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STRUCTURAL MANAGEMENT OF AN AGING CONCRETE BOX GIRDER VIADUCT ON THE AUCKLAND MOTORWAY NETWORK

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Abstract: Victoria Park Viaduct (VPV) is a vital link on the Auckland Motorway network, carrying more than 100,000 vehicles daily. Constructed in 1964, the viaduct is comprised of twin parallel bridges each consisting of 24 prestressed concrete spans and 9 semi-continuous cast-in-situ box girder spans. In the 1980s, widespread Alkali-Silica Reaction cracking on the box girder sections was noted, which led to a suite of Carbon Reinforced Polymer strengthening to increase the deck capacity. In 2013, High Productivity Motor Vehicles (HPMVs) were introduced to the New Zealand State Highway network to improve freight movement countrywide. The introduction of these vehicles highlighted the structural deficiency of VPV based on traditional assessment techniques. In addition, the local regional network authority has had aspirations of allowing heavy-axle double-deck buses across the structure, which have been restricted as a result of previous assessments. VPV forms a critical link in the central motorway junction of Auckland and needs to continue to function well into the future. WSP/Opus[1] has developed a strategy to better understand the structure, looking at avenues to more accurately determine its capacity in order to assess it for HPMV loading. This involved building a Finite Element Analysis model, live load testing, deflection monitoring, and detailed site inspections to understand the behaviour and conditional aspects of the asset. As a result, it was demonstrated that VPV can be opened up to greater freight and public transport requirements, serving tomorrow's society well into the future.

1 AUCKLAND MOTORWAY ALLIANCE

In 2008, the Auckland Motorway Alliance (AMA) was established by Transit NZ (now the New Zealand Transport Agency, or NZTA), to maintain and manage the 220km of motorway network that surrounds Auckland City. The AMA joint venture aimed to merge the asset owner (NZTA), consultants (WSP/Opus, BECA, Resolve Group), and contractors (Fulton Hogan, Armitage) into a business unit that more effectively and efficiently manages this critical network. The AMA network equates to over 1,100 structural assets incorporating tunnels, bridges, viaducts, culverts, and retaining walls.

The Auckland motorway network carries over a million journeys daily and is a very linear and intensive network. Auckland is locked between two water masses and has unique geographical constraints, distinguishing it from other international cities which traditionally have a radial transport network – such as Sydney, London, and Dublin. These cities also have more extensive public transport networks, with multiple modes available to alleviate congestion on motorway networks. Auckland has limited public transport alternatives and, due to its geographical constraints, has limited resilience and alternative motorway routes,

[1] WSP/Opus is a wholly owned subsidiary of WSP Global Inc.

funneling large traffic volumes over key infrastructure. Some of this bridge infrastructure carries over 200,000 vehicles daily, equating to approximately 12% of Auckland's population relying on a single piece of infrastructure. With Auckland City responsible for 35% of the national gross domestic product (GDP), these critical pieces of infrastructure can have a significant impact on the growth of New Zealand Inc.; "Keeping Auckland Moving" is therefore vital for the economy of New Zealand and the city of Auckland.

2 MANAGING AMA BRIDGE ASSETS

There are 305 bridge structures with over 1,200 spans on the AMA network which have an average age of 35 years. In terms of the typical 100-year design life, the AMA bridge stock is relatively young. The majority of the bridges are either post-tensioned, pre-tensioned, or reinforced concrete, and are generally in good working order, with the expected defects of a 35-year-old inventory. Like any network, there are structures with capacity- or condition-related issues that need to be managed to maintain the safety of the users and full access to the network. The AMA is a customer-focused organisation striving to "Make New Zealand Grow by Keeping Auckland Moving". While it is generally unacceptable to reduce live loading, every effort is made to ensure that this and imposing restrictions is avoided, the consequences of which could negatively impact the economy of Auckland and New Zealand.

The AMA works on the principles of the "4 R's" when it comes to managing their assets: Right Time, Right Place, Right Treatment, and Right Risk. This can be simply explained in the Asset Management Circle of Inspection – Investigation – Analysis – Risk Management – Intervention, shown in Figure 1. The asset management circle is critical in understanding assets to better address issues. This, in turn, allows the appropriate actions at the right time within acceptable risk levels.

