Auckland Harbour Bridge Box Girder Strengthening Design and Construction

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Abstract The economic vitality of Auckland depends upon the movement of people and freight around the city’s motorways and the Auckland Harbour Bridge (AHB) is a crucial component of the network. Traffic loads derived from weigh-in-motion (WIM) data measured on State Highway 1 were found to have increased 50% since the last extension bridge assessment and upgrade in the 1980’s. The bridge was found not to satisfy current standards and so to support the regional economic growth strategy major intervention was needed to upgrade the structure for current and future demands. The addition of extension bridges to the original truss bridge was an innovative achievement in 1969 increasing highway capacity from 4 to 8 lanes. Getting the most out of the existing steel orthotropic box girder structure to extend the service life of the crossing was the key challenge for this project. Strengthening work was completed in 2010 using innovative techniques to deliver the required construction quality and fatigue endurance. More has been gained out of the AHB box girders than ever anticipated and the landmark bridge has been preserved for decades to come.

Introduction

The crossing comprises the truss bridge opened in 1959 and twin box girder extension bridges added in 1969 after the growth in traffic volume rapidly exceeded initial estimates. Beca has carried out an on-going programme of assessment, upgrade and strengthening works on the Auckland Harbour Bridge on behalf of New Zealand Transport Agency (NZTA) for the past twelve years. Previous upgrade works include seismic retrofit in 1999 and strengthening of the truss bridge in 2006.

Traffic loading on the AHB has been measured by weigh-in-motion equipment since 2000 and the load data was used to develop a bridge-specific live load for
the extension bridges for assessment and design of strengthening in 2007. Traffic volumes have multiplied 20-fold since the original truss bridge was opened and weights of vehicles have increased significantly. Traffic loads were found to be approximately 50% higher than those used for the last assessment of the extension bridges in 1987. This dramatic increase in live loading meant that structural elements throughout the 1100m long extension bridges fell significantly below current assessment standards. Interim safety measures were introduced while the design and construction of strengthening works proceeded. These included banning heavy vehicles from the outer lanes and introducing traffic incident management procedures.

Measurement and monitoring of traffic loading has allowed Beca to minimise intervention and limit the extent of strengthening works while building in an appropriate growth margin to allow unrestricted traffic in future.

The design philosophy was to add strength and stiffness to critical areas of the box girders to maximise their load-carrying capacity without affecting the appearance of the bridge. State-of-the-art assessment methods and structural analysis tools were used in the design process to gain the most benefit out of the existing structure. Complex analysis was carried out where stiffener buckling capacities were found not to comply with standards. New internal stiffeners and plating were designed to precisely balance loadings applied. An allowance for future traffic growth was made during the design process to enable the critical 244m main span to carry the maximum feasible traffic loading.

To optimise the capacity of the bridge, a carefully planned installation sequence was specified that allowed the most highly stressed areas to be strengthened first thereby using the additional strength to carry subsequent loads.

While resource efficiency and design for minimum weight were guiding principles the scope and scale of the strengthening works was unprecedented for this type of bridge. 900 tonnes of new steel was distributed along the full length of the twin extension bridges. This included:
• 2,300m of deck stiffeners closely fitted to the steel deck during night time closures
• 14,000m of new and strengthened web stiffeners fitted over existing steelwork
• 190 tonnes of bottom flange stiffeners in compression zones
• 300 cantilever cross girders strengthened outside the box girders
• Internal strengthening of 12 pier brackets plus additional external stress bars.

Most of this material had to be delivered inside the box girders through narrow diaphragm openings just 1200mm high. An innovative materials handling system was designed and built as advanced works for the main contract comprising a mechanical lifting device and a miniature electric train that could deliver all the elements inside the box girders on a just-in-time basis.

![Fig 2: Traffic lane loads were measured to derive bridge-specific live loading which includes the effects of tidal flow.](image)

The installation of the steelwork was designed and planned to minimise impacts on traffic flows on the bridge which utilises moveable lane barriers for tidal flows of 165,000 vehicles a day – see Figure 2 above. Detailed design of installation and welding sequences were developed to limit locked-in stresses in the structure which had to remain in service throughout a 2½ year construction period. Carefully detailed connections were designed to limit on-going maintenance liabilities associated with fatigue.

An appropriate procurement strategy was implemented in such a way that the works could be carried out as quickly as possible with close collaboration between NZTA, Beca and contractor Total Bridge Services (TBS), introducing incentives to provide cost effectiveness while maintaining the high levels of quality and safety needed for the job.

The box girder strengthening and the understanding of live loading on the bridge gained in this programme of work has contributed to the management plans for the
AHB and will help determine future service life of the existing structure. Already this work is feeding into the planning for an additional Waitemata Harbour crossing in the future.

