Grafton Bridge Strengthening

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SYNOPSIS

The strengthening of the Grafton Bridge is a sustainability project to expand the use and extend the life of a historical Auckland landmark. Originally designed to carry pedestrians and horse-drawn traffic in 1906, the bridge had an 8 tonne vehicle weight limit imposed in 1970. This strengthening project aims to upgrade the structure to carry modern traffic loading and become a dedicated bus route as a key link in Auckland City Council's Central Connector – a new public transport corridor between Britomart and Newmarket.

The structural works will include New Zealand's biggest ever carbon fibre reinforced polymer (FRP) bridge strengthening project. The original design did not cater for earthquake loading and the construction work will include a major seismic retrofit of the bridge piers using techniques sympathetic to the architectural vision of the original designers. This paper outlines the history of previous construction works to this heritage structure, describes material and physical load testing carried out to confirm assessment findings and explains the principles of strengthening proposals now being implemented to preserve the integrity of a beautiful 100 year old piece of architectural engineering.

Figure 1 – Grafton Bridge looking towards Symonds Street Cemetery

1.0 GRAFTON BRIDGE HISTORY

1.1. World Record Breaker

Designed in 1906 and built by the Ferrocement Company of Australasia, Grafton Bridge was the longest reinforced concrete span in the world when it was opened in 1910. As a pioneering example of this type of structure a great deal of attention was paid to the record-breaking 98m arch span. The design was checked by Professor Moersch in Germany, and a condition of payment for the turn-key project was that the arch had to be load tested prior to opening. Road aggregate, weighing 5kN/m^2 was placed on half the arch and deflections of 3.5mm measured. Then two 17 tonne steam rollers were moved across the bridge simultaneously proving the load-carrying capacity. The grand opening marked a huge achievement for the city. However, the contractor went bust during construction and it appears not enough attention was paid to the approach spans, since within a decade major shear failures of the 25m span vierendeel girders were seen and the first load restrictions were put in place.

Figure 2 – Steamrollers load testing Grafton Bridge prior to opening in 1910

1.2. 1936 APPROACH SPAN RECONSTRUCTION

Auckland City Council's chief engineer, Mr. A.J. Dickson, described in detail in the proceedings of the 1940 New Zealand Institute of Engineering Conference the reconstruction of the vierendeel girders. The deck was temporarily propped, the lower chord and failed vertical elements demolished, reusing reinforcement where possible, new piers were built in at mid-span, and the main beams reconstructed, greatly improving performance while not compromising appearance of the bridge as a whole. In Mr. Dickson's words *"once again this vital artery in the traffic routing of the City of Auckland is in full service, after an application of 'plastic surgery' which has removed an inherent weakness… The appearance has definitely not been impaired and is considered by many to have been improved"*

This very informative paper on the 1936 reconstruction has provided valuable details of the bridge structure. It was retrieved from the family archives of Andrew Dickson of Beca who was asked to carry our assessment of his grandfather's beam column joints – and happily found these to be sufficient. I mention this to illustrate the generational impact of a landmark like Grafton Bridge. As the bridge ages gracefully several waves of engineers have passed and carried out maintenance and repair works to the enduring structure, including:

- Expansion joint replacement and surfacing 1953
- Spandrel column repairs and shotcrete coating 1957
- Concrete repairs 1973
- Handrail repairs/crack injection 1990's
- Parapet screen installation 2000

The original bridge was commissioned by the City Council, not because it was the cheapest or most risk free solution but because it offered an attractive alternative to a steel girder option, and would require less maintenance. I believe the hundred year life so far, and the fact that it is still cherished and ranked as the highest grade heritage monument by the New Zealand Historic Places Trust is a testament to the vision of the city fathers.

