INTEGRAL BRIDGES USING PRECAST SUPER TEE BEAMS –
A CASE STUDY OF SH1 INTERCHANGE BRIDGE AT HOROTIU

PETER ROUTLEDGE, MICHAEL CHAN, PETER WILES
Opus International Consultants

SUMMARY

Integral bridges are recognised for their superior durability and lower long-term maintenance costs. As a result they are becoming increasingly popular throughout the world. The State Highway One Horotiu Interchange Bridge recently constructed as part of the Te Rapa Section of the Waikato Expressway is examined in detail in this case study. The paper outlines the project and development of the preliminary and detailed design. The benefits of integral construction are highlighted and aspects of the bespoke beam design are briefly discussed. It also highlights specific features of the case study solution which provided construction, economic and aesthetic benefits.

INTRODUCTION

The State Highway One (SH1) Horotiu Interchange Bridge is a road bridge recently constructed as part of the Te Rapa Section of the Waikato Expressway, located north of Hamilton in New Zealand. It is located between the two roundabout intersections which connect to the Te Rapa Section and the future Ngaruawahia Section, and carries four lanes of local road traffic over the Waikato Expressway.

The successful tenderer was Te Rapa Alliance, comprising of New Zealand Transport Agency (NZTA), Opus International Consultants and Fulton Hogan. They developed a solution using precast concrete SuperTee bridge beams with fully integral abutments and pier. This solution proved to be cost-effective in terms of both capital and whole of life costs and is also graceful in its appearance.

This paper is a case study of the SH1 Horotiu Interchange Bridge. The paper outlines the project and development of the preliminary and detailed design. The benefits of integral construction over simply supported construction are highlighted and aspects of the bespoke design of the beams are briefly discussed. Finally, the paper outlines the construction and highlights the economic and aesthetic benefits of the design.

THE TE RAPA SECTION OF THE WAIKATO EXPRESSWAY PROJECT

The Te Rapa Section is a spur of the Waikato Expressway, a staged project that will provide a continuous four-laned highway between Auckland and Cambridge, south of Hamilton, New Zealand. The Waikato Expressway is a NZ$1 billion plus project that will reduce congestion and shorten the travel time between Auckland and Cambridge by 20 minutes.

The existing State Highway 1 route takes traffic from Horotiu, through the industrial area of Te Rapa’ Park, passes the newly developed The Base shopping complex, along Avalon Drive and connects to the recently constructed Avalon Drive Bypass.
The proposed 7.3km route of the Te Rapa Section will take traffic away from the industrial/commercial area of Te Rapa Park, and eliminates the need for state highway traffic to travel through roundabout and signalised intersections. The route connects to the local roads via grade separated interchanges at Horotiu, Central Road and Gilchrist Road. The northern end of the route is to be connected to the future Ngaruawahia Section of the Waikato Expressway (see Figure 1).

Major bridge structures for the Te Rapa Project include the SH1 Horotiu Interchange Bridge, NIMTR Bridge, Central Interchange Bridge, Gilchrist Road Bridge and two local road underbridges. The NIMTR Bridge and Gilchrist Road Bridge are of steel-concrete composite construction, and other bridges will comprise of precast prestressed concrete beams. This paper will focus on the design and benefits achieved for the SH1 Horotiu Interchange Bridge.

The Te Rapa Project has been procured through a competitive alliance process for NZTA, a New Zealand government agency. The Te Rapa Alliance is the successful tenderer for the NZ$210 million project, comprising of NZTA, Opus International Consultants and Fulton Hogan.

**BENEFITS OF INTEGRAL CONSTRUCTION OVER SIMPLY SUPPORTED**

Integral bridge construction is becoming increasingly popular around the world as it offers several significant advantages including:

- Simply supported construction generally requires the bridge to be supported on bearings which enable the bridge to articulate. Bridge bearings commonly have an design life of 25 years, after which they may need to be replaced. Bearing replacement can be a costly and labour intensive exercise, potentially involving traffic management, hydraulic jacks and sophisticated machinery. Integral bridges eliminate the maintenance liability that bridge bearings impose. This minimises the whole of life cost for the bridge.

- The use of bearings implies the need for a bearing shelf which provides a ledge on which debris and water ponding can occur. This creates an environment which can be damaging to the concrete and makes inspection of the bearings and structure in the vicinity difficult. Integral bridges avoid the need for bearing shelves, completely eliminating such issues.