Figure 1: Asset Management Circle

A key step in better understanding assets is ensuring that they are regularly inspected. AMA bridge structures are inspected in accordance with NZTA Standard 6 "Bridges and other significant highway structures inspection policy", which states that all structures require a Principal Inspection every 6 years, and General Inspection every 2 years, which is in line with most international best practices (New Zealand Transport Agency 2017). The AMA has adopted the risk-score matrix shown in Table 1 for defects, which quantifies risk using the likelihood and consequence of failure. Owners that use this type of risk matrix have found that when it comes to near misses of infrastructure failures, over 70% are due to unaddressed conditional defects in excess of a risk score of 12 (high risk, highlighted in dark red). Risk-scoring defects means that it is possible to prioritize routine and structural interventions based on risk, and that Forward Works Plans can be developed from the "bottom-up". The risk scoring process can also quantify the maintenance backlog based on a level of risk, and establish an asset risk profile.

Table 1: AMA Risk Scoring Matrix

Consequence	Likelihood: 5 Almost Certain >70%	4 Likely >50% - 70%	3 Possible >30% - 50%	2 Unlikely >10% - 30%	1 Rare <10%
5 Very High	25	20	15	10	5
4 High	20	16	12	8	4
3 Medium	15	12	9	6	3
2 Low	10	8	6	4	2
1 Very Low	5	4	3	2	1

The AMA takes a proactive approach in carrying out investigations to keep asset managers better informed, especially when it comes to risks such as hidden critical elements. This is done by improving the analysis and decision-making processes of the Asset Management Circle. The observed deterioration of elements is captured in analysis, indicating the level of overstress and whether live load restrictions are required on an asset. If a structure's level of overstress cannot be maintained, risk management processes are implemented until a physical intervention can be planned, financed, and installed. Victoria Park Viaduct is a prominent example of this management philosophy on the AMA network.

3 VICTORIA PARK VIADUCT

Victoria Park Viaduct (VPV) is a vital piece of infrastructure on the Auckland network that carries up to 100,000 vehicles daily. It was built between 1961 and 1964, and originally supported north and southbound traffic on State Highway (SH) 1. Following the Central Motorway Junction improvement in the 2000s and the opening of Victoria Park Tunnel (VPT) parallel to VPV in 2012, the structure now carries a new motorway arrangement. It is located on a critical section of the AMA network, supporting traffic travelling southbound on State Highway (SH) 1, SH16 traffic travelling to the Port of Auckland, and the SH16 western motorway. The location and layout of the structure are shown in Figure 2 and 3, below.

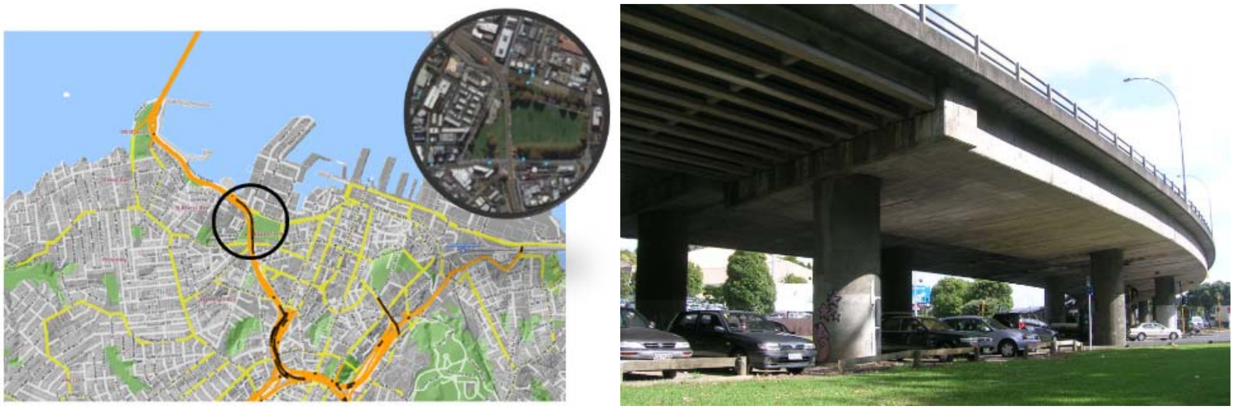

Figure 2: Location Map (left), Elevation Photo of North VPV Box Structure (right)