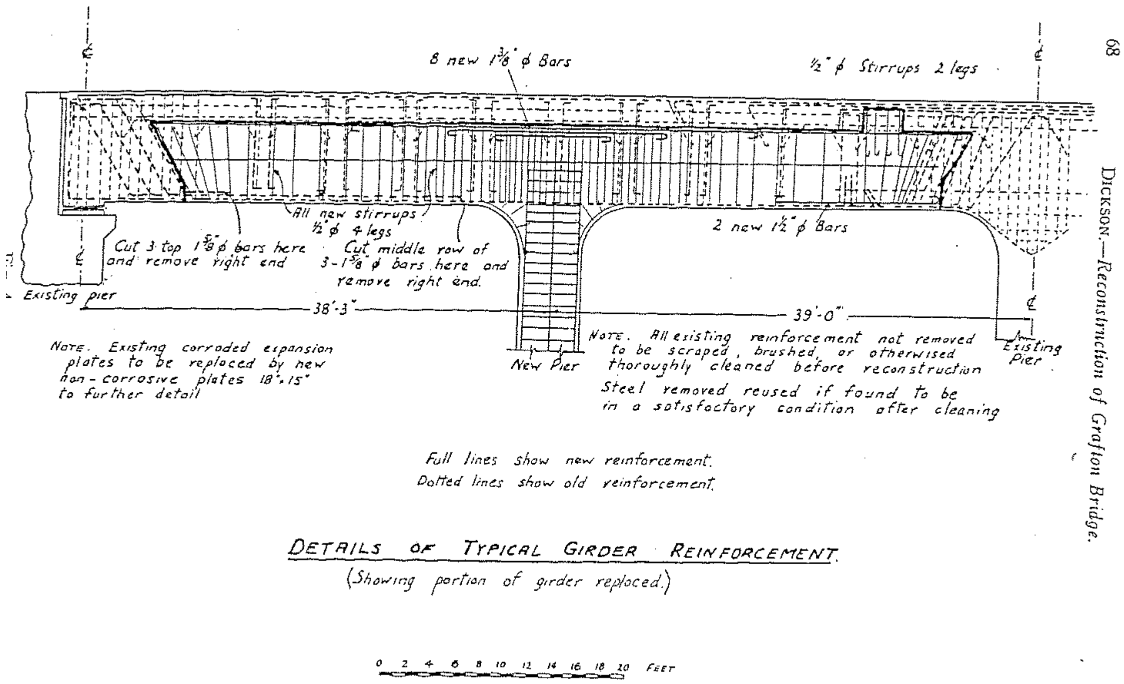

Figure 3 – 1936 Reconstruction Drawing of New Pier and Replacement Beams

2.0 STRUCTURAL FORM AND MATERIALS

The Grafton Gully motorway has more recently been threaded beneath the 98, span 3 pinned arch, and the 180m of reinforced concrete approach spans. The approach spans are divided into separate structures separated by movement joints and sliding bearings at abutments, with intermediate piers built in carrying loads down to Waitemata Series Sandstone. The big architectural piers either side of the arch span are hollow shell structures with a "soft storey" of three longitudinal walls at their bases.

At Scheme Assessment stage concrete was tested and found to have a cylinder strength of 15.6MPa. Reinforcement is all undeformed mild steel bars with yield strengths between 210 and 250MPa. Carbonation tests were carried out and penetration of carbon dioxide was discovered up to 40mm into the concrete. Reinforcement cover is generally 50mm.

3.0 STRUCUTURAL ASSESSMENT

Beca was appointed in 2004 to design strengthening to enable the bridge to carry HN72 traffic loading in accordance with the NZTA Bridge Manual. Many of the details of this early reinforced concrete structure, however, simply do not comply with current standards. And so methods for assessment of the existing structure had to be adapted from various authorities overseas and verified by material testing.

The arch itself was found to be adequate for carrying modern loads, as were Mr. Dickson's 1936 replacement beams. Reinforced concrete design had come a long way since the turn of the 20th Century, and halving the approach spans was a tidy way of limiting liabilities. Beca did not have that option and so rigorous assessment of each individual element was necessary.