- Simply supported construction has traditionally required the use of movement joints although recent moves towards semi-integral construction mean this is not always the case. Nevertheless, the use of movement joints creates a maintenance liability and the need for joint replacement numerous times during the life of a bridge, requiring costly traffic management and disruption. Also, in spite of the best efforts to seal movement joints, there is a high probability of water ingress through them with the consequent adverse impact on the durability of structural components in the immediate vicinity. Integral abutments avoid the need for movement joints which improves the durability at the abutments and reduces whole of life cost.

- Simply supported bridges usually require longitudinal linkage bolts between the superstructure and the substructure to reduce the risk of span unseating under seismic events. This is a maintenance liability requiring inspection and potential replacement at some point during the life of the bridge. Integral abutments and piers avoid the need for linkages by tying the superstructure directly to the substructure. They also provide additional robustness during extreme seismic events.

- Simply supported bridges usually require shear keys to transfer transverse seismic loads from the superstructure into the abutments and piers. These are an additional element to be constructed which can be avoided through the use of integral construction.

- Integral construction provides the opportunity for improved aesthetics through the use of smooth clean lines without additional shear keys, ledges and gaps.
The specimen design for the SH1 Horotiu Interchange consisted of two 2-laned bridge structures spanning over the Waikato Expressway at a skew angle of 25 degrees and total length of approximately 60m. Six 1200mm deep SuperTee beams were utilised for each of the structures. The final alignment was optimised by the geometric designers, resulting in a single 4-laned bridge spanning over the Waikato Expressway at a minimal skew angle of 4 degrees and total length of 45m. The layout of the bridge was governed by factors such as Principal's Requirement to have spill-through abutments and over-dimension headroom clearance to the Expressway.

Several superstructure options were developed for the bridge during the tender phase, including steel ladder-deck structures, precast concrete hollowcore beams and a precast concrete SuperTee solution. In combination with the superstructure options, several options for the substructure were also developed and evaluated.

The precast concrete SuperTee superstructure option was selected as it provided the following benefits:
- The lowest total capital cost compared to other superstructure options, (see Table 1)
- Advantages in the whole of life analysis by adopting integral piers and abutments.
- A shorter lead time compared to structural steel, resulting an earlier switch over of SH1, which was the critical path
- A shallower structural depth compared to the structural steel ladder deck options, reducing the amount of embankment fill
- A lower number of beams compared to the precast concrete hollowcore option, minimising number of lifts and transportation
- Enhanced aesthetics and relatively slender appearance in comparison to the hollowcore and structural steel options. Aesthetics are important as this is the connection bridge between the Te Rapa Section and the future Ngaruawahia Section.

<table>
<thead>
<tr>
<th>No.</th>
<th>Option</th>
<th>Description</th>
<th>Rate per m² of deck area</th>
<th>Total cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>900SHC</td>
<td>Option F1 hollow core 900 deep with pad footings</td>
<td>$1,939</td>
<td>$1,785,000</td>
</tr>
<tr>
<td>3</td>
<td>SuperTees</td>
<td>Option F2 super tee 875 deep with pad footings</td>
<td>$1,744</td>
<td>$1,605,000</td>
</tr>
<tr>
<td>4</td>
<td>Steel</td>
<td>Option F3 1.95m deep steel beam on pads</td>
<td>$1,537</td>
<td>$1,414,000*</td>
</tr>
<tr>
<td>5</td>
<td>Steel</td>
<td>Option F4 1.5m deep steel beam on pads</td>
<td>$1,862</td>
<td>$1,714,000*</td>
</tr>
</tbody>
</table>

*Note these values do not include the cost of embankment fill, which would make the cost of the two steel options significantly higher

**Table 1** – Cost comparison of different superstructure options for SH1 Horotiu Interchange Bridge.

**DEVELOPMENT OF THE FINAL BRIDGE SOLUTION**

Refinement to the bridge solution was carried out by all engineering disciplines during the detailed design phase. One example was a raise in finished road level from the tender design due the safe sight stopping distance requirements. A slightly deeper SuperTee beam was adopted, increasing to 1000mm deep from 800mm from the tender design. This allowed the number of beams to decrease from 11 to 9 beams, hence reducing the number of lifts during construction and simplifying the congested integral connection. The final two-span bridge has a pier supported on three 900mm diameter concrete columns, and founded on nine and five 600mm diameter driven steel shell piles at the pier and abutments respectively.
DETAILED DESIGN OF THE SUPERTEE BEAMS

Use of Standard SuperTee Beams
The 2008 NZTA Research Report 364: ‘Standard Precast Concrete Bridge Beams’ provides standard superstructure designs using SuperTee beams for spans between 20m and 30m and for skews up to 15 degrees. These superstructure designs assume simply supported construction and therefore cannot be used directly for fully integral construction. Hence a bespoke design of the beams is required. However, the standard designs provide a useful starting point for the analysis and detailing. Furthermore, CAD drawings of the standard designs are available for easy modification of details to suit the particular circumstances of the project. The following sections briefly highlight some of the issues that need to be considered when undertaking the bespoke design of the SuperTee beams.

