Post-tensioned tee-roff beams made with self compacting concrete.

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7th Austroads Bridge Conference, Auckland, New Zealand, May 2009
**Biography**

Tracy Joseph is a Senior Structural Engineer at URS New Zealand Limited. In recent years Tracy has specialised in bridge design. On her most recent project, Tracy was the main structural designer for the Chapel Street Viaduct. This bridge is the subject of her paper.

**Synopsis**

Chapel Street Viaduct is the largest of the bridges on the Tauranga Harbour Link (THL) Project. It is some 560m long and 40m wide at its widest point. Stage 2 of the THL project, which includes Chapel Street Viaduct, was tendered and let as a Design and Construct project in 2007. The successful bid utilised post-tensioned tee-roff beams made with self compacting concrete. This is the first time post-tensioned tee-roff beams have been used in New Zealand and it is also the first major application of self-compacting concrete bridge beams in New Zealand.

Chapel Street Viaduct crosses over two major roads, one minor road and a railway. To overcome these obstructions and numerous site constraints the optimum pier spacing was determined as approximately 35.5m. This is a little beyond the normally accepted limit for 1500mm deep tee-roff beams with conventional pre-tensioned strand. Therefore the solution was to design the beams with a mixture of pre-tensioned strands and post-tensioned tendons. This combination optimised the beam design while still allowing daily casting cycles in the precast yard.

Self compacting concrete (SCC) has been used for the manufacture of all the tee-roff beams on Chapel Street Viaduct. Although the material cost is a little more than normal bridge beam concrete, savings come from the speed of concrete placement and the elimination of labour requirements for concrete vibration. This paper discusses the technical challenges faced during the design of the tee-roff beams for Chapel Street Viaduct.
Introduction

Chapel Street Viaduct (CSV) forms a critical part of the Tauranga Harbour Link Project connecting Takatimu Drive to Tauranga Harbour crossing. The viaduct comprises a 4-lane elevated portion of roadway crossing three roads, a railway corridor and an industrial area in central Tauranga. It is approximately 560m long and 40m wide at its widest point and has three ramps connecting to the surrounding roads. The longest of these ramps, Mirrielees Eastbound off-ramp, is approximately 280m long.

Site constraints including those listed above created a complex geometrical alignment that required longer than normal span lengths for a relatively shallow (available) structural depth. Various conventional arrangements were considered but quickly discounted due to cost and time penalties. The optimal solution that was chosen was to modify a conventional pre-tensioned open top super tee beam (also known as tee-roff beam). A post-tensioned tendon was added to each beam along with small modifications to the typical cross section. This enabled an increase in both the span capability and overall width of each beam. It also allowed greater flexibility to accommodate the required edge curves and variation in carriageway widths.

With over 170 beams required for the viaduct, fabrication of the beams had major time and cost implications. The use of high strength self compacting concrete (SCC), with accelerated curing techniques, allowed a daily casting cycle for beam manufacture. This also reduced the need for vibration of concrete and improved the speed of concrete placement.

The addition of the post-tensioned tendon in the beams and use of high strength SCC for beam fabrication had major benefits for both the geometric design and the construction programme. This paper discusses the technical challenges faced during the design of post-tensioned tendons and high strength self compacting concrete in tee-roff beams.

Background

Tauranga Harbour Link (THL) Project- Stage Two is a design build project administered by the New Zealand Transport Agency. Fletcher Construction Company Limited is the Constructor with URS New Zealand Limited as their lead Designers.

