Upgrade of Esmonde Road Underpass
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Synopsis
The existing Esmonde Road Underpass was upgraded as a part of the Northern Busway Project in Auckland, New Zealand. The deck of the underpass needed to be widened by up to 1.5m and raised by a maximum of 500mm to accommodate the modifications required at the motorway interchange. This necessitated extensive strengthening to cater for the new alignment and to comply with current loading standards. The paper describes the upgrade to the bridge with an emphasis on the key constraints faced by the designers and solutions implemented to widen and strengthen the bridge.

1 Introduction
The Esmonde Interchange on the Northern Motorway, Auckland was modified to accommodate a new east to west movement (previously only travel from the west to east was permitted), bus access to the adjacent Bus Station, and improved access for vehicles to the motorway as a part of the Northern Busway Project. It is a NZ$44M project undertaken by Transit New Zealand in collaboration with North Shore City Council to improve the public and private transport around the north of the Harbour Bridge in Auckland. The works involved construction of a new retaining wall under the western abutment spans for the northbound motorway on-ramp loop, a new motorway underpass bridge alongside the existing underpass and modifications to the existing Esmonde Road Motorway Underpass (Figure 1). The design and construction observation of the project was jointly provided by Opus and Beca. The project was completed and opened for public in May 2007.

Figure 1 Aerial View of Esmonde Interchange and Surroundings
This paper deals with the upgrade undertaken to the existing Esmonde Road Underpass. It describes the geometrical and structural modifications needed to the underpass to fit the new alignment and to carry the current design traffic loads. Structural assessments were carried out to determine the extent of strengthening required to the underpass. Retaining and strengthening of the existing underpass was compared with constructing a new bridge, however constructing a new bridge was found to be uneconomical. A summary of the findings of the assessments were presented along with options considered and the ones chosen for modifying and strengthening the underpass.

2 Description of Underpass
The underpass is a four span (13.7m/18.3m/18.3m/13.7m) continuous bridge supported by three intermediate piers and abutments at each end. Figure 2 shows the elevation and plan views of the existing underpass. The superstructure is a three cell reinforced concrete box girder of depth 1.1m. The middle pier and the other two piers are located in the median and shoulders of the motorway carriageway respectively. Each pier is supported on a 2.74m square by 1.07m deep pile cap by a group of six 450mm diameter bored cast in-situ concrete piles. The corner piles in each group are vertical and the middle piles are raked at 1 in 4 transverse to the bridge. The western abutment is supported on eight 450mm diameter bored cast in-situ concrete piles raked at 1 in 4 longitudinally. The eastern abutment, which is cast monolithically with the bridge superstructure, is supported on sixteen 450mm diameter bored cast in-situ concrete piles raked at 1 in 4 longitudinally.

The original bridge was designed to H20-S16-44 loading standard and was built in the late 1950s. The original design compressive strength of concrete of the existing structure is 21MPa.

3 Modifications to the Alignment
The old alignment of the underpass was on a horizontal spiral curve with varying super elevation along its length. The new horizontal alignment at the motorway interchange required the underpass to be widened gradually to maximum 1.5m at the western abutment as shown in Figure 2 (Plan View), where the shaded area shows the widening at the western end. Additionally, the underpass needed to be raised by a maximum of 500mm to suit the vertical curve of the new alignment.

Raising the superstructure deck up to 500mm, by constructing a solid slab on top of the existing deck, amounts to a considerable increase of dead weight. Hence, to reduce the additional dead weight the existing box girder webs were extended and a new slab of 150mm thick was constructed, by filling the voids with polystyrene blocks as shown in Figure 3. This was considered an economical and easier to construct option than others including the use of light-weight concrete solid deck. Constructing a new structural deck slab over the whole length of the bridge has the additional benefits of: (a) providing an improved vertical alignment at the eastern end of the bridge; and (b) increasing the structural capacity of the deck cantilevers to carry the rigid side barrier loadings and the additional cantilever width on the western span.
Figure 2 Existing Underpass Elevation and Plan Views
4 Structural Assessment

The modifications to the underpass has resulted in increased demand due to additional dead load from new deck slab, extended web girders, and widening at the western end. Additionally, the bridge needs to carry the current design traffic loading HN-HO-72 in accordance with Transit New Zealand Bridge Manual, which is higher than the original design traffic load H20-S16-44.

