module, as shown in Figure 7. These custom made modules filter the data from each transducer and convert the analogue signal from the transducer to a digital data stream. Each box was then in turn connected by cable to the next box in either parallel or series.

The final module was connected to the power supply which provided power to the system and buffered the test data during download to the host laptop computer, as shown in Figure 8. Software on the host computer allowed the display of the strain readings in real time enabling the testing engineers to check the responses and the operation of the system.


*Figure 7 Modules used during the load test*

*Figure 8 Power supply and host computer*

## 3.3 The Load Test

Controlled load tests were performed using a 23tonne three-axle dump truck and a 50t (40t GVM) mobile crane. Each vehicle was driven along three different prescribed lanes at crawl speed. During each run, strains from each gauge were continuously recorded along with the vehicle's position. Tests were performed twice in each path to ensure reproducibility of the testing procedure and of structural responses. Typical strain gauge measurements are shown in Figure 9, which shows the response change in strain with truck front axle position.

To limit traffic disruption testing, was carried out at night. During testing the bridge was closed to traffic for approximately two minutes at a time during each truck passage, and then re-opened for traffic between tests. The testing was complete within an hour.

## 3.4 Analytical Model

### *3.4.1 Preliminary Assessment of Data*

Field data was initially assessed graphically to determine the quality of the information and provide a qualitative assessment of the structure's live-load response. The information was used to determine effective deck and connection stiffness when establishing the initial model.

The preliminary assessment concluded:

- Responses from identical truck paths were reproducible as shown in Figure 9. This provided a good indication that all live-load responses of the bridge were linear-elastic.
- The strains on the main arch recorded near the abutment indicate that there was significant end-restraint provided by the abutments and piers.

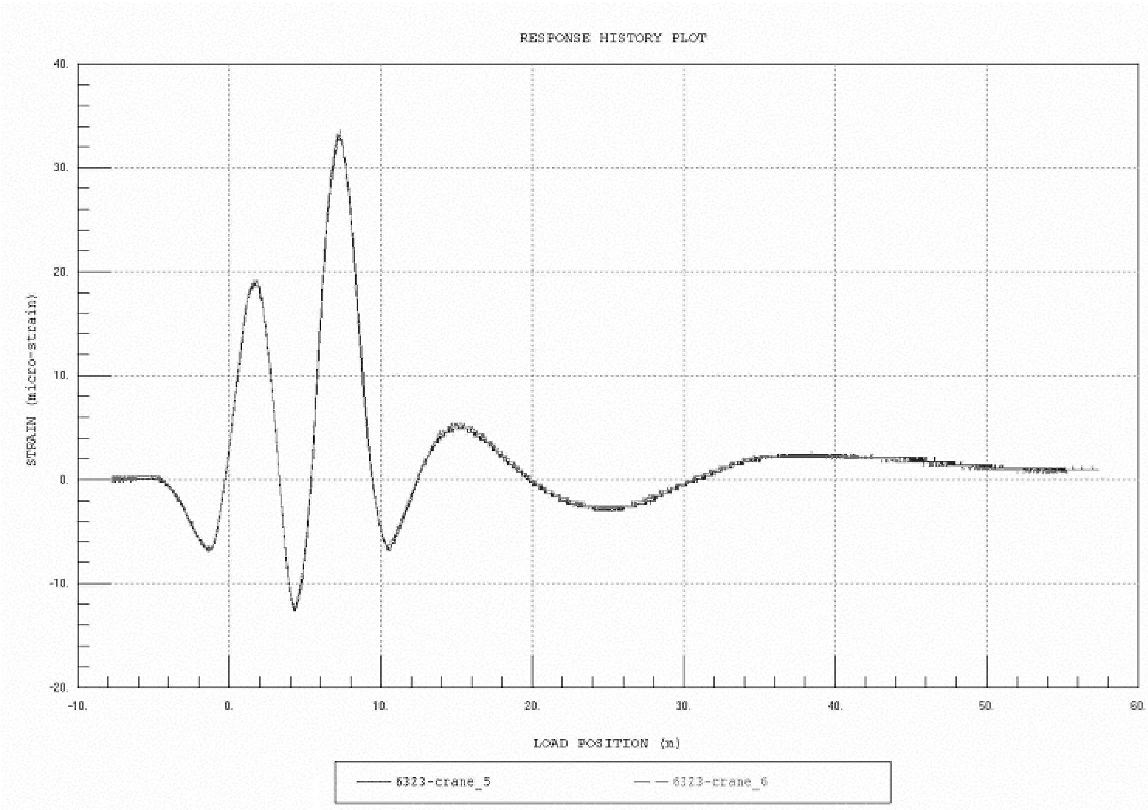


***Figure 9 Reproducibility of Load Response – Midspan Girder 5 Longitudinal Member***

### *3.4.2 Modelling and Model Calibration*

Once the qualitative assessment was completed, an analytical model was developed with the objective of developing a structural model that responded in a similar manner to the measured response of the actual structure.