The main largely architectural piers were found to rock under earthquake loading with an annual probability of exceedance of 1/1000 years, and to have insufficient lateral shear strength. Similarly the shorter fixed piers were found to attract more horizontal load than the larger more flexible piers and to have insufficient bending reinforcement at depths up to 12m below ground level.

Deck beams over the main arch were found to have inadequate strength to carry the design traffic loading, and could fail under maximum bus axle loads.

Figure 4 – 3d Structural Analysis Model

4.0 PHYSICAL LOAD TESTING

The deck beams constructed in 1908 have some unusual detailing that defy a code approach to assessment and design. Reinforcement was fixed in so called "trusses" with top and bottom longitudinal bars held by vertical shear bars with split ends formed into a fish-tail detail around main bars. The spacings of these fish-tailed bars varies with a higher concentration close to supports reducing towards mid-span regions. One or two of these "trusses" are fixed in beams with additional main bars bent up over supports of continuous beams.

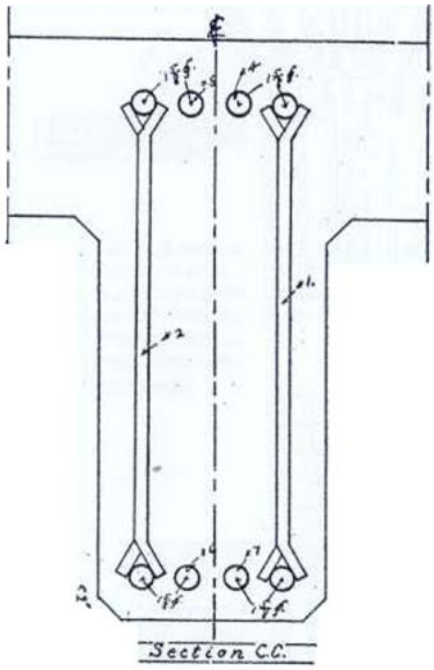

Figure 5 – Shear Bar Drawing

Figure 6 – Shear Bar Photo showing exposed reinforcement

In order to test the anchorage strength of the fish-tail 24 samples of 12mm, 16mm and 20mm diameter mild steel bars with varying bond lengths were made and tested in Opus laboratories. The tests indicated that the length of bonded plan bars was much less effective than the fish-tail detail and that a very short length of fish-tailed bar could develop the strength of the original steel section.

The shear strength of reinforced concrete beams is addressed by different methods with a range of equations in a variety of international standards. The equations for the contributions of concrete and steel to beam shear strength are based upon highly variable empirical data from test results of simply-supported rectangular beams. Codes still largely rely upon a 100 year old strut and tie analogy to evaluate the contribution steel reinforcement makes to the shear strength of beams when reinforced in accordance with current practice.

Of course we have standards to help us and we have peer reviewers to check that our designs comply with standards. We had much debate about the theoretical behaviour of these fish-tailed shear reinforcement bars and agreed to carry out physical load testing of beams on the bridge to verify our assessment findings. We also consulted one of the authors of NZS 3101 the Concrete Structures Standard of New Zealand, Professor Richard Fenwick of Auckland Uniservices, and he provided some very useful advice on the testing methodology.

We arranged for testing of approach span transverse beams, of which there are approximately 200. If the code approach was followed and the unusual 1906 detailing was rejected as non-compliant these beams would all require strengthening. However, upon testing to ultimate loads no significant cracking was observed in 15 load tests and the secondary beams were accepted as capable of carrying ultimate design loads.

