New Standard Bridge Beams for New Zealand

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SYNOPSIS

This paper outlines the development of a new range of standard concrete bridge beams for the New Zealand Transport Agency (formerly Transit New Zealand and Land Transport New Zealand) to be used in the roading industry in New Zealand. The beams have been developed under a research project that culminated in the design of a range of standard beams for road bridges. These beams replace standard beams that were developed by the Ministry of Works in the 1970’s.

The development of the beams has been undertaken by Beca Group Ltd (Beca) and Opus International Consultants Ltd (Opus) in conjunction with Precast New Zealand. This team was awarded the project to research and develop the new standard beams in 2002.

This paper describes the various project stages and how a small number of beam types were selected for detailed design and production of standard details that could be readily used by bridge designers to reduce the design effort for individual bridges, and allow standard formwork systems and details to be adopted by beam manufacturers. It describes how detailed construction drawings and specifications were developed for publication.

The beam design included application of partial prestressing for standard bridge beams which ensured that cost effective state of the art solutions were developed that fully met the requirements of NZS 3101 – Concrete Structures Standard, and the Transit New Zealand Bridge Manual.

This paper presents an overview of the beams that have been developed and that are now available for use by industry from the New Zealand Transport Agency website.

1. INTRODUCTION

The New Zealand Transport Agency (as predecessor organizations Transfund New Zealand and later Land Transport New Zealand) commenced a research project to research and develop a new range of standard concrete bridge beams for the New Zealand roading industry in 2002. The intent of the project was to replace the range of standard bridge beams developed in the 1970’s by the former Ministry of Works that had become out of date with respect to international best practice and design standards in New Zealand.

Beca and Opus together with Precast New Zealand proposed the research project to the New Zealand Transport Agency and subsequently commenced the project in two stages, namely:
• Stage 1 – Identification of new standard beam shapes
• Stage 2 – Detailed design and preparation of construction drawings for selected beam shapes

Stage 1 of the project, which was completed in 2003 comprised a number of distinct activities to identify the most suitable beam shapes for use in New Zealand. Stage 2, which commenced in 2006, included the detailed analysis and design of the prestressed beams and production of construction drawings and specifications that would allow the beams to be readily used by bridge designers. The start of the design stage was delayed by the introduction of a new version of the New Zealand concrete design code NZS 3101 and by changes to the Transit New Zealand Bridge Manual. This stage was completed in 2008 with a two tier verification process for the designs.

The paper describes the key project stages, the challenges faced and provides an overview of the new bridge beams that are now available for use by bridge designers from the New Zealand Transport Agency website.

2. THE PROBLEM

The standard bridge beams developed by the Ministry of Works in the 1970’s were highly successful and became the standard for nearly all short and medium span highway bridges constructed in New Zealand up until the early 2000’s. The beams provided a range of shapes including single, double and triple hollow core beams for short spans up to 20m, and T-beams, I-beams and U-beams for medium spans up to 32m. The designs covered a range of deck widths with and without footways and provided fully detailed prestressed beams, composite deck slabs and connection details to piers and abutments, as well as different types of edge barriers. The designs became widely used across the whole industry including consultants and local authorities as well as the Ministry of Works. They were published in the well known “Blue Book”.

By the current decade the designs had become out of date, and whilst they had proved to be both economic and reliable, design standards in New Zealand had changed, the Transit Bridge Manual had new requirements and new more economic and buildable shapes were starting to enter the market. Of particular concern were the durability issues related to transverse stressing of hollow core beams and the cover provided to I-beams, but there were other issues related to increased deck widths, higher standards for edge protection and the introduction of partial prestress design that also needed to be addressed. It is also worth noting that by this time a significant number of the beam types in the “Blue Book” had fallen into disuse with only the single and double hollow core, I-beam and U-beam decks remaining popular.

New beam shapes that were entering use in New Zealand included a single hollow core deck unit with rectangular void and the Super-T beam and T-Roff beams which had been developed in Australia, all of which offered economic and buildability advantages.
These issues led to the proposal to research and design a new range of standard bridge beams and this was fully supported by government and industry which were enthusiastic for more up to date designs that would standardise the new beam shapes that were entering the market.