Partial Prestress Design
The standard beams in the above Research Report 364 are designed as cracked (Class C) prestressed (or partially prestressed) sections in accordance with NZS 3101 clause 19.3.2 and so for a bespoke design to be at least as efficient as the standard beam designs then partial prestress design needs to be used. Partial prestressing has less onerous serviceability limit state requirements than that required for Class U (uncracked) or Class T (transitional between cracked and uncracked) sections. It acknowledges that a degree of cracking is not detrimental to durability in a similar way to cracks in non-prestressed reinforced concrete sections. In the case of SH1 Horotiu Interchange Bridge, the site is situated inland so it has a relatively low risk exposure classification (Class A2) and the Principal’s Requirements allowed the beams to be designed as cracked.

The analysis of partially prestressed sections is more complex than that required for uncracked prestressed sections since the position of the neutral axis changes with the degree of bending moment applied. For serviceability design, the stress range in the prestressing and reinforcement steel after decompression of the concrete needs to be checked against codified limits. Road Research Unit Bulletin No. 69: Partial Prestressing in Concrete Bridges provides guidance on the analysis of partially prestressed beams. The analysis is further complicated in the case of SuperTee beams with a composite deck slab due to the strain discontinuity at the interface with the composite slab. Analysis of Cracked Prestressed Concrete Sections: A Practical Approach by Robert F. Mast provides a useful method of accounting for this in the analysis.

Temperature, Creep and Shrinkage Effects
Temperature, creep and shrinkage effects are often significant to both the superstructure and substructure of integral bridges. Stresses in all the elements were analysed using guidance on the creep and shrinkage properties of concrete from Road Research Unit Bulletin No. 70: Creep and Shrinkage in Concrete Bridges. Designing for these effects for an integral structure is a complex process compared to designing a simply supported structure and the relevant locked-in stresses are dependent on the final construction sequence adopted for the structure. In particular it was found that creep and shrinkage effects imposed significant flexural demand at the tops of the abutment piles.

Seismic Response
The structure resists longitudinal seismic forces by horizontal frame action between the superstructure and the piled foundations. This increases the stiffness of the bridge compared to an equivalent simply supported bridge which reduces displacements but increases the seismic loads required to be carried. However, since the piles develop double curvature the resistance of the piles is increased. This also imposes additional flexural demand on the beams which would not occur in simply supported construction and needs to be accounted for in the design of the beams and their connections into the abutments and pier.

Prestressing and Longitudinal Reinforcing
Integral construction enables reduced midspan bending demand due to continuity at the abutments and piers. In the case of SH1 Horotiu Interchange Bridge, this allowed the 1000mm deep SuperTee beams to require less prestressing strands than the Standard Precast Concrete Beam Detail (see Figure 2).
However, additional longitudinal reinforcing is required in the deck topping at the piers and abutments to resist the integral hogging moments, with the bars terminating with a hook into the abutment diaphragm beams. There may not be direct savings from prestressing strands and reinforcing quantities, but integral construction provides savings in the whole of life cost of the structure as mentioned earlier in this paper.

Figure 2 – The SuperTee beams for SH1 Horotiu Interchange Bridge (left) have six less strands than the Standard Precast Concrete Bridge Beam details (right).

Continuity Detailing
Continuity detailing, especially at the piers, had to be carefully considered to ensure reinforcing or strands coming out of the beams fit in the available space. The SH1 Horotiu Interchange Bridge beams had strands extending out of the ends and anchored into the in situ concrete at the pier cap. The size of the pier cap was governed by the anchorage length of the strands. Strands were selected for the integral connection as it was reasonably flexible to shift on site compared to large diameter reinforcing bars. The strands were locally unwound and splayed to improve the anchorage. Transverse Reid bars were connected into couplers cast into the precast beam, similar to the standard precast concrete bridge beam details.

Precast Barriers
The use of precast barriers was selected for the bridge, improving safety on site as it eliminated the need to use formwork and casting concrete barriers at the edge of the deck. The geometry of the precast barrier was developed with aesthetics in mind. This included a downstand which was detailed to conceal the joint between the precast SuperTee flange and the in situ deck. This detailing provided a smooth pre-cast finish along the whole length of the bridge viewing from the side and from the Waikato Expressway below (see Figure 3).
Barrier starters in the insitu deck were set out to avoid clashing with the precast barrier starters. When the precast barriers had been landed and set using shim pads and levelling mortar, a cast insitu stitch was poured connecting the barriers to the deck, providing the strength required for the Test Level 4 (TL-4) barrier loads. A non-structural footpath was then poured on top of a debonding membrane in between the barrier and the structural kerb on the northern side of the bridge.