Figure 3: 1962 View of VPV and ASR Cracks (left), View of VPV and VPT looking South (right)

3.1 Structural Form

VPV consists of two identical 33-span structures nearly 600m long, separated by a 50mm gap. Twenty-four of the spans are precast post-tensioned concrete I-beams with nine beams supporting each State Highway per span. The remaining nine spans are cast-in-situ reinforced concrete three-celled box structures, constructed using a balanced cantilever arrangement with two half-joints per structure. The Northern end of the structure over Victoria Road has five box spans, while the Southern end of the structure over Beaumont Street has a four-box-span arrangement. Both box girder decks are comprised of four 1.68m-deep beams spaced at 2.5m centres, connected by 150mm-thick deck and soffit slabs to form three box cells. The web thicknesses vary between 200mm and 400mm from midspan to the pier locations. The boxes are supported on a single 1.8m cast-in-situ reinforced concrete column and spread footing. Selected as-built drawings of VPV are shown in Figure 4.

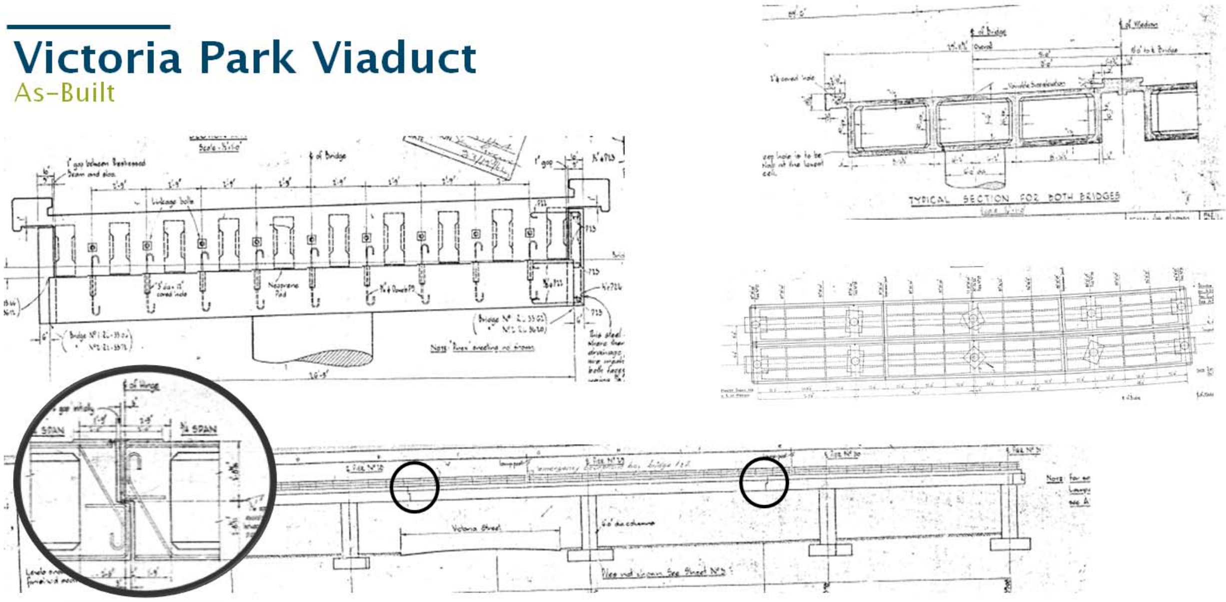

Figure 4: As-Built General Arrangements

3.2 Current Condition & Previous Physical Interventions

VPV has a number of perceived condition issues which have led to years of investigations, physical interventions and live load restrictions on the structure. The primary defects identified to-date include:

- Cracking of the deck of the box girder structure;
- Cracking of the webs of the box girder structure; and
- Sagging of the half-joints in the box girder structures over Victoria & Beaumont Streets.

In the 1980s, a number of AMA structures were displaying signs of Alkali-Silica Reaction (ASR), including VPV. Numerous concrete investigations have been carried out since then, confirming the presence of ASR in VPV. Due to the extensive nature of the cracking (Figure 5), concern was raised about the capacity of the asset. Literature reviews conducted by WSP/Opus on the subject concluded that the presence of ASR may reduce the tensile capacity and Young's Modulus of the concrete. The reviews also found that ASR may increase the shear capacity of sections through the pre-stressing effects of the expanding concrete.