Analyses were undertaken to determine the increased demand and were compared with the structural capacities of the underpass. Two primary models were developed using the structural analysis software SAP2000: (i) a 3-D grillage model incorporating the widening of the structure to study the effects due to design traffic load; and (ii) a spine model with super structure modeled as stick elements to study the effects due to dead loads and seismic forces.

4.1 Superstructure

The existing cantilever slabs were found to have adequate capacity to carry additional dead load resulting from the wet concrete of up to 500mm thick. The new reinforced concrete deck slab was designed to satisfy the demand due to the design traffic load and vehicle impact forces on the new TL-5 rigid side barriers.

The assessments indicated that the extended web girders with the new deck slab had sufficient flexural capacity, in both positive and negative bending moment regions. However the shear capacity of the web girders, especially the external web girders, close to the piers was only sufficient to carry 70% of the demand due to the design traffic load (HN-HO-72). Therefore strengthening of external web girders in the region close to the piers was found necessary.

4.2 Substructure

The existing pier caps are 915mm thick solid reinforced concrete diaphragms connecting all the webs inside the box. The pier caps were found to have inadequate capacity both in flexure (in the positive moment region) and shear near the pier columns under the critical load combination of dead and live loads.
The pier columns are 990mm diameter reinforced concrete columns, which are reinforced with 26/32mm diameter longitudinal bars and 12.7mm diameter hoop reinforcement at 305mm centres. These columns are fixed both at the top into the pier cap diaphragms and at the bottom into the pile caps. The columns were found to be adequate for the dead and live load combination, but not for the demand due to the current seismic requirements. Strengthening of columns was thus required to increase the shear capacity and confinement of the hoop reinforcement.

Pile caps were assessed using strut and tie models, and were found to have inadequate steel reinforcement for the critical dead and live load combination, requiring strengthening.

Both pier and abutment piles were found to have adequate capacity.

5 Modifications and Strengthening
Options for modifications and strengthening of the underpass were considered in light of constructability over the live motorway traffic. During the construction phase the underpass was closed for traffic. The new bridge, which was constructed alongside the existing underpass was completed and was used to carry the diverted traffic from the underpass.

5.1 New Deck Slab
Reinforcement bars were epoxied into the pre-drilled holes of the web girders to extend the webs and to construct the new deck slab (Refer Figure 4). An L-shaped bar was epoxied into the centre of the web girder at a given location, which eliminated the difficulty of hitting/cutting existing reinforcements in the deck slab and web girders. Polystyrene blocks cut onsite were used to provide the form to construct the new concrete slab (Refer Figure 5).

Figure 4 Construction of the New Deck Slab

5.2 Box Web Girders
Carbon Fibre Reinforced Polymer (CFRP) composites were chosen to enhance the shear strength of the external web girders near the piers. Two sheets of Sika wrap HEX-103C (600mm wide x 0.34mm thick) at 600mm spacing was applied vertically approximately 5m either side of the pier on the inside and outside of the external web girders. Manholes through the soffit of the box at the central piers and through the
deck slab at the outer piers were provided for access to the inside of the external web girders. Figure 6 shows the application of CFRP inside an external web girder.

Figure 5 Polystyrene Blocks Providing the Form to Pour the New Deck

Additionally, two horizontal sheets of Sika Wrap HEX-230C (300mm wide and 0.2mm thick) were applied at the top and bottom of the web girders over the vertical sheets to prevent the vertical sheets pulling out in tension.

Figure 6 CFRP Strengthening Inside an External Web Girder (Photo courtesy of Contech)
Composites were considered for a number of reasons including light weight and easy to handle, especially on scaffolding over a live motorway, less intrusion, and less additional weight compared to other conventional materials and methods.