The bridge was initially drawn within CAD software and imported into custom analysis software with finite element capabilities. Frame elements were used to represent the main structural elements and plate elements were introduced to model the deck transferring the wheel loads to the main structural members. Elastic supports were used for the main arch girders and longitudinal beams at the abutments and pier to simulate effects of the support conditions. Certain member types were modelled with a property offset due to the bridge having a large structural depth and dummy members were introduced to model the effect of the overall structural depth including vertical links to represent the out-of-plane stiffness of the transverse members. Figure 10 contains the 3-D model generated using CAD. The final model contained

- over 4000 members,
- nearly 2500 nodes, and

- 26 different member and restraint types.

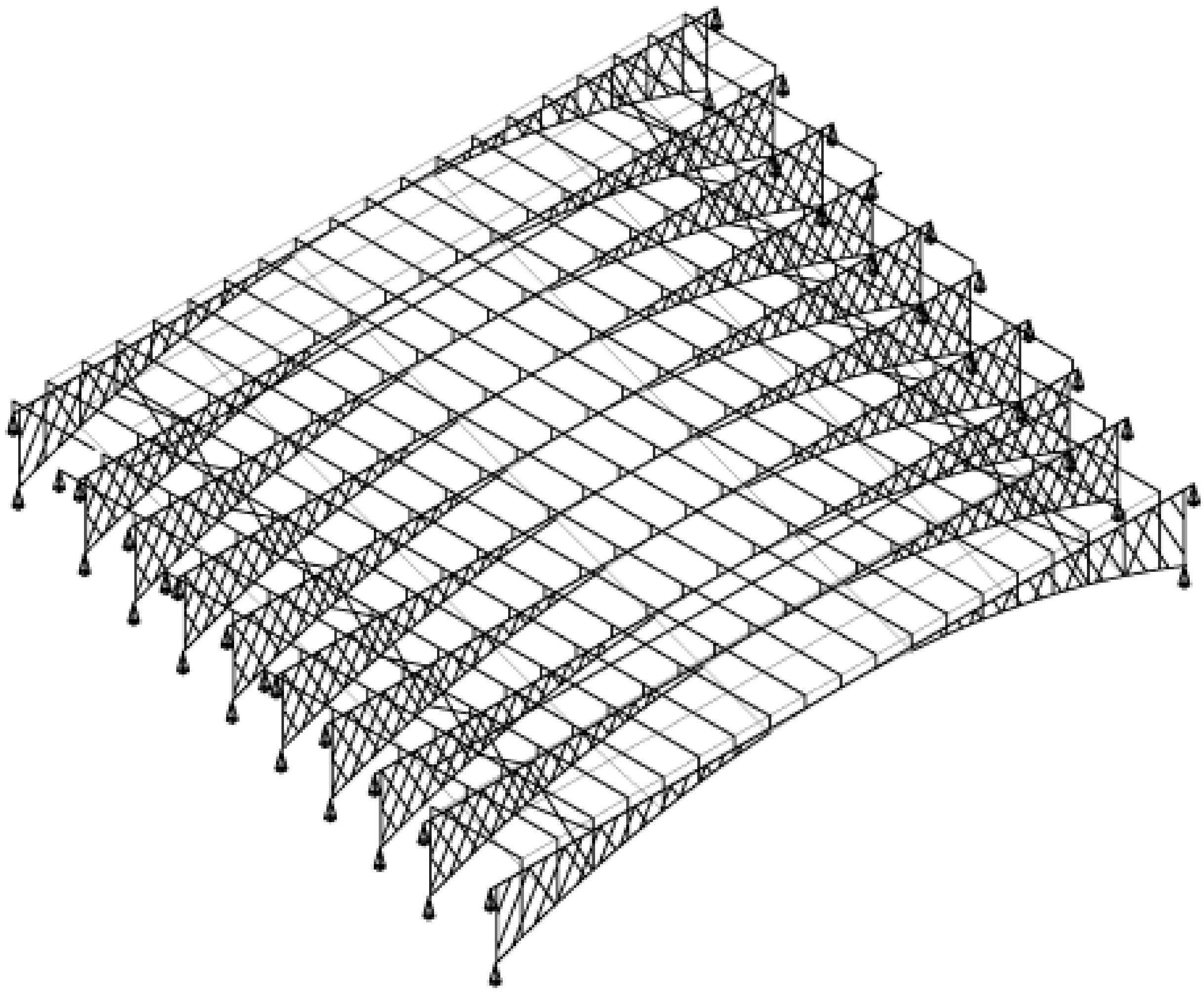

***Figure 10 Three-Dimensional Finite Element Model***

The structural analysis software has been specifically developed to allow the strain gauges to be located within the model. This allows the model calibration process to be streamlined as model results can be quickly compared with field data. Importantly, the facility provides a high degree of confidence the model is calibrated correctly.

The test vehicles were passed over the model along the same lanes as the test. This allowed direct comparison of strain values between the model predictions and the measured values. The initial model was "calibrated" by modifying various properties and boundary conditions until the results matched those measured in the field.