Figure 5: ASR Cracking to Half-Joint (left), ASR Cracking to Deck Soffit (right)

There is no doubt that the cracking of the structure will impact its durability. Although VPV is in close proximity to the sea waterfront of Auckland, testing has shown little evidence that chlorides are penetrating the concrete to reach the steel reinforcement. Without fully understanding the extent of the ASR on the capacity of the structure, a suite of epoxy crack injection repairs were made between 1990 and 1995. These included the application of coatings to prevent moisture ingress and to minimize further ASR cracking.

Until 1990, access was only possible to the external faces of the structure. Due to the extent of cracking on the external faces and investigations confirming ASR, the decision was made to create access hatches into all box girder cells to inspect hidden areas. Once inside the boxes, Engineers found extensive cracking, most notably to the deck slab soffits (Figure 5 – right) and pier diaphragms, along with what appeared to be shear cracking to the webs of the boxes.

In 2009, cracking to the deck slab soffit of the box girders was considered so extensive that in order to maintain serviceability and durability, all major cracks on the internal deck soffit were epoxy-injected. This was followed by the application of two-layer Fibre Reinforced Polymer (FRP) over the full soffit area to increase capacity.

Aside from ASR, the South structure has a noticeable 70mm sag from the horizontal at the half-joint over Victoria Street. The box structures were originally built with a pre-camber that is assumed to account for initial deflections. The possible cause of the remaining sag and its effects on the structure needed to be considered, prompting the investigations that began in 2013. These included an HMPV assessment to better understand the impacts of condition-related issues on the structure.

With the recent boom in the New Zealand economy and net immigration, Auckland is seeing over 40,000 new vehicles being added to the network each year. Under the current proposal for a new second Waitemata Harbour crossing, it is being muted that the current viaduct will be removed as part of the project. This project is not expected to be completed for twenty to thirty years. The current vehicle usage, upward trend in new vehicles, increasing freight requirements, and public transport needs will increase the pressure on VPV. The AMA must ensure the longevity of the asset until a new crossing can be completed.

4 MANAGEMENT OF THE STRUCTURE

4.1 Inspections

In 2011/12, WSP/Opus conducted an extensive crack mapping inspection regime on the inside of the boxes, which looked at the condition of all 66 boxes and 146 cells. Photographs from this inspection are shown in Figure 6, below. Significant cracks inside the structure were located and recorded, particularly those in excess of 1mm. In 2015/16, this exercise was repeated and both the crack length and width were recorded for cracks exceeding 0.4mm in width. A diagram of crack lengths and widths is shown in Figure 7. In the years between inspections, it was noted that a large number of the cracks had propagated from the webs of the boxes into the floor. The propagation of the cracks within a short period warranted further investigation to establish a better understanding of their nature.

Figure 6: Example of Condition Inside Box Cells

Research conducted by WSP/Opus on the structural behaviour and effects of ASR-type cracking on the durability of VPV specifically highlighted that cracks with a width of less than 1mm in the webs did not detract from the web capacity. It also showed that cracks with a width of 0.7mm would not significantly reduce the durability of the structure, provided that the boxes remain dry. As such, the decision was made to carry out more rigorous analysis and load testing of the asset.