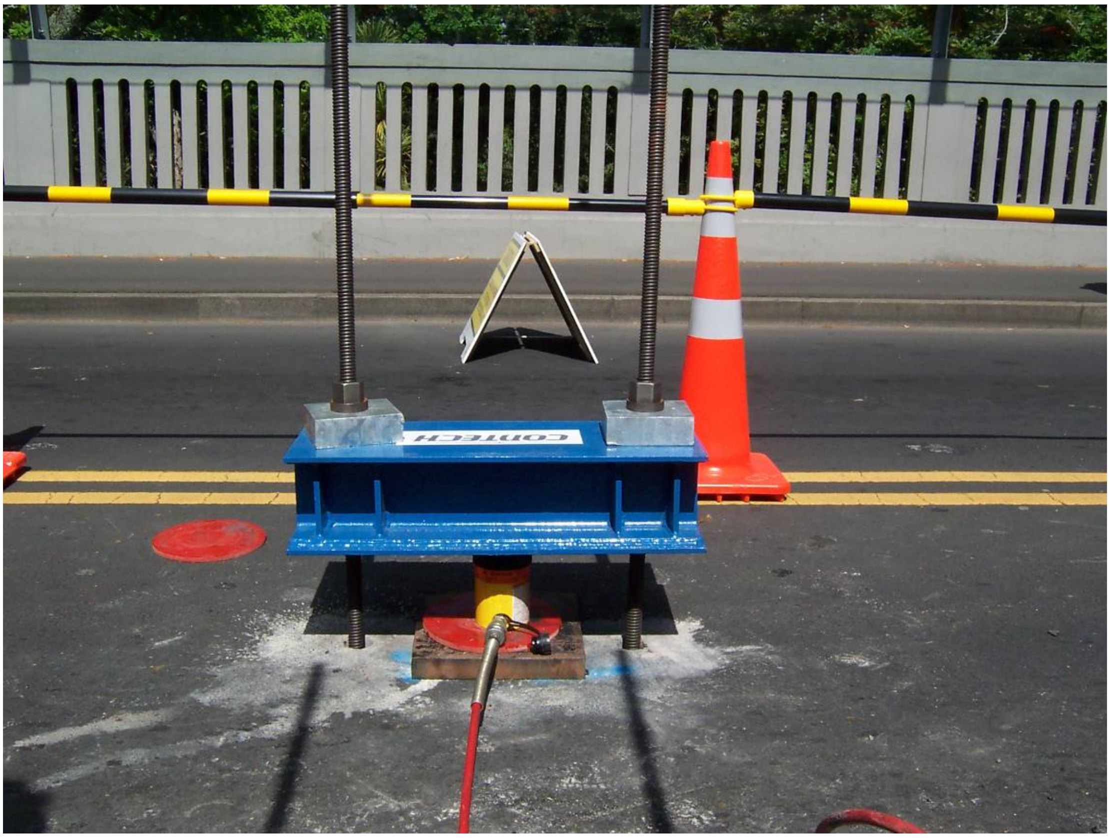

Figure 7 – Load Test Equipment Above Deck

Figure 8 – Load Test Reaction Beam Below Deck

For the main longitudinal beams supported off the arch 40m over the Grafton Gully which could not be tested safely we carried out assessment to the UK Highway Agency's BD44 Assessment of Reinforced Concrete Bridge Structures to find upper and lower bound shear strengths by including or excluding the contribution of the fish-tail bars. The beams in this location were found to have deficiencies in bending and shear strength and we opted to add shear strengthening to cater for the lower bound existing beam capacity.

5.0 DESIGN OF STRENGTHENING FIT FOR A LANDMARK

The original construction of the Grafton Bridge was an ambitious historic achievement by Auckland City. The 1936 reconstruction of its approach spans was a major invasive operation that was carried out with great attention to the impact on architectural form and overall proportion. Beca's 2006 design to significantly increase strength and stability had to be even more subtle limiting intervention where possible with the 100 year old structure, while respecting the architectural and heritage value of the landmark bridge.