The structural analysis software has optimisation routines to assist in the calibration process. The optimisation routine compares strain measured in the field with the analytical model results to compute relative errors and correlation coefficients (a measure of curve similarity). Parameters were set within the software for adjustment of certain defined parameters within recognised engineering boundaries. The software then adjusted the parameters in an iterative process to determine the effect on the error and correlation then seek out the value of each parameter which minimised the error.

Parameters adjusted both by visual comparison and by the automated optimisation routine include:

- effects of the varying deck plate support conditions,
- effective offset of properties for the arch members,
- effective stiffness of the arch member when connected to the lattice members,
- effective rotation restraint provided at the abutment and pier,
- effective stiffness of the deck plates in both the tramway and roadway,
- effect of tram tracks on deck stiffness,
- effective composite properties of members connected to the deck plates,
- effect on stiffness of external decorative plates and balustrade, and
- effective out-of-plane stiffness of transverse members

Following the calibration procedures, the model produced a good correlation indicating the calibrated structural model closely matched the behaviour of the actual structure. Table 1 shows the initial and final error and correlation coefficient for model. Figure 11 shows a typical response history after model calibration. The continuous line represents the field measured results and the points the analytical model. Similar curves were produced for all 40 strain gauges.

***Table 1 Comparison of error between initial and calibrated model***

| **Error/Accuracy Term** | **Initial Model** | **Calibrated Model** |
|---|---|---|
| Absolute Error | 31484.3με | 5404.9με |
| Percent Error | 145.9% | 15.3% |
| Scale Error | 47.3% | 9.0% |
| Correlation Coefficient | 0.59 | 0.95 |