**Bridge-specific Load Assessment**

**Steel box girder structure**

The extension bridges comprise independent box girder structures on either side of the truss bridge supported on trapezoidal box pier brackets stressed onto the original concrete piers (see photo in Figure 1). The eight span bridge has a 244m main navigation span with depths varying from 3.5m at mid-span to 9.2m at main span piers. The approach spans range from 42m to 176m with constant depths of 4.2m making a total continuous length of bridge of 1100m between expansion joints.

The box girders were a pioneering example of this type of light-weight stiffened structure designed by Freeman Fox and Partners in the mid 1960’s. The steel orthotropic deck was fabricated from 11mm thick plate with 6mm thick trapezoidal trough stiffeners. The webs were fabricated from 9mm thick plate stiffened by 125mm deep angles between transverse web stiffeners. The deck plate and troughs are thinner than the orthotropic decks of today and are subject to fatigue cracking, requiring continual maintenance and repairs. The original mastic asphalt has been replaced with approximately 40mm of polyurethane surfacing which enhances composite action for better fatigue performance.
**Detailed Assessment**

Because of the potential vulnerability of the box girders and the inherent difficulties in strengthening them in service, extra detailed steps were taken to make an accurate load assessment so as to eliminate the conservatism that is found in bridge assessment standards. Dead loads from Bills of Quantities were used verified by records of girder weights measured on site. Records of surfacing thickness were used to precisely calculate superimposed dead loads. The original construction sequence was replicated to evaluate the locked in dead load stresses.

Yield strengths of the steel used to fabricate the bridge were calculated from mill certificate data resulting in allowable stresses higher than originally specified.

Deck trough stiffeners and longitudinal web stiffeners were found not to satisfy code shape limitations for local buckling. As it is known that the design codes are conservative in this area the assessment standard BD56 Assessment of Steel Highway Bridges was used to gain more accurate allowable stresses for buckling assessments of stiffened panels.

Detailed finite element (FE) models were used to assess the buckling strengths of the deck trough stiffeners. This showed that their slender webs were prone to local buckling effects at critical stresses far in excess of applied stresses. However, after rigorous assessment of the whole bridge it was clear that deck
troughs in the navigation span were a limiting factor in the bridge’s load-carrying capacity.

**Strengthening for Maximum Capacity**

**Navigation span deck optimisation**

The key challenge for future-proofing the crossing was to provide sufficient strength to cater for future traffic loads in the navigation span where deck trough stiffeners were found not to satisfy current assessment standards. Adding new longitudinal stiffeners (as shown in Figure 4) increased weight and a limit to the additional load that could be carried by the deck was identified. An innovative way of enhancing strength with minimum additional weight was to introduce new transverse cross girders between existing girders. This solution enhanced trough stiffener capacity by approximately 15% with a small weight increase. To optimise the box strength new longitudinal stiffeners were needed between the deck troughs and after the effects of the additional weight were re-assessed, it was found that the bottom flange also needed tensile strengthening to balance the section. The combined solution optimised the potential capacity of the box girders and provided a 10% margin for future live load growth.

To gain the maximum strength out of the top flange, an installation sequence was prescribed. Construction loads were limited to avoid locking in stresses. Installation began in the middle of the navigation span and moved incrementally north and south making the new stiffeners continuous as they were installed. In this way the critical central stiffeners acted to support the weight of the outer stiffeners, which meant that their size could be reduced and significant weight reductions made with the knock-on benefits in costs and reduced impacts on other areas of the structure.
Fig 4: Installation of navigation span deck stiffeners in a prescribed sequence. New stiffeners located between existing deck troughs.

The extra load of the strengthening resulted in a permanent deflection of approximately 0.5m at mid-span. A physical load test was carried out by Beca to verify the stiffening effects of the strengthening works in which deflections due to strategic placement of a pair of 20 tonne trucks was measured during a night time closure of the south-bound extension.

**Advanced design techniques**

For cost effective strengthening solutions advanced design techniques were employed. The interaction of existing and new structural elements of the box girder is complex. In order to utilise the full capacity of the old steelwork and minimise the incorporation of new steel detailed finite element analysis of critical members was necessary. The use of the latest design software successfully enabled rationalisation of designs to allow minimum intervention and to extract maximum resource efficiency from existing structures.

Deck cross girders serving a dual purpose of supporting local axle loads and restraining orthotropic deck panels were found not to satisfy standards at the inner cantilevers. In order to include the restraining effects of deck troughs and web connections in assessments detailed analysis was carried out. The use of an FE model shown in Figure 5 helped to identify a first mode of buckling that was limited to a segment of web between stiffeners close to the root of the cantilever.

FE analysis was used to design strengthening measures in the form of local stiffening that would effectively prevent this mode of buckling. This detailed
analysis of a complex arrangement of girder and deck stiffeners helped to minimise the amount of construction work at height over water on over 300 external girders.

The original design and construction of the “clip-ons” was a pioneering example of retrofitting the existing bridge to increase capacity of the motorway. The strengthening of the extension bridges called for similarly innovative approaches to cater for increasing traffic loads.