THL stage 2 is the second stage of the construction work to create a 4 lane expressway through Tauranga and Mount Maunganui. It connects the existing expressway along Takatimu Drive, Tauranga to the end of the THL stage 1 section at Hewletts Road, Mount Maunganui. Stage 2 comprises of the construction of 4 road bridges, these being the New Harbour Bridge, Chapel Street Eastbound Offramp Bridge, Aerodrome Bridge and Chapel Street Viaduct (CSV), the associated embankments and roadways connecting the structures, as well as raising an existing pedestrian overbridge on Takatimu Drive. Figure 1 shows an overall plan of the THL stage 2 project with CSV on the left hand side of the figure.
The CSV superstructure is constructed with precast concrete pre-tensioned and post-tensioned tee-roff beams with a cast insitu reinforced concrete deck composite with the tee-roff beams. The beams are simply supported spanning between pier lines. Pier lines consist of reinforced concrete pier beams on reinforced concrete columns and piles. There are expansion joints at all abutments and at 3 locations along the length of the bridge, dividing the bridge into 4 sections. Seismic resisting systems at the joint locations consist of a series of reinforced concrete shear keys, seismic dampers, loose linkage systems at the abutments and mechanical bearings.
Overall, the structure consists of 17 spans along the mainline, 9 spans on the Mirrielees Eastbound Off-ramp and 2 spans on both the Chapel Street Eastbound On-ramp and Chapel Street Westbound Off-ramp. Refer to Figure 2 for a general layout of the viaduct.

The layout of the constraints and obstructions at ground level largely dictated the pier set-out. An optimal pier layout of approximately 35.5m spacing was developed with the exception of the span over Chapel Street. A 37.5m spacing of pier support lines was required over Chapel Street in order to achieve the specified lateral roadway clearances between pier supports under the viaduct. Larger hammerhead piers with pier beams approximately 4m wide were developed for the two pier support lines either side of Chapel Street. The typical pier spacing along with the hammerhead piers at Chapel Street enabled the maximum beam span of 34m (bearing to bearing) to be achieved.

Minimising the number of beams required for the viaduct had significant benefits for costs and the programme for the project. To reduce beam numbers, the beam layouts across each span were optimised with a maximum beam width of 3.5m.

A standard conventional pre-stressed 1500mm deep tee-roff beam can typically span up to 32m with an overall maximum width of approximately 2.8m. This fell a little short of the required span parameters. Increasing the beam section to the next standard beam size of 1800mm increased the overall structural depth and this had significant implications to the geometric design throughout the entire project as well as other implications such as additional materials, production cost and lifting weight per beam. Modifications to the standard 1500 deep tee-roff section allowed a 1525mm deep x 3500mm wide tee-roff beam to be utilised for CSV. Not only did this help minimise overall structural depth, it also lessened the volume of concrete per beam which in turn limited the overall self weight of the beams for transportation, lifting and substructure design.
Design

The tee-roff beams were designed in accordance with Transit New Zealand Bridge Manual\(^1\), NZS3101\(^2\) and AS5100\(^3\). The beams were modelled in RM2006 software\(^4\) which takes into account the various stages of construction and the time dependant effects on the individual components and on the whole composite beam. Time dependant effects were based on guidance in RRU Bulletin 70\(^5\).

The standard type ‘T4-2’ 1500 deep tee-roff section from AS5100.5, Appendix H\(^6\) was the basis for the design of the beams. The beam cross section was modified to have 100mm thick top flanges throughout, 150mm web thickness in the end zones, a single 31 strand post-tensioned tendon was added in the bottom of the section and a tapered bottom flange adjacent to the end block was added to allow for raising the tendon anchorage to near to the beam neutral axis. EHT (Extra High Tensile) low relaxation strand (15.7mm diameter) was used for both post-tensioned and pre-tensioned strands. A concrete compressive strength of 60MPa was utilised in the design with the minimum of 40MPa required prior to the pre-tension load being applied and 60MPa required prior to the post-tension load being applied. Figure 3 shows the standard cross-section from AS5100.5 and the modified section used for CSV.

![Standard and Modified Tee-Roof Sections](image)

**Figure 3: Tee-roff cross-sections**

The 15.7mm diameter EHT pre-tensioned strand enabled slightly higher stressing loads but was insufficient to gain an extra 2m span length and 0.6m width. The post-tensioned tendon was introduced near the bottom of the beam to enable the span to be increased to the required length as it introduced significantly larger compression stresses into the section.

For simply supported beam design the larger stresses were beneficial at mid-span as

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2 NZS3101, Concrete Structures Standard. The 1995 edition was used for material design with the durability requirements as set out in 2006 edition.
3 AS 5100:2004 Australian Standard, Bridge Design
4 RM2006 is a 4D static and dynamic design and analysis package used for bridge design.
6 AS 5100.5:2004 Australian Standard, Bridge Design Part 5:Concrete
the high compressive forces generated by the pre-stressing and post-tensioning
counteract the tensile forces generated from the mid-span bending moments, both
under dead load and live load. However at the ends of the beam where there is little
or no bending moment the high compressive forces needed to be accommodated in
the reinforced concrete section.