**CONSTRUCTION**

The construction of this bridge was relatively straight forward. The ground was excavated to allow for the driving of the piles and ground improvement works at the abutment slopes. The pile capping beams, columns and crosshead were constructed next.

The 18 No. precast 1000mm deep Super Tee beams were cast in Stahlton yard in Auckland. The two bottom rows of prestressing strands were extended and cast into the pier crosshead and abutments to achieve a full integral connection.

One of the difficulties on site was avoiding clashes between the substructure reinforcing bars and the extended strands from the beams (see Figure 4). Some reinforcing had to be cut and lapped in order to land the beams to its position. Some of the diaphragm bar couplers also did not line up properly, resulting in a non-contact lap for the transverse bars and additional couplers being used, which was checked by the designer.
Once all the beams were landed, the in-situ deck was cast. The thickness of the deck was varied to achieve the final level for the road. Barriers starters were also cast into the deck, set out to line up with starters extending from the precast barriers. The precast barriers were then connected to the deck by an insitu stitch, and a non-structural footpath was then cast in between the barrier and the kerb.

The construction of the bridge began in November 2010 and was open to public in December 2011.

**CONCLUSION**

Integral bridge construction is becoming more common around the world. Many road controlling authorities specify that bridges under a certain length (commonly 60 metres) and skew (commonly 30°) should be designed as integral structures. Furthermore, the NZTA Bridge Manual Clause 4.7.1 (c) implies this should be the case for bridges designed in New Zealand. The whole of life and economic benefits of removing known maintenance issues from bridges on State Highway One, New Zealand’s major North to South route, are well documented.

A relative comparison for the per m² rate of the physical bridge construction costs in the Te Rapa Section (see Table 2) is evidence that well-designed integral structures can provide the lowest capital cost solution as well as the optimum whole of life solution.
<table>
<thead>
<tr>
<th>Bridge</th>
<th>Description</th>
<th>Cost per m² ($/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SH1 Horotiu Interchange</td>
<td><strong>Fully integral</strong> 45m two-span SuperTee bridge on a 4° skew</td>
<td>1,816</td>
</tr>
<tr>
<td>NIMTR</td>
<td>Simply supported 150m four-span steel beam and concrete slab structure on a 61° skew.</td>
<td>2,585</td>
</tr>
<tr>
<td>Central</td>
<td>Simply supported 64m four-span Double Hollow Core on a 33° skew</td>
<td>2,615</td>
</tr>
<tr>
<td>Te Kowhai</td>
<td>Simply supported 41.5m three-span Single Hollow Core with composite concrete deck</td>
<td>2,130</td>
</tr>
<tr>
<td>Local</td>
<td>Simply supported 40m three-span Single Hollow Core with composite concrete deck</td>
<td>2,295</td>
</tr>
<tr>
<td>Gilchrist</td>
<td><strong>Fully integral</strong> 60m two-span steel ladder deck bridge on a 24° skew.</td>
<td>2,255</td>
</tr>
</tbody>
</table>

**Note:** Physical bridge construction costs only – no allowance for P&G or approach formation included

Table 2: Construction Cost Rates for Te Rapa Bridges

The SH1 Horotiu Interchange bridge has demonstrated that SuperTee beams can be used effectively in fully integral construction. Due to the significant interaction between the superstructure and the substructure, a standard design is not possible and thus the standard NZTA bridge designs cannot be used directly. For integral bridges a bespoke design is required and such design is complex compared to that required for simply supported construction. However, this paper has highlighted that there are cost and durability benefits in using integral construction despite the additional design effort required. The non-standard design approach also provides the opportunity to economise the design solution whereas the standard NZTA bridge designs economise on the design effort but possibly at the expense of construction economies. In the case of SH1 Horotiu Interchange Bridge, the bespoke design ameliorated the overall beam depth to a site specific solution, hence offering increased economy for the approaches.

The final solution for SH1 Horotiu Interchange Bridge is a magnificent example of a well-designed and constructed integral bridge structure. The structure is robust and simple to construct, with bridge completed on time and on budget. The final result is also an aesthetic bridge that signals the transition to the Te Rapa Section of the Waikato Expressway (see Figures 5 and 6).
Figure 5 and 6 – The final bridge solution is cost-effective, relatively simple to construct and robust whilst being aesthetically pleasing.