3. BEAM SELECTION PROCESS

General
The first stage of the project, to identify new beam shapes for design, included looking beyond New Zealand to ensure that the most suitable beams were adopted and a comprehensive process of industry consultation to ensure that bridge designers, constructers and beam manufacturers views were captured. The process also looked at the current beams being manufactured in New Zealand and availability of precast mold shapes to ensure that the beams selected would suit industry’s capacity to manufacture beams without major investment in new forms and casting beds.

Once beams had been selected for consideration analysis of the shapes was undertaken to assess their efficiency and cost effectiveness. Beam types were selected for preliminary design, and cost estimates prepared and economic analysis undertaken. Final beam shapes were then recommended for detailed design.

Review of Current New Zealand Practice
This first step looked at current New Zealand practice to confirm the problems identified by the research team and gain a better understanding of the issues to be addressed. This confirmed that the changes of design standards to be addressed related to:

- Increased durability requirements
- Changes in bridge widths
- Enhanced edge protection
- Changes to bridge design live loading
- Changes to design criteria

Other issues to be addressed were identified as:

- Reflective longitudinal cracking in surfacing on some bridges above longitudinal joints between double hollow core beams
- Problems during manufacture of voided slabs due to void flotation in wet concrete
- Health and safety concerns in erecting permanent formwork between widely spaced I-beams
- Economy of current designs for longer span ranges (typically >25m).

The review also identified that in addition to the Ministry of Works beam shapes, new beam shapes that were being used on a project by project basis, were:

- Hollow core deck units with a single rectangular void for spans up to 25m
- Super-T and T-Roff beams developed in Australia
- A variety of beam shapes and refinements that individual beam manufacturers had developed.
Literature Search of Current International Practice
The literature search focused on countries with a similar approach to bridge construction to that in New Zealand, namely:
• Australia – due to proximity and similar traffic loadings
• United Kingdom – due to the wide range of shapes available and new shapes recently adopted
• North America – due to similar traffic loadings and new beam shapes recently developed by some states.

The findings of the search were that Australia was the most relevant country to compare beam shapes with not only due to its geographic proximity but also because of the similar approaches to bridge construction, similar environmental conditions, common design standards and the scale of the industry. The United Kingdom had developed new beam shapes but with the differences in design loading, materials, design codes and longer span lengths related specifically to motorway widening projects, the relevance to New Zealand was limited. Similarly, North America had developed beams that were suited to their particular conditions resulting in a wide range of beam shapes some of which were too long and heavy for New Zealand conditions.

Survey of New Zealand Precast Bridge Beam Manufacturers
The survey was aimed at collecting data on recently constructed highway bridges in New Zealand to determine trends in beam shapes and deck shapes over the previous 5 years.

Survey results were obtained from ten precast beam manufacturers, six in the North Island and four in the South Island. Data was collected on 102 recently constructed bridges covering six types of beams. The findings of the survey were:
• The majority of responses indicated the popularity of double hollow core bridge decks in all regions
• Single hollow core deck units were popular in two regions
• I-beams and U-beams were being used for longer spans, but were used less than double hollow core deck units
• Single core beams with a large rectangular void was used on specific projects.

Industry Consultation
Industry consultation took the form of an industry group with representatives of client organizations, consultants, contractors and precasters, and consultation workshops that were held in Wellington, Auckland and Christchurch.

The workshops presented the early findings of the project, discussed current issues with standard beams and ranked them, identified important criteria for selection of new beam shapes and allowed participants to vote on their preferences for new beam shapes.

The issues highlighted by consultation were:
• A preference for full superstructure designs including deck and edge protection, not simply standard beam shapes requiring detailed design on a project basis
• Reflective longitudinal cracking in hollow core decks to be addressed
• Designs to recognize trends to continuous decks with minimal joints
• Minimising joints to improve ride quality and reduce maintenance
• The need for flexibility in design to accommodate curvature, skew and superelevation
• Designs to include new edge protection standards

The results of the poll on preferred beam types were:

<table>
<thead>
<tr>
<th>Beam shape</th>
<th>Number of votes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double hollow core</td>
<td>25</td>
</tr>
<tr>
<td>Single hollow core</td>
<td>5</td>
</tr>
<tr>
<td>I-beam</td>
<td>6</td>
</tr>
<tr>
<td>U-beam</td>
<td>3</td>
</tr>
<tr>
<td>Super-T/T-Roff</td>
<td>22</td>
</tr>
<tr>
<td>Double-Tee</td>
<td>1</td>
</tr>
</tbody>
</table>

*Figure 1: Survey Results of Preferred Beam Types*

On the basis of the poll results, it was determined that retention of the double hollow core deck units and the I-beams were preferred from the existing beam shapes with the Super-T/T-Roff beams from Australia preferred as a new beam shape.