For the CSV beams the post-tension tendon was straight along the bottom of the
beam for the majority of the length and curved over the length of the end block. This
allowed the centre of the tendon to be closer to the neutral axis of the section at the
end of the beam, as shown in Figure 5, and therefore the compressive forces from
the addition of the post-tension tendon to be more evenly distributed within the end
block.

Staged construction of the beam stressing sequence was designed to allow optimal
use of concrete strength gain to counter balance the applied stresses. After the
beams were cast, the pre-tension load was applied at 40MPa concrete compressive
strength. The beams could then be removed from the mould and cured for a further
28 days or until 60MPa concrete compressive stress was achieved. Once 60MPa
compressive strength was achieved the post-tension load could be applied.

Due to the complex geometry of the viaduct almost every tee-roff beam varied in
length, width and end skew. The alignment was such that uniformity between beams
was nearly impossible and the detailed design needed to be flexible enough to
accommodate as many beams as possible without potentially overstressing the
beams during the construction stages. Two reinforcement arrangements were
developed along the length of the beam. Typically these were governed by shear and
torsion requirements.

Design of the pre-tensioned strand and post-tensioned tendon arrangement was
more complicated due to the stress variations along the beam and variation in
demand during the various stages of construction. For the pre-tensioned strand,
three debonding arrangements were used and for the shorter beams, with no post-
tensioned tendons, the number of pre-tensioned strand varied. The post-tensioned
tendon was typically a 31 strand tendon in a 118mm diameter steel duct, however
variations in the number of strands in the tendon were used for the beams with lower
demand.

End block design

The design and detailing of the beam end block proved to be complex. The effective
cross-section of the beam was relatively small compared to the magnitude of the pre-
tension and post-tension loads applied and a large amount of confinement and anti-
splitting reinforcement was required to control the bursting forces generated by the
anchorage and to distribute the forces into the beam.
In some locations the beam geometry resulted in a high end skew on the beams (end skew in excess of 40 degrees) while the post-tensioned tendon anchorage needed to be perpendicular to the beam centreline. This was overcome by effectively ‘squaring off’ the ends for the beams while leaving the top flanges skewed to match the piers at each end, as shown in Figure 5.

Other aspects that complicated the design included the beam end geometry being unique for almost every beam and due to the introduction of the post-tensioned tendon there was limited space for fixings for mechanical pot bearings under the end blocks.

Figure 4: End block reinforcing

Figure 5: Tee-roff end block and end skew arrangement
**Flange modifications**

Increased width requirement of the beams meant that the standard 75mm thick top flange did not have sufficient capacity during the construction stages to carry the cantilever loads into the main body of the beam. The flange thickness was increased by 25mm to 100mm total thickness to accommodate the higher loads. This also had the added benefit of increasing the section modulus and therefore the ability to accommodate the stresses from the pre and post tensioning in the section. Shear lag effects were sufficiently small so that the whole section contributed to the strength.

**Web modifications**

With an increased span and width, the beams attracted a considerably higher load than a standard 1500mm deep beam and the resultant shear forces in the end regions were much larger. Based on a 100mm thick web section the shear stresses generated in the end regions exceeded the maximum shear stress limitations in the Concrete Structures Standard. The solution was to increase the web thickness to 150mm which gave greater concrete shear capacity and allowed more width to place larger bars. The increased web thickness was only implemented over the critical section in order to keep the over beam weight down.

**Self Compacting Concrete**

The use of SCC in the design process is very similar to traditional vibrated concrete. The Concrete Structures Standard, NZS 3101 allows SCC to be designed using the same rules as conventional concrete. One notable exception is the value used for the co-efficient of thermal expansion. The standard suggests that this is normally 10% to 15% higher than conventionally placed concrete. NZS3103:2006 gives guidance on the co-efficient of thermal expansion that should be used for self compacting concrete. For CSV the beams were designed with a co-efficient of expansion taken as $10.5 \times 10^{-6}/^\circ\text{C}$ based on a greywacke aggregate type being used.