5.3 Pier Caps

Strengthening to enhance the shear and flexural (positive bending) capacity of the pier caps were achieved by externally post-tensioning the pier caps. New reinforced concrete leaves of 350mm wide were constructed either side of the pier caps’ outer cells to facilitate the post tensioning as shown in Figure 7(a). These reinforced concrete leaves were transversely post-tensioned as shown in Figure 7(b). Reinforced concrete end-blocks (Figure 8) were constructed outside the pier caps for the longitudinal post-tensioning which consisted of four (two for each concrete leaf), 50mm diameter Macalloy 1030 bars for each pier cap.

5.4 Pier Columns

The pier columns were wrapped with CFRP composite sheets at the top and bottom to enhance the shear capacity and confinement at the plastic hinges, which improved the ductility of the structure.
The top and bottom 1200mm were wrapped with Sika wrap HEX-103C (600mm wide x 0.34mm thick), where the top/bottom 600mm with two sheets and the next 600mm with single sheet. Figure 9 shows CFRP wrapping of the top part of a pier column and shear strengthening of the adjacent external web girder near a pier cap.

CFRP composites were found to be an efficient retrofit solution under the given circumstances where these columns are close to the motorway carriageway and thus required minimal disruptions to traffic. Although night work was considered for the installation of CFRP composites it was dropped due to concerns over the formation of dew on the freshly laminated CFRP. Instead the work was undertaken with a single
lane closure during low traffic flow that avoided the morning and evening peak traffic periods.

5.5 Pile Caps
A number of options were considered including post tensioning to strengthen the pile caps of piers. Reinforced concrete overlays were eventually chosen as the appropriate option for strengthening all pile caps. This involved removing the cover concrete of the pier columns, drilling and epoxying reinforcement into the existing pile cap (Figure 10). This work was executed within the limited access available during day time while the traffic was on the adjacent motorway lanes.

Post tensioning the pile cap would be an efficient method of strengthening however it was unsuitable in this situation due to the limited access available for the stressing equipment and bars.

![Figure 10 Pile Cap Strengthening with Concrete Overlay](image)

6 Construction Challenges
The proximity to the motorway traffic lanes meant restrictions on access to the underpass and the use of large machinery. The lanes were narrowed to achieve safe work space within the median and shoulders, where access scaffolding was provided for underneath and to the sides of the underpass.

The use of CFRP composites for strengthening the web girders and pier columns helped reduce the heavy material and equipment handling on site. The installation took place in a relatively short period compared to other works such as widening and raising the bridge deck slab.
The CFRP application subcontractor chose to saturate the Sika Wrap with the 2-part epoxy resin Sikadur-300 at their factory to minimize the installation time on site and to achieve improved quality of epoxy mixing and saturation of CFRP composite sheets. Dry ice was used to keep the temperature low and to retard the curing of these prewetted sheets during transport to site.

It was found that spacing of the existing steel reinforcement in the deck slab and web girders was not as shown in as-executed drawings. Impact drilling was originally specified to minimize damage to the existing deck steel, however this was found to be impractical due to the tight spacing of the longitudinal bars. After further assessments, coring through a finite number of longitudinal bars was permitted. However, the web stirrups could not be compromised and their spacing was verified by breaking out small inspection holes to ensure that they were not damaged during the coring operation.

Larger access holes to the inside of the box cells than originally planned were constructed to ease the difficulties with access and working in these confined spaces for long periods of time.

7 Quality Assurance Tests
In addition to the conventional material testing for concrete and steel a number of QA tests were undertaken for material quality and installation of CFRP. Material acceptance tests prior to the installation of CFRP included tensile strength, barcol hardness, and glass transition temperature. Samples were made on site during the installation and later tested in the laboratory and compared against the test results of the accepted materials. QA on installation included adhesion pull out tests, cure of resin observation, fibre orientation and delamination. The test results indicated that the material used and the installation of CFRP were to the expected quality and workmanship.

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