**Analysis of Research Results**

The analysis of the research results identified the following preferred beam shapes:
• Hollow core deck units 1144mm wide with either double circular voids or a single rectangular void for spans up to 18m
• Hollow core deck unit for spans up to 25m with void shape to be determined (either twin circular voids or rectangular)
• Existing I-beams retained for spans up to 32m, updated for changes to design standards
• Super-T beams for spans up to 30m.

**Preliminary Design of New Beam Shapes**

The preliminary design focused on establishing the criteria to be adopted for design of the new beam shapes and confirming the dimensions and details of the beams and the associated deck slabs, edge barriers and connection details. The design criteria are described in section 4 below.

Key issues addressed in the preliminary design of the new beams were:
• Span range and beam depths for each beam shape
• Width of hollow core deck units and spacing of I-beams and Super-T beams
• Void shape to be used for hollow core deck units – circular or rectangular
• Material strengths – concrete grades, strand types
• Whether to use transverse prestressing or reinforced overlays to hollow core decks to provide transverse capacity
• Edge protection requirements – type and test level for barriers
• Improvements to details of longitudinal joints between hollow core deck units to improve load transfer
• Durability and maintenance issues such as exposure conditions, concrete cover and materials.

The assessment of the void shape to be used for the hollow core deck units adopted the Guyon Ratio (P) to assess structural efficiency:

\[ P = \frac{r \times r}{y^t \times y^b} \]

where \( r \) is radius of gyration and \( y^t \) and \( y^b \) are depths from neutral axis to top and bottom flanges.

The Guyon Ratio confirmed that the rectangular voided slab was more structurally efficient than the twin circular voided slab and that it required less material to achieve the same load capacity, and hence should be adopted for detailed design.

**Cost Estimates and Economic Analysis**

Costs for the proposed beam shapes were assessed using historical cost data obtained from recent New Zealand projects reduced to cost per square metre of bridge deck, as follows:

<table>
<thead>
<tr>
<th>Beam Type</th>
<th>Span range</th>
<th>Cost of bridge deck NZ$/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hollow core deck</td>
<td>Up to 18m</td>
<td>$500 to $600/m²</td>
</tr>
<tr>
<td>units</td>
<td>18m to 25m</td>
<td>$600 to $700/m²</td>
</tr>
<tr>
<td>I-beams</td>
<td>Up to 32m</td>
<td>$400 to $900/m²</td>
</tr>
<tr>
<td>U-beams</td>
<td>Up to 26m</td>
<td>$700 to $900/m²</td>
</tr>
<tr>
<td>Super-T beams</td>
<td>Up to 30m</td>
<td>$750 to $850/m²</td>
</tr>
</tbody>
</table>

*Figure 2: Cost Estimates*

It was concluded that hollow core deck units were cost effective for shorter span bridges and that the I-beam and Super-T beams were cost effective for medium span lengths up to 32m. U-beams were confirmed to be more expensive than other beam types and were discounted from further consideration.

**Beams Selected**

The final beam shapes selected for detailed design to the criteria below were:

• 587mm deep double hollow core beam with circular voids for spans up to 14m (existing beam to be updated)
• 650mm deep hollow core beam with rectangular void for spans up to 18m (new beam)
• 900mm deep hollow core beam with rectangular void for spans up to 25m (new beam)
• 1500mm and 1600mm deep I-beams for spans up to 20m and 24m (existing beams to be updated)
• 1025m and 1225m deep Super-T beams for spans up to 22m and 30m (new beams).
4. DESIGN CRITERIA

It was determined that the new beams should be designed for criteria that would give the widest possible use and that were typical of new bridges being constructed in New Zealand. The criteria adopted were:

- Two lane rural highway bridge without footways with an overall deck width of 10.35m allowing for two 3.5m traffic lanes, 1.2m wide shoulders and concrete Test Level 4 barriers
- Single span simply supported bridge
- 100 km/h design speed
- Live loading HN-HO-72 with serviceability live loading factor of 1.35 as Transit Bridge Manual amendment
- Design to Transit New Zealand Bridge Manual including September 2004 and December 2004 amendments
- Design to NZS 3101:2006 – Concrete Structures Standard\(^1\) and NZS 3109:1997 – Concrete Construction
- Durability Class B2 for coastal perimeter and coastal frontage to NZS 3101:2006
- Square span that can be used for skews of up to \(15^0\)
- Partial prestress (cracked section) analysis of beams to NZS 3101 to give economic solutions.