The cement content and the water/cement ratio in the SCC were kept within low to normal ranges in order to help control creep and shrinkage of the beams. Mix designs were tested for creep and shrinkage in accordance with AS 1012. Results from these tests are reported in a companion paper titled “Creep & shrinkage of high performance bridge concrete in New Zealand”. The results fell conservatively below the creep and shrinkage parameters used in design, i.e., RRU Bulletin 70.

The use of vibrators during casting of the tee-roff beams was initially excluded due to the potential to cause segregation in the SCC, however construction issues on site lead to the use of pencil vibrators being used in a very limited capacity to prevent cold joints forming in the upper zones of the webs.

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7 NZS3101:1995, Concrete Structures Standard
8 Clause C5.2.9 NZS3101:2006 Concrete Structures Standard
9 AS1012 Methods of testing concrete, Parts 13 and 16
10 Creep and shrinkage of high performance bridge concrete in NZ, P Lipscombe
Beam Deflection

The estimated beam hog deflections were large due to the high stresses associated with the addition of the post-tensioned tendon. For the longer and more highly stressed beams the estimated hog deflections were in excess of 170mm. While this could be used advantageously for the over vertical curves in the geometrical alignment, it was penalizing for the under vertical curves. Taking the variation out in the deck topping alone was an issue as the additional dead load resulting from increasing the deck topping had the potential to overload the beams. Keeping the deck topping thickness to a minimum was critical. The solution was to set the beam bearing levels in order to compensate for the beam hogs and geometrical alignment while minimizing the required deck topping thickness.

Conclusions/summary

Post-tensioning of tee-roff beams proved to be an effect method to increase the spanning capability of conventional tee-roff beams for use on Chapel Street Viaduct. Modifications to the standard tee-roff section which were utilised in the design included:

- Top flange thickness increased to 100mm throughout,
- 150mm web thickness in the end zones,
- a single 31 strand post-tensioned tendon was added in the bottom of the section, and
- a tapered bottom flange adjacent to the end block was added to allow for the tendon curvature.

Some of the most important aspects to consider when combining pre-tension and post-tension design in tee-roff beams are the accurate modelling of the construction stages. For these beams the maximum allowable stress range in the concrete was utilised at the pre-tension stage, post-tension stage and under maximum design load. These highly stressed beams exhibit significant pre-stress, post-tension and creep deflections which need to be taken into account in the design of the beam and setting out of the beams.

Due to the high concentration of stresses carried by the end block, the end block design is critical. Reinforcement congestion in beam end blocks requires careful detailing to enable constructability.

Self compacting concrete is an efficient means of constructing the tee-roff beams, especially with congested end blocks. Careful consideration needs to be made of the creep and shrinkage parameters assumed during design. Confirmation of these parameters through testing should be undertaken for construction.

With careful planning and detailing, post-tensioning of tee-roff beams can be an effect method to increase the spanning capability of convention prestressed tee roff beams. Some modifications to the standard section commonly used in NZ are needed and this method would ideally be used where a large number of beams are required.
Acknowledgements
The author would like to thank New Zealand Transport Agency and Fletcher Construction Company Limited for permission to write this paper. Thanks should also be extended to Fletcher Construction Company Limited and Firth for contributing test results and information relating to the content in this paper.

References

NZS3101-2006, Concrete structures standard: Part 1, the design of concrete structures, SNZ, Wellington, New Zealand

AS5100.5-2004, Bridge Design Code, Section 5: Concrete, Standards Australia, Sydney, Australia.

RM2006 – TDV Professional Software, TDV Technische Datenverarbeitung, Dorian Janjic & Partner GmbH, Austria


AS1012.13:1992, Methods of testing concrete – Determination of the drying shrinkage of concrete for samples prepared in the field or in the laboratory, Standards Australia, Sydney, Australia

AS1012.16:1996, Methods of testing concrete – Determination of creep of concrete cylinders in compression, Standards Australia, Sydney, Australia

Lipscombe P, 2009, Creep and shrinkage of high performance bridge concrete in New Zealand, 7th Austroads Bridge Conference, Auckland, New Zealand