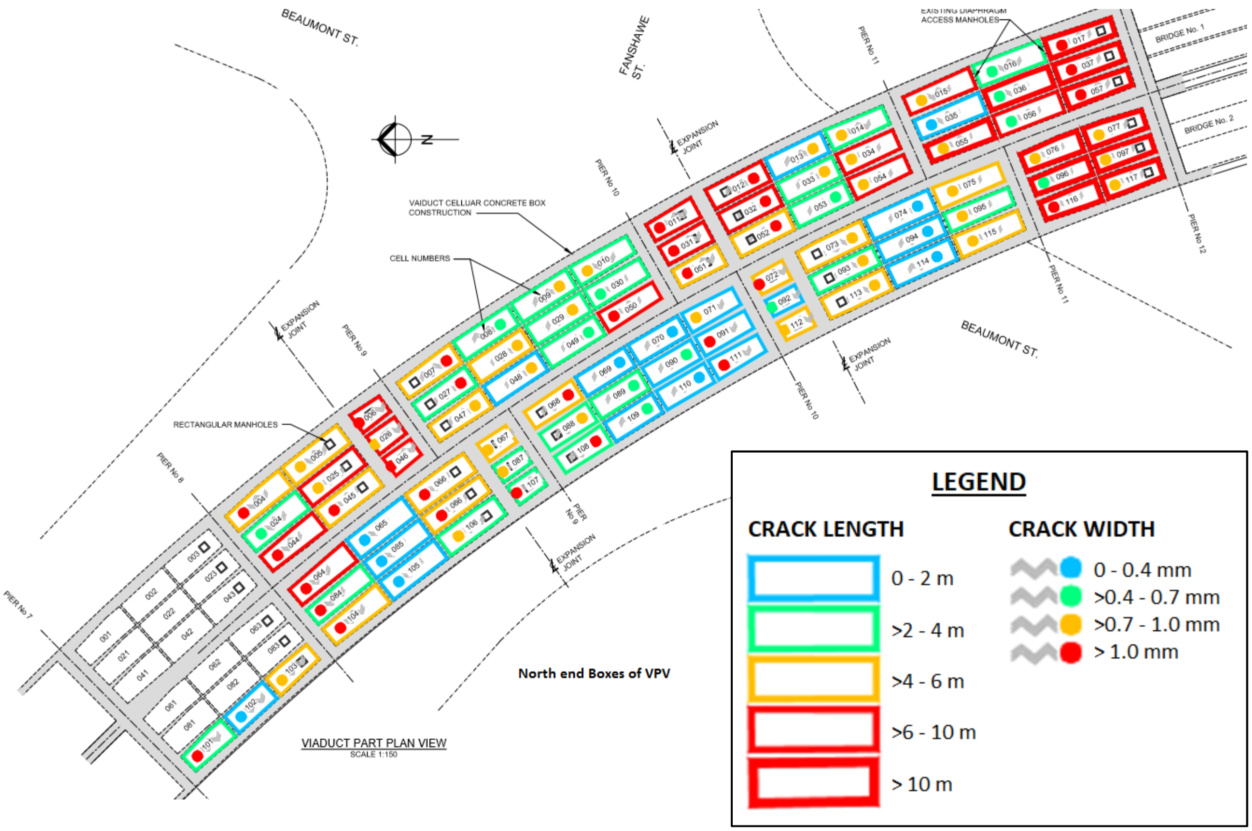

Figure 7: VPV Box Condition Diagram from 2015 Inspections – Crack Length and Width

4.2 Numerical Analysis

Prior to 2013, WSP/Opus conducted a number of simple state / grillage level 1 numerical assessments on the structure. The effects of cracking, sagging, and other conditional aspects were not accounted for in these assessments. In 2013, WSP/Opus carried out a more detailed numerical assessment of the North and South box structures. This was done to establish the residual capacity of the structure, and to try to capture the effects of cracking on its capacity. The assessment was done using a LUSAS grillage model and condition factors in accordance with SP/M/022 NZTA Bridge Manual. The inputs to the model were the live loading conditions as per the Bridge Manual: HN (normal) and HO (overload) loading. Both live load cases consist of a uniform load and a pair of axle loads positioned in critical locations along the bridge. The assessment found that the VPV boxes had full HO-HN-72 capacity if the structure remained within certain conditional boundaries, one of which was that cracking of the webs did not exceed 1mm.

During the 2011/12 and 2015/16 internal inspections, cracking in excess of 1mm was noted. It was also noted that the previously marked cracks had extended and propagated. The internal cells are benign and completely dry, with moisture prevention coatings to the external faces. This gives a level of confidence that the ASR is not active, and that the cracks are extending due to the application of live loads on the structure.

Although the 2013 assessment stated that full HN-HO-72 capacity (the typical highway loading standard in New Zealand) should be achievable, a structure with full capacity should not be exhibiting active cracking, giving cause for concern. Knowing that the cracking in the structure is propagating and that there are a number of members in the boxes with cracking in excess of 1mm, the AMA elected to perform a more detailed analysis to better understand the true behaviour of the bridge.

