Westgate Bridge Strengthening With External Post Tensioning

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Abstract Westgate Bridge is the largest bridge in Melbourne. The main span over the Yarra river is 336m long and made of a cable stayed steel box girder. The approach viaducts are made of prestressed concrete multicell box girders. The Western viaduct consists of 10 spans at 67m each and the Eastern Viaduct consists of 13 spans at 67m each. The traffic loading is to be increased by converting the outer shoulders into typical traffic lanes. Accordingly, the entire bridge is to be strengthened to enhance its structural capacity. The Western viaduct has already been partly strengthened in 2002. Strengthening is made of carbon fibre strips outside of the box girder, and additional external prestressing inside the box girder. Freyssinet Australia was awarded the installation of external prestressing tendons in both Eastern and Western viaducts. It consists of 300 tons of strands in both viaducts. Tendons are made of bare strands injected with cement grout in HDPE ducting. Straight 13C15 tendons are installed at midspan in the Western viaduct and 19C15 deflected tendons are installed in the Eastern viaduct. Deflector and end blocks are made of cast-in situ reinforced concrete blocks stressed to the webs with 50mm diameter Freyssibar. They are fitted with flared shape diabolos to allow for tendon misalignment and deviation. Tendons are deviated across pier diaphragms with a double formed diabolo (no steel tube). Freyssinet Australia also carried out the jacking of the bridge to relocate the deck at the abutment.

Introduction

This paper will first present a general overview on external post tensioning, in order to put into perspective the strengthening works carried out on Westgate Bridge, and to have a better understanding about the range of options available for external post tensioning. Then, section two will deal with the detailing and the installation of the external post tensioning tendons for Westgate Bridge.
General overview about External Post Tensioning

Technology

It is common practice to retrofit a bridge box girder with external post tensioning tendons in order to upgrade the structural capacity of the deck when the live loads are increased due to additional traffic lanes being placed on the deck, or due to a change in the applicable design standards. External post tensioning tendons are of three types whose advantages and disadvantages are discussed hereafter:

Table I. Types of external tendon

<table>
<thead>
<tr>
<th>TYPE of external tendon</th>
<th>TYPE 1: Bare strands Injected with grout</th>
<th>TYPE 2: Greased &amp; Sheathed strands injected with grout</th>
<th>TYPE 3: Bare strands injected with grease or wax</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advantage</td>
<td>• Cost Effective</td>
<td>• Good durability</td>
<td>• Good durability</td>
</tr>
<tr>
<td></td>
<td>• Conventional strand installation</td>
<td>• Very good corrosion protection</td>
<td>• Good corrosion protection</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Strand by strand replacement</td>
<td>• Conventional strand installation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Easier stressing (monostrand jack)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Very low friction coefficient (0.05/rad)</td>
<td></td>
</tr>
<tr>
<td>Disadvantage</td>
<td>• Ensure high quality cement grout to</td>
<td>• Longer strand installation</td>
<td>• Cost of filling material</td>
</tr>
<tr>
<td></td>
<td>obtain durability</td>
<td>• Duct fully supported prior to grouting</td>
<td>• Hot injection of grease or wax</td>
</tr>
<tr>
<td>Freyssinet Australia</td>
<td>• Western Link (1996)</td>
<td>• Pheasant Nest (1994)</td>
<td></td>
</tr>
<tr>
<td>References</td>
<td>• Westgate (2009)</td>
<td>• Burnley Bridge (2010)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Yarra Bridge (2011)</td>
<td>• M2 Upgrade (2011)</td>
<td></td>
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</tbody>
</table>

Between these three types, type 1 is the most commonly used in Australia and it is also the case for Westgate Bridge, the main reason being cost. Types 2 and 3 are relatively new in Australia and getting some acceptance by use on projects.

For type 2, it shall be noted that in the curved sections, within the bundle of strands, the transverse pressure of the top layers leads to ripping of the individual HDPE sheaths, too thin to withstand the corresponding strains. Simultaneous
tensioning of all the strands with multi strand jack doesn’t solve the problem. This issue can be addressed by two categories of solutions:

- Physical separation of the greased and sheathed strands along their entire profile with multitube saddle at deflection and anchorage point.
- Injection of cement grout in between the greased and sheathed strands before tensioning of the tendon.

**Replaceability**

A key advantage of external post tensioning tendons is the replaceability. Although they shall be designed and installed to target the best durability, unforeseen events may require replacement, which is possible once a few provisions are made.

Firstly, the structure must be able to withstand the removal or loss of an external tendon under reduced live loads. In those conditions, the damaged tendon is then easy to detect, and, with some precautions, to replace.

Secondly, the replacement of an external tendon depends on the tendon type. Type 1 tendons cannot be replaced strand by strand. Full tendon has to be severed with sufficient personnel protection when the tendon releases its energy. Practically, the tendon can be cut from an opening through the top slab or with a remote controlled robot and nobody is allowed inside the bridge while cutting takes place (refer tendon replacement carried out on Durance bridge by Freyssinet in 2001).