The extension bridges are supported on rocker bearings on the pier brackets which are stressed onto the original concrete piers. The diaphragms inside the brackets were found to be another limiting element in the bridge capacity. The arrangement of each bracket is unique, so detailed FE analyses of the complex stress concentrations in the stiffened structures were carried out as illustrated in Figure 6. Using advanced analysis techniques allowed tailor-made strengthening solutions to be found to fit each pier bracket individually.

The stress bars connecting two of the brackets at pier 4 were found to have insufficient capacity and additional 50mm diameter high strength bars were installed to provide additional strength. Design and installation of such a retrofit solution to the “clip-on” structures was a delicate operation that required precise fabrication and fitting of elements prior to stressing of the bars under a closure of the east and west box girders.
Sustainable Construction Methods

Following the minimisation of impacts through design, sustainable construction principles were followed during installation to reduce social, environmental and financial effects of the strengthening work. Measures were taken during the construction contract to minimise impacts on road users and local residents, to avoid adverse effects on the aesthetics of the landmark bridge, and to enhance the health and safety environment in and around the bridge.

Collaborative contract form

A key contribution to the positive outcome of this project was Beca and NZTA’s preparation of a form of contract that enabled a collaborative approach to solving problems as they arose. Client, project managers, designers, main contractor and sub-contractors worked together throughout the construction period to find the best solutions for the bridge, despite intense pressure at some key points in the programme.

The contract included a target cost basis for payment with pain\gain incentives for achievement of targets. Packages of work were progressively released and competitively bid with rates and lump sum elements agreed at the outset. Productivity targets, key performance indicators, and programme incentives were used to drive value for money for NZTA.
Involvement of the AHB maintenance contractor TBS early on in the design phase allowed open discussion of preferred options for constructability, ease of fabrication and cost effectiveness. As the work progressed value engineering solutions were developed to improve some elements, such as replacement of bolted transverse web stiffeners with welded stiffeners which had major productivity benefits and saved money for the client.

**Safe working in the box**

Working on the AHB has inherent hazards and risks to both construction workers and to the safety of road users. A number of innovative features were introduced during the strengthening work to eliminate the major project risks.

The construction contract was tailored to fit in with annual programmed maintenance operations including re-surfacing the bridge during Christmas closures. In order to complete the works as quickly as possible, an innovative materials handling system was designed and installed as an enabling works package during the detailed design phase of the project.

The mechanical lifting equipment and electric train shown in Figure 7 was used to deliver loads of up to 1 tonne at precisely the right time to suit the installation programme. The train which runs on rails at the centre of the box and fits neatly through 600mm wide diaphragm openings along the bridge has travelled the equivalent of the length of New Zealand and back during the construction period - saving thousands of man-hours on the job and providing incalculable health and safety benefits.

Hazards in working in the box girders included confined spaces, working with lead paint, and working 40m above water as well as the inherent risks involved with welding inside a highly-stressed live structure. Health and Safety procedures and the welfare of workers were of paramount importance to the team and it is a credit to all the contractors involved that the project was the Supreme Winner of the New Zealand Health and Safety Awards in 2010.
Minimising disruption and future liabilities

Customer satisfaction is NZTA’s major concern and to this end both the travelling public and local residents were kept informed and updated on project developments throughout the contract. To avoid grid-locking Auckland the welding to the bridge deck was carried out at night during extension bridge closures after the evening peak traffic period. Traffic management plans were coordinated with the Auckland Traffic Operations Management Centre to avoid traffic delays resulting from the strengthening work.

Since the volume of traffic using the AHB was already close to its limit during tidal flow operations at peak times, the avoidance of future emergency closures was important. The stiffened steel deck has an inherent risk of fatigue damage from the repetitive wheel loading. In order to minimise the future liability to
fatigue cracking small weld gaps were specified. The 40 year-old deck, however, is far from flat so an innovative laser scanning system was used to measure the deck profile to an accuracy of + or – 35 microns. The measured deck profile was downloaded directly to the profile cutting machines in the fabrication facility. Each stiffener was individually made for its unique location and installed in the prescribed sequence. Close fit-up tolerances for stiffeners were continuously achieved and so the use of the high tech scanning process paid dividends in productivity and minimised the impacts on the motorway from additional closures during construction.

Conclusions

The AHB extension bridges broke new ground in 1969 by spanning up to 244m using minimal amounts of steel. In the latest strengthening project new analytical techniques helped engineers to improve the accuracy of assessment of the existing structure where load-capacity short-falls were found under increasing demands.

Resource efficiency is a primary concern in the sustainable development of transport infrastructure. However, future maintenance liabilities and continual serviceability are often found to be conflicting concerns for engineers and bridge owners. In the latest strengthening of the Auckland Harbour Bridge state-of-the-art tools have been applied to gain more out of the existing structure than was ever anticipated. New and innovative methods of adding capacity in service have been employed to allow strengthening without disrupting New Zealand’s main north-south transport route. Load monitoring and on-going maintenance of the structure has enabled this vital crossing to be future-proofed and to remain operable for decades to come.

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