To accomplish this, the AMA generated a 3D LUSAS finite element shell model of the South structure, which was used to determine the distribution of loads on the bridge. The model looked at the effects that previous interventions have had on the bridge, along with the permanent sag. A screenshot of the analysis is shown below in Figure 8, which illustrates the distribution of shear stress in the webs. The stresses are indicated by colour (legend shown on the left, kN/m^2), with higher stresses shown in blue and red.

The finite element analysis (FEA) model also provides the possibility to apply conditional effects such as reduced shear capacity, cracked section properties, and losing a member to excessive defects. This could be indicative of how these changes may affect the overall capacity of the structure should the AMA decide to investigate them in the future.

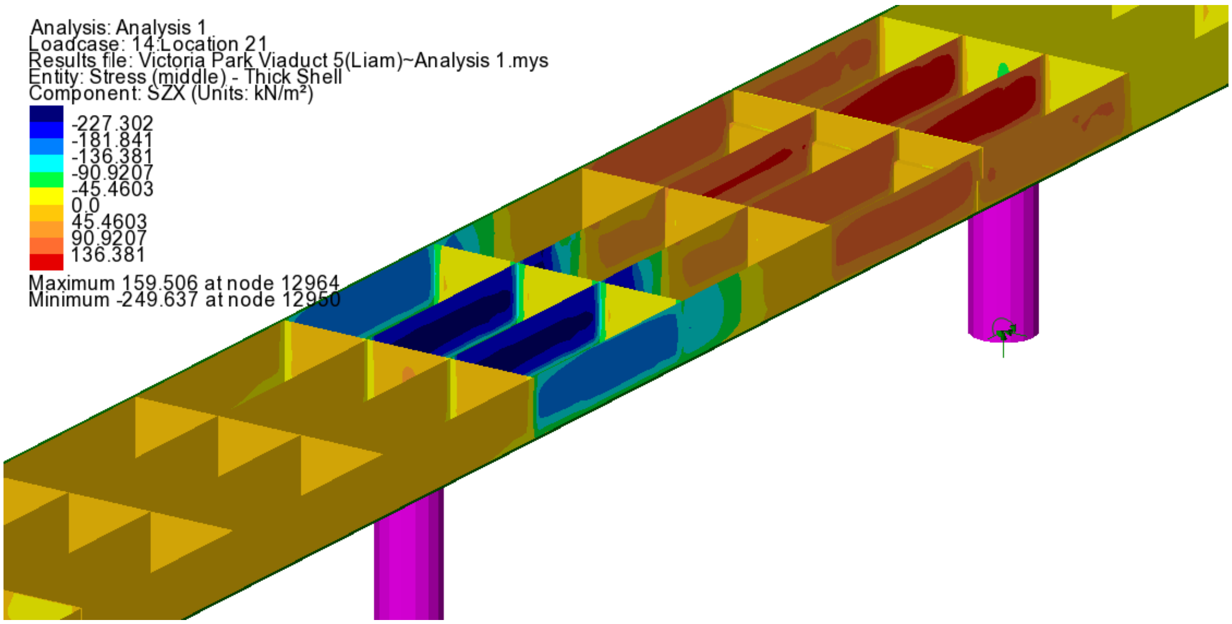

Figure 8: Finite Element Model of South Box Structure over Victoria Street

4.3 Live Load Test

Within WSP/Opus International Consultants Ltd., there exists a research and development division called "Opus-Research" specializing in the monitoring of assets. Their experience ranges from the use of simple movement gauges to full real-time structural health monitoring systems. Opus-Research was commissioned to develop a system for VPV that could record vertical displacement. This would be used to record how much the structure deflected under known loads at pre-defined locations.

In September 2016, a load test of the SH1 South box structure was performed using two 20-tonne aggregated-filled dumper trucks of known weight and axle configuration. Photographs taken during the testing are shown in Figure 9. The test involved measuring the static vertical deflection at the half-joint of span 30 and at the outer edges of the deck. At each of the 21 loading points, the truck remained static for 120 seconds. This allowed sufficient time for the structure to recover and find its new deformed shape. Before and after the load test, daily rush-hour traffic movement was recoded to get a sense of scale between the live and static loading conditions.