5. DESIGN PROCESS

Designs were undertaken by Beca and Opus with each designing some of the new beams and alternating the verification of the designs. Due to the importance of the designs a second independent verification was undertaken for all beams by URS New Zealand Ltd.

The designs were limited to the bridge superstructure only and excluded substructures, bearings and seismic aspects of the design which need to be assessed on a project basis.

It was recognized that design liability for the long term and repetitive use of the designs was an issue that needed to be addressed in order to limit the liability for their use with respect to both the New Zealand Transport Agency and the designers. The solution was to make the designs available for use at the risk of the user. This requires each designer using the standard designs to satisfy themselves as to their suitability for use on particular project. The results of the research project are available on the basis that New Zealand Transport Agency and its designers exclude all liability for use of the designs by third parties.

6. DESIGN CHALLENGES

Partial Prestress Design
The design of the beams using a partial prestressing approach was a particular challenge as partial prestress had only limited application in New Zealand bridges.

Partial prestressed concrete member design was undertaken in accordance with chapter 19 of “Concrete Structures Standard, NZS 3101-2006. Staged construction was accounted for in the SLS design. For SLS conditions, the beams were designed for zero tension under permanent loads, and cracking of concrete was permitted in the tension face for short term loads with change in steel stress limited to the code values of 150 MPa for load combination 1A and 200 MPa for combination 4.

Long-term steel and concrete stresses were calculated by the “Modified Effective Modulus” methodology as outlined in Appendix CE of NZS3101. The concrete section was then modelled in the software “Response 2000”. The long-term steel and concrete stresses were applied to the non-composite concrete section. The top slab was then added with the strain discontinuity at the interface between the beam and top slab. Loads due to finishes were applied to the composite section and stresses in tendons and reinforcement bars were recorded. Live load was then applied and the change in stress between this step and the previous step was checked for compliance with the maximum stress range permitted in the code.

An in-house spreadsheet, based on moment curvature response of pre-stressed concrete sections, was developed for this project. The spreadsheet used a “method of slices” to solve the section. The in-house spreadsheet has been benchmarked against Response 2000 with very good correlation achieved.

Transverse Design of Hollow Core Beams
A significant challenge for the project was achieving a practical design that overcame the problem of cracking of longitudinal joints that has occurred with existing hollow core beam bridges under normal service conditions. This cracking is considered to be a maintenance and durability issue for some existing bridges with reflective cracking through surfacing and potential water ingress. To prevent cracking at the longitudinal joints sufficient transverse prestress has been provided so that the section will not crack under service conditions. In addition to the transverse prestress, the shear key shape and detailing has been enhanced to provide a better vertical shear connection between beams and a double corrosion protection system has been provided for transverse stressing to protect the stressing in the event that water penetrates the longitudinal joints.

The transfer of the increased vehicle impact load from the rigid Test Level 4 barriers to the bridge deck has resulted in a significant increase in torsion demand for the outer beams of the deck as the deck must be designed for 120% of the barrier design loads to provide capacity for barrier overstrength. The torsional capacity of the precast units and the transverse prestress together resist the barrier overstrength moment at the ultimate limit state. As a result, the outer hollow core beams have a significant increase in the quantity of torsion reinforcement compared to the inner beams.
As with the existing double hollow core units, a solid section at the outer edge of the deck has been provided for the fixing of barriers and the anchorage of transverse prestressing. This also provides a measure of robustness against the barrier impact loading.