5.1 FRP Deck Strengthening

110 of the main longitudinal bridge beams required strengthening to increase bending and shear strength. In order to minimise visual impact, while offering a cost effective solution that was appropriate and buildable, carbon fibre reinforced polymer (FRP) strengthening was chosen. Of the two types of FRP: wet lay-up fibre wraps, or prefabricated laminate strips the latter was selected for a number of reasons. Firstly, some of the beams were under strength by a large margin and in order to utilize the full existing beam section for flexure, shear strengthening should be applied across the full depth of the beam, and be anchored into the compression zone at the top of the slab. Secondly, a stubborn shotcrete layer applied in the 1950's had to be removed prior to applying the FRP to the concrete structure. So in order to limit the extent of removal of shotcrete discrete strips of FRP were favourable to complete wraps of material around beam soffits and webs. Pull-off tests were carried out on the concrete substructure to verify adequate bond strength for the adhesion of the FRP to the concrete surface.

Flexural strengthening was designed in accordance with fib Bulletin 14 Externally bonded FRP reinforcement for RC structures. The principles of strain compatibility between reinforced concrete beam and carbon fibre strips were applied in design, bond lengths calculated to avoid peeling off of the new material, and serviceability limit state checks made to account for safe loading of beams in the event of the loss of the FRP material.

Shear strengthening comprised L-shaped strips of FRP laminate material that is inserted into slots cut through the deck slab and anchored with strong epoxy adhesive into the top of the beam section. Pairs of L-shaped strips are fixed one over the other to provide discrete U-bars at regular spacings which enhance the shear capacity of the reinforced concrete beam. This type of shear reinforcement has been tested on T-beams in laboratories in Switzerland to verify the equations used in design for additional shear strength.


Figure 9 – Laboratory Testing of FRP Shear Strengthening

5.2 Seismic Upgrade of Approach Spans

No provision was made for earthquake loading in the original design. In the 1936 reconstruction the approach spans were designed for horizontal seismic accelerations of 0.1g. While the bridge is not on a life-line route in the event of a major earthquake, it is an important crossing for the city. It was agreed by Auckland City Council that an annual probability of exceedance of 1 in 1000 years was an appropriate level of earthquake resistance for a bridge that is already 100 years old and whose remaining life is limited.

Beca carried out response spectrum analysis of 3 dimensional models of the whole bridge structure. In longitudinal and transverse modes of vibration the stiffer, shorter piers were found to attract large forces. These piers are 3 foot (0.915m) by 5 foot (1.525m) in cross section, extend up to 15 down through soft strata to founding material and are very lightly reinforced.

12 of the approach span piers were found to have insufficient bending strength at depth below ground level. The majority of the piers that need to be strengthened are in the Symonds Street Cemetery. This is another grade A historic place that pre-dates the bridge, and several of the bridge piers were constructed between graves from the 19th century. In order to avoid damage to the fabric of the cemetery it was decided to strengthen piers by coring down through the existing concrete from deck level, then inserting new reinforcement bars into the section and grouting them in. The tops of the piers are to be extended with new reinforced concrete sections tying the new vertical bars into the longitudinal beams.

As well as the works to the piers the seismic upgrade includes provision of shear keys between separate approach and main span structures, and longitudinal ties to reduce potential damage during earthquakes. These small scale reinforced concrete elements will be tucked up bearing shelves under the bridge deck between longitudinal beams hidden from view.

5.3 Main Pier Foundation

Another feature of the bridge requiring major work was the main piers on either side of the arch span. The arch itself is founded on separate thrust blocks cast between three walls at the base of the piers. The bearing pressure beneath those large pad foundations are relatively low. However, the piers themselves, although hollow shells are 35m tall and quite massive structures, founded on three strips of wall 1 foot (0.305m) wide. Trial pits were dug at the base of pier 7 in the cemetery to identify and test Waitemata sandstone at the founding level. Boreholes were drilled at pier 11 at the side of the motorway where rock was some 6m below existing ground level. It was found that additional bearing area was needed to support lateral earthquake loading, and that the pier walls themselves required major strengthening to be able to transfer forces to the founding rock layer.