Figure 9: Dumper Trucks during Load Test (left), View of VPV Monitoring System (right)

In an attempt to calibrate the FEA model with the load test results, the dumper truck configuration was replicated within LUSAS. The test load was placed at the same 21 locations along the structure that were loaded in the field. The high-level observations from the load test were:

1. The vertical displacements from the static tests and general traffic sampling are in the same order of magnitude, indicating that the measurements were consistent.
2. The maximum static displacement at mid-span under static loading is higher when compared to the general traffic load case (dynamic sampling). This may be due to the relieving effects of the continuous action of a fully loaded structure.
3. The difference in deflection between the numerical model and on-site testing was approximately 5-8% (static load case), which is deemed appropriate for an exercise of this extent, and with a structure of such inertia. Achieving higher levels of correlation would require more significant modelling and testing, which is not considered appropriate for this exercise at this point in time.
4. Results of the live load traffic sampling indicate that higher-weight traffic typically uses the left lanes, as anticipated.

4.4 Live Load Calibration and Assessment Findings

Once the FEA model was suitably calibrated, an analysis was conducted by WSP/Opus to compare the dead and live load effects on the structure to the strength of its structural elements. The analysis was done in accordance with SP/M/022 NZTA Bridge Manual for both Rating and HPMV evaluations. The LUSAS Vehicle Load Optimization (VLO) tool was used to determine the worst possible HPMV and HN-HO load cases on the structure for shear, positive bending, and negative bending independently.

Similar to the results from the 2013 grillage analysis, the evaluation using the FEA load distribution showed that the structure has adequate capacity for full HN-HO and HPMV loading. It also highlighted areas of maximum anticipated stress under loading (Figure 8), which will be closely monitored in future inspections.

To observe the differences between the load distribution techniques, the capacity results of the FEA and grillage models were compared using the same member strengths. The FEA model showed an average increase in capacity of 14% over the grillage model for the Rating evaluation, as expected. The HPMV FEA results were not as consistent, with an overall average decrease in capacity of 8% from the grillage model. This is likely due to the envelope-type live loading of the grillage model, which does not consider the same extent of loading possibilities as the VLO tool. Overall, the difference in capacities between the two methods justifies the refining of the analysis, with increased confidence in the ability of the structure to support both HN-HO and HPMV loading.

5 CONCLUSIONS

The AMA works on the principles of right time, place, risk, and treatment to manage the deteriorated and vital infrastructure on their network. This approach requires detailed inspections, investigations, analysis, and interpretation to establish an understanding of how defects affect capacity, if at all. Although analysis can provide an understanding of capacity and levels of overstress, structures often have inherent strength with reserve factors which can be utilized to achieve greater capacity.

Previous experience has shown that structures do not always act as designed or assumed. To address this issue, as was done for VPV, it is possible to calibrate desktop models with live load field testing. The AMA elected to use this method to more accurately determine the capacity of VPV so that it could be assessed for HPMV loading. Contrary to the results using traditional assessment techniques, the detailed analysis showed that VPV has adequate capacity to support HPMV loading within specific conditional boundaries. Lifting the HPMV restriction on VPV will improve freight movement on both the New Zealand State Highway network and countrywide.

In addition to better understanding the live load capacity, the calibrated finite element model of VPV has allowed the identification of stress hot spots on the structure. A detailed inspection of the existing cracking has also identified potentially vulnerable areas in terms of future reductions in durability. If the cracking were to propagate, possible reductions in capacity could also be expected. The crack inspection information as well as FEA results will therefore be used to provide guidance on which areas of the bridge will need closer inspection, investigation, and potentially monitoring into the future. Targeted inspections are recommended in addition to the standard General and Principal Inspections, the aim of which will be to identify and provide early warning of areas of distress. This will improve the overall management of the structure by identifying the most favorable and appropriate times to perform physical works throughout its remaining life.

As was evidenced by VPV, there are options other than closure or strengthening to manage the risks when an analysis indicates that a structure is deficient. Loads can be restricted in the short-term, and real-time monitoring can be installed. The key to this approach is to capture structural defects, determine their impact on capacity, and manage the associated risks throughout the life of the structure.

Acknowledgements

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