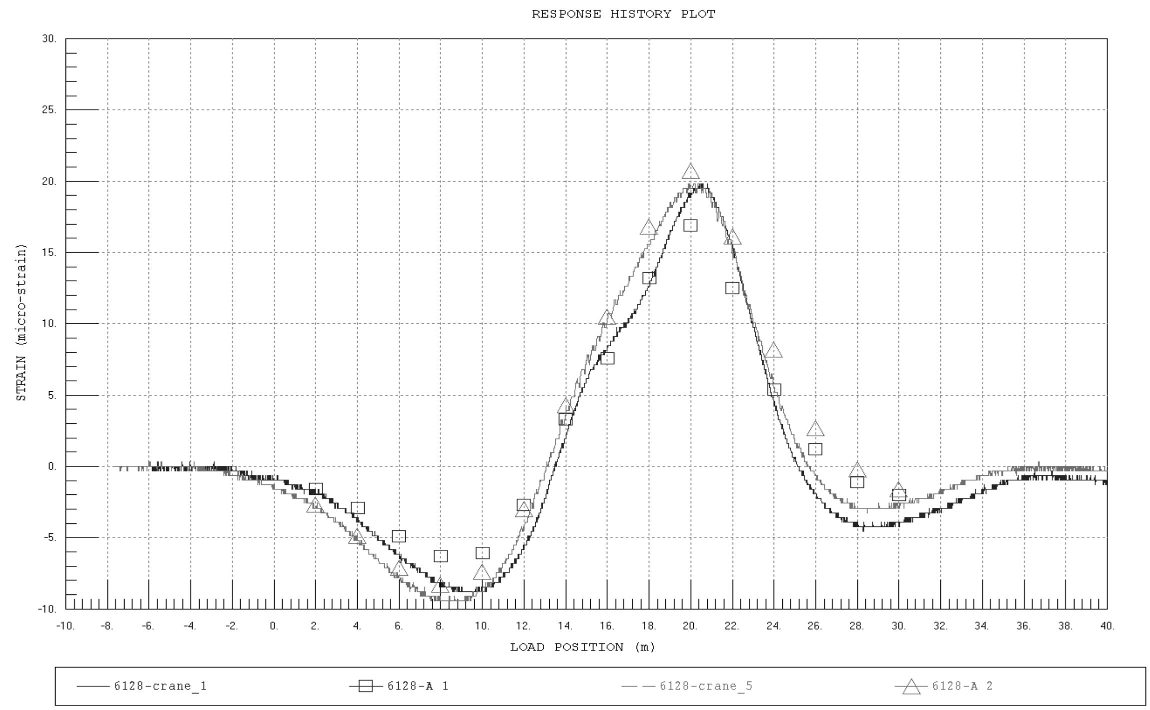


***Figure 11 Response History Comparisons between Measured and Analytical Results***

### *3.4.3 Load Assessment and Strengthening*

Using the calibrated elastic model design load effects were calculated for all critical members in the structure for the following load combinations:

- Mass Limit Review vehicles
- 'Z' and 'C' class trams and trams in combination with trucks,
- Pedestrian loading
- Additional dead loads from possible future overlays and utility services

It was found there was significant variation in the design load effects using the calibrated model compared to the results from the desk top analysis.

The design capacities of the members were calculated using the results from the material testing, and it was found there was approximately a 10% increase in capacity from the desk top analysis.

The outcomes from this refined load assessment process showed the majority of the structure did have adequate capacity for Mass Limit Review vehicles, including all principal structural members, such as the main arch girders. The members failing to achieve an adequate rating were:

- The riveted connections between the lattice members and the longitudinal and arch members
- The longitudinal members supporting the deck

The longitudinal member only marginally failed to achieve an acceptable rating and by accepting a slightly lower impact factor consistent with the low speed environment of the bridge, it was decided this member did not require strengthening.

It was agreed to replace certain rivets at lattice member connections with friction grip bolts to increase capacity. This work is being undertaken as part of a repainting contract for the bridge in order to optimise the access costs.

Following the initial desktop assessment, cost estimates for the strengthening work were in the order of $3 million. A budget figure for the strengthening work after the results from the load test were estimated at $500 000, representing a significant cost saving to the community.

## 4 CONCLUSION

The diagnostic load testing has effectively restored the long-term relevance and functionality of the bridge for the 21st Century. The outcomes have shown that with relatively minor strengthening work the bridge will have sufficient strength to take the new legally loaded vehicles.

Importantly the community will continue to have a fully functioning structure as the focal point of cultural activities of the city.

The testing of the Princes Bridge has shown the relevance of higher level investigation, including diagnostic load testing as a means of computing accurate load ratings and for the design of retrofits for a structure. In the case of Princes Bridge this has resulted in significant savings in time, cost and in heritage values.

## 5 ACKNOWLEDGEMENTS

The Princes Bridge Load Testing and Strengthening Contract was undertaken by Pitt & Sherry Holdings Pty Ltd with the load testing and analysis carried out by Van Ek Contracting Pty Ltd.

The authors would like to thank Melbourne City Council for permission to present this paper.

## 6 REFERENCES

MELBOURNE CITY COUNCIL “Design Brief, Princes Bridge – Strengthening Works Option and Design Documentation” *Princes Bridge Investigation*, MELBOURNE CITY COUNCIL ENGINEERING SERVICES GROUP, August 2002.

COE D. “Princes Bridge Load Rating”, PITT & SHERRY HOLDINGS P/L, June 2003

BRIMFIELD A. “Princes Bridge Load Testing and Rating Report”, VAN EK CONTRACTING PTY LTD, May 2003

McEWAN W. “Princes Bridge Melbourne – Mechanical and Metallurgical Properties of Steelwork” CTI CONSULTANTS PTY LTD., May 2003