**Buildability**

The design of the beams follows extensive consultation with the construction industry. One of the most important outcomes of this consultation was to ensure that buildability issues were properly considered in design, as summarised below:

- Concrete strengths have been selected on the basis of the maximum strength and cycle times preferred by the precast industry. A 28-day concrete strength of 50 MPa has been adopted with a prestress release strength of 30 MPa.
- Reinforcement and prestressing steel has been chosen to conform to the grades available locally and normally stocked by the precast industry. Grades of reinforcement conform to AS/NZS 4671 and pre-stressing to AS/NZS 4672.
- Prestressing strand adopted as the basis of the designs is the size commonly stocked by the precast industry (15.2mm and 12.7mm diameter super-strand with minimum breaking loads of 250 kN and 184 kN).
- Super-T beams are inherently stable during construction and have a low site formwork demand compared to I-beams.
- Single rectangular hollow core voids are formed using a reusable collapsible form.
- Double hollow circular core void formers are left in place (sacrificial).
- New torsion reinforcement detailing is provided to hollow core beams to mitigate buildability problems encountered with the previous designs.
- I-beams allow a variable height pap to enable construction of curved bridge decks.
- The new I-beams are pre-tensioned only, with post tensioning not required, which reduces on site activities.
- Super-T beams do not require formwork for deck construction and width of outstand flanges can be varied to suit deck width and tapered or curved decks.

**Design for Durability**

The durability requirements of NZS 3101:2006 have been applied with designs generally accommodating exposure conditions commonly encountered within the New Zealand state highway network. This equates to B2 exposure environment, providing for most bridges including those sited in the coastal perimeter and coastal frontage zones (which can extend 0.5 km inland). Bridges crossing saline estuaries or near the sea falling into exposure category C, require a substantially increased level of cover concrete and are not catered for in these designs.

Increased cover demands from the above requirements mean that I-Beams have been provided with increased cover, and thicker webs are required compared to existing designs. The reinforcement detailing of double hollow core units has also been revised to provide the necessary increase in cover to reinforcement.
7. THE BEAMS

Beams Depths and Span Ranges
The beam depths and span ranges for the new standard bridge beams are shown in the table below:

<table>
<thead>
<tr>
<th>Beam type</th>
<th>Beam depth (mm)</th>
<th>Span (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>12</td>
<td>14</td>
</tr>
<tr>
<td>Double Hollow Core Beam</td>
<td>587</td>
<td></td>
</tr>
<tr>
<td>Single Hollow Core Beam</td>
<td>650</td>
<td>900</td>
</tr>
<tr>
<td>I-Beam</td>
<td>1500</td>
<td>1600</td>
</tr>
<tr>
<td>Super-T Beam</td>
<td>1025</td>
<td>1225</td>
</tr>
</tbody>
</table>

*Figure 2: Beam Depths and Spans*

Deck Cross Sections
The standard deck cross section adopted is shown with Super-T beams in Figure 3.

*Figure 3: Deck Cross Section*

Beam Shapes
The new standard beam shapes are shown in Figure 4.
Figure 4: Beam Shapes
8. CONCLUSIONS

The new standard precast bridge beams are the culmination of five years of research, consultation and design carried out under a research project awarded to a team comprising Beca, Opus and Precast New Zealand.

The project team undertook extensive research into current New Zealand practice for the design of standard precast concrete bridge beams for use in roading bridges, investigated international practice for bridge beams covering Australia, United Kingdom and North America, developed options for new standard bridge beams and consulted with industry to determine their needs and preferences.

A range of new bridge beams were then selected for detailed design covering spans up to 30m. Criteria were developed for the design of the new beams which were fully designed and detailed ready for use by bridge designers, requiring only substructures, bearings and seismic aspects to be addressed in detail.

The new standard bridge beams provide full construction details for the superstructures of single span bridges with spans up to 30m spans with two 3.5m wide traffic lanes, 1.2m shoulders and Test Level 4 concrete edge barriers. The designs comply with the Transit New Zealand Bridge Manual and NZS 3101:2006 and utilise partial prestressing.

The new standard precast concrete bridge beams were published by the New Zealand Transport Agency in December 2008 and are available from the website.

9. ACKNOWLEDGEMENTS

The authors would like to acknowledge the New Zealand Transport Agency for permission to publish this paper and for their ongoing support to this project.

They would also like to thank all the contributors to this project who have greatly assisted in reaching a successful outcome, including the various members of the design teams in Beca and Opus, the independent verifier URS New Zealand Ltd, Precast New Zealand and the industry working group and those who participated in the industry consultation.

10. REFERENCES

3. Standards New Zealand, 2006, NZS 3101 – Concrete Structures Standard