At pier 7 access is extremely restricted on the steep slopes of the cemetery, so ground anchors were selected that can be bored using small demountable drilling rigs. Rock is very close to the surface and shallow reinforced concrete beams will be cast within the pier walls to transfer forces to the ground anchors.

At pier 11, however, ground levels have been raised to build the motorway and access is not restricted around the base of the structure. Five 900mm diameter piles will be constructed on either side of the pier. Pile caps will be connected through the existing pier walls to a series of beams cast within the shell structure. The only visible signs of this work on completion will be reinforced concrete walls across the front face of the pier bases. The extent of proposed strengthening works is shown in figure 10 below.

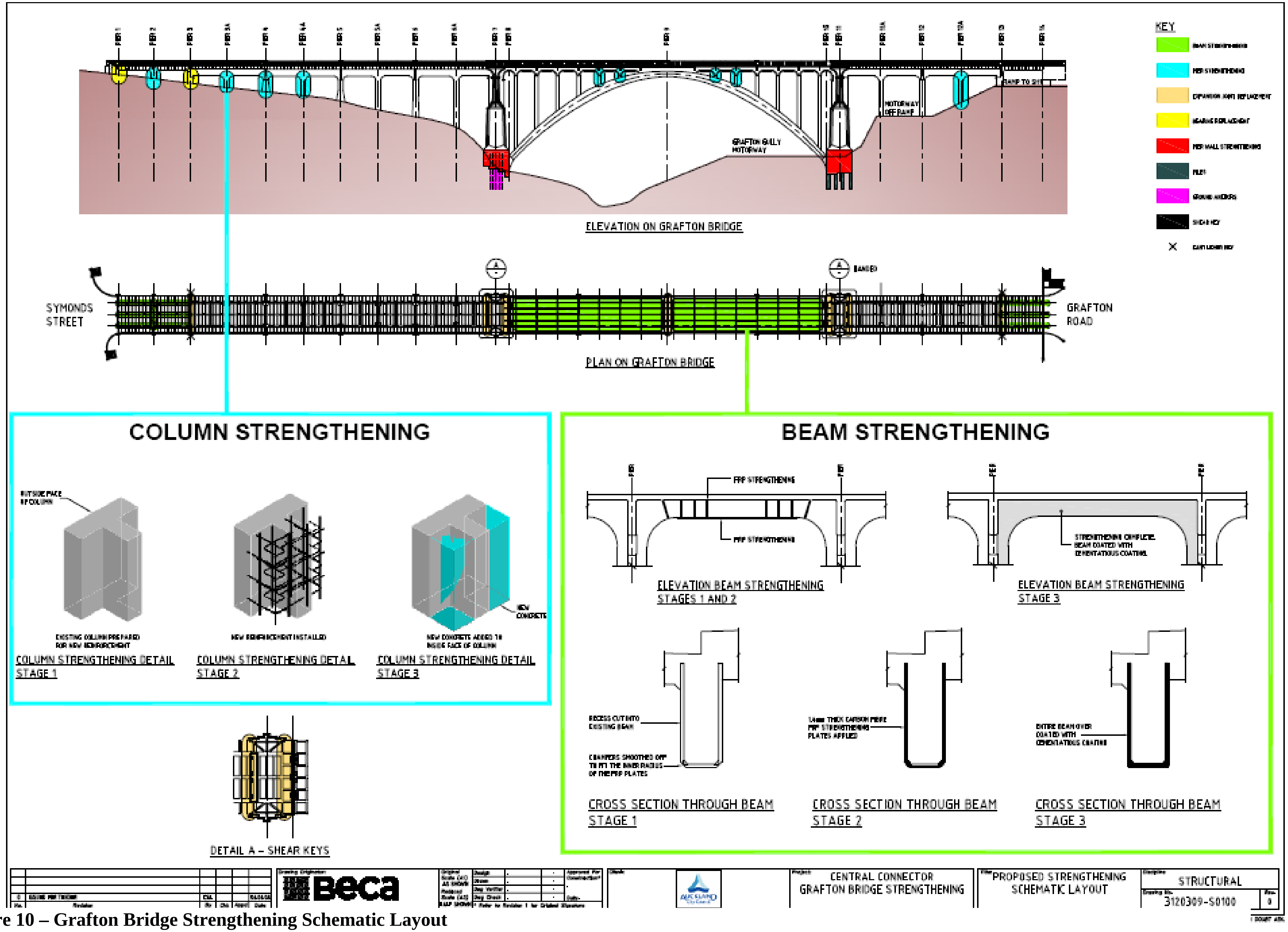

Figure 10 – Grafton Bridge Strengthening Schematic Layout

6 Consultation, Consents and Concrete Repairs

Our approach to design was to intervene as little as possible to the existing structure to bring it up to standard and all intervention must be done in sympathy with the character of the bridge. We explained our assessment and testing methods to the Heritage division of Auckland City Council, and the New Zealand Historic Places Trust when we presented our design proposals for the strengthening work. Their understanding of this approach to the bridge strengthening, acceptance of the materials to be used, and the construction methods that would be employed was vital in gaining approval for the consents required. As a registered heritage site resource consent is needed to do any upgrade work to the bridge. Much attention was paid to the method of works within the cemetery with restrictions on access and close management and control of works required to ensure the protection of historic graves and protected trees.

Close collaboration between a team of heritage architects, planners, arborists, lawyers, bridge engineers and clients made the consenting process run smoothly and successfully.

A large part of the proposed work includes restoration of the bridge as well as structural upgrading. A number of parts of the bridge are to be repaired and replaced including:

- Replacement of corroded steel bearings
- Replacement of expansion joints
- Restoration of bridge lighting
- New thin epoxy footpath surfacing
- Road re-surfacing
- Concrete repairs
- Protective coating of concrete structure

For the first time in decades a detailed inspection of the entire bridge structure has been carried out. This involved some innovative access methods such as abseiling for high level areas, large mobile cherry pickers for motorway spans during night-time lane closures, and working off suspended scaffolds where extensive strengthening works are to be carried out.

Approximately 300m of crack repairs have been identified during inspections and a few areas of spalled concrete, but relatively little corroded reinforcement for a bridge of this age.

However, carbonation of the concrete cover has been found, and in order to prevent further ingress of acidic carbon dioxide into the structure, an anti-carbonation coating is to be applied to all exposed concrete faces below parapet level. We consulted widely on the type of coating to use, have had trial panels approved by the client and heritage architect and have opted for an elastomer-modified cementitious spray-applied coating that is intended to look like new concrete when finished.

Figure 11 – High Level Inspection by Rope Access

7 Construction Progress

The contract for the strengthening works is currently underway and due for completion at the end of the year. The main contractor is Brian Perry Civil who have sub-contracted a number of specialist abseilers, scaffolding suppliers, drilling sub-contractor and concrete repair specialists. FRP strengthening is being installed by Construction Techniques who are the local approved applicators for the Sika Carbodur materials being used.

The FRP material has been tested at Auckland University to verify a tensile strength of 2800MPa. Quality Assurance during application is assisted by ongoing pull-off tests on substrate preparation, adhesion tests on samples of installed FRP and Glass Transition Temperature tests on samples of the epoxy adhesive taken from site.

At the time of writing coring has commenced inside the cemetery piers and preparations are being made for the main pier foundation works.

By the start of 2010 we hope to have completed another chapter in the life story of a living monument. By strengthening for increased road traffic demands, adding robustness and stability to resist earthquakes, restoring the fabric of the bridge and adding an enhanced layer of durability to the structure we hope to extend its working life, and preserve this cherished feature of Auckland's landscape for generations to come. On its 100th birthday the Grafton Bridge will be re-opened with a new role in a new era as a key link in a new public transport route. The Central Connector will be an important new edition to Auckland's rapidly expanding transport network.