Type 2 and type 3 tendons can be destressed strand by strand. Single strand replacement for type 3 tendons has been successfully trialled for Kudan Kulam power plant project in India in 2004, Arbre Viaduct and Pont-Kanal de Sarre in Belgium in 2000. From a practical point of view, a long cap filled with wax shall be provided at one end of the tendon to enable tendon de-tensioning. Then each existing strand is coupled to a new strand with a compact coupler installed on the king wire and then the new strand is winched through in place. With this technique, only the prestressing strands are replaced, whilst the external HDPE duct, the grout and the individual sheaths of the strands remain in place.
Durability

External prestressing is a durable construction technique (refer Fig 1, bridges built in France in the 1950s currently in excellent condition with their original external tendons). However, several failures in external prestressing tendons of type 1 have been recorded in the last decade for instance at Mid-Bay Bridge in Florida in 2000 or at Durance Bridge in France in 2000.

For type 1 tendon, cement grout and the outer HDPE duct are the main corrosion protection barriers. The grout mix shall be correctly formulated and tested, to avoid bleed and creation of liquid or pasty areas at the high points. Grout mix specification such as the recent RTA specification borrows on international state of the art and ensures high quality grout. Furthermore, the leak tightness of the HDPE ducts shall be air tested prior to grouting, to ensure a safe grouting operation and avoid any future water ingress near the strands.

Besides, for this particular type of external tendon, the cement grouting turns the bundle of strands into a monolithic composite element, where the force of one or several broken or severed strands can be anchored by bonding to the remaining ones. There is a risk of sudden tendon failure once the stress level in the remaining strands exceeds the tensile strength. Certain countries consider that sudden failure of a grouted external tendon is an unacceptable OHS risk for the bridge inspectors. Consequently, for example in France, the use of external tendon made of bare strands injected with cement grout is forbidden since 2001.

![Fig. 1. Example of bridges constructed in the 1950s with external prestressing tendons](image)

Failure mode is different for external tendons of type 2 (greased and sheathed strands injected with grout) and type 3 (bare strands injected with flexible product) since for these types, the strands are independent between each other. Thus the failure of one strand doesn’t affect the stress level in the remaining strands. From
a structural point of view, the loss of capacity is therefore progressive. Strengthening of Westgate Bridge with external post tensioning

**Background**

The Westgate Bridge was originally designed to carry 25 tonnes vehicles, but now carries B-Double vehicles weighing up to 68 tonnes. Also, it was decided to provide a fifth lane in each direction bringing to ten the total number of traffic lanes on the deck. The structural analysis undertaken by SKM showed that the existing structural capacity was insufficient and concluded that the bridge needed to be retrofitted with external post tensioning tendons.

Outside the cable stayed central span (336m long), the approach viaducts are made of prestressed concrete multicell box girders (refer Fig 2). The Western viaduct consists of 10 spans at 67m each and the Eastern Viaduct consists of 13 spans at 67m each. Both viaducts are made of precast concrete segments tied together with internal prestressing tendons (refer Fig 2) and assembled by the balanced cantilever construction technique.

Due to the width of the deck (more than 30m), the top slab is supported by external concrete struts which were made precast and attached to the central segments with transverse post tensioning tendons. The deck is continuous from the abutment to the connection with the steel section and is resting on concrete piers that are articulated both top and bottom to allow for thermal expansion and contraction of the deck.
Generally, the concrete inside the bridge is in good condition and is not showing any sign of major distress. The Western viaduct has been partly strengthened in 2002 using external post tensioning tendons type 1 (bare strands injected with cement grout).

**Tendon layout**

In the Eastern viaduct, the external tendon layout consists of 3 types of draped tendons T1, T2 and T3 (refer Fig 3 below). T1 is continuous and coupled through a concrete block every 3 spans. The longest tendon T1 is approx 235m and the typical tendon T1 is approx 200m. T2 and T3 are shorter tendons (typical length is 80m) running across only one pier diaphragm.

All tendons are made of 19C15 anchorages filled with 17 bare strands 15.7mm diameter at 279kN GUTS to EN-10138 and stressed to 3795kN (80% of the GUTS). External tendons are made of HDPE duct injected with cement grout.

**Concrete blocks**

The external tendon installed in 2002 in the Western viaduct were anchored, coupled and deviated by external steel brackets (refer Fig 4). However, to avoid having to handle large steel fabricated brackets inside the box girder and to provide better durability, it was decided to use reinforced concrete blocks instead.
Fig. 4. Westgate Bridge - Western Viaduct – External Tendons installed in 2002

The concrete blocks in the Eastern viaduct are of three types (see Fig 3):

- **End blocks**: they are located towards the extremities of the Eastern viaduct and used to fully anchor two tendons.
- **Deflector blocks**: they are located at contraflexure points in each span and used to deviate two tendons and fully anchor one tendon.
- **Coupler blocks**: they are located every three spans, at midspan, and used to couple together two tendons T1.

The concrete blocks are designed by pair and clamped across the vertical web wall separating the middle cell from the outer cell. Clamping is achieved by tensioning 50mm diameter stress bars such that the ratio force to be anchored on clamping force doesn’t exceed 0.4. The force to be anchored at a block is dictated by the number of tendons terminating in that block and by the angle of the deviated tendons. In practice, end blocks have 12 bars and deflector blocks have 8 bars.

Fig. 5. Westgate Bridge – construction of deflector block
The design philosophy is based on friction between the new concrete of the block and the old concrete of the existing structure. Some N16 starter bars are used to link the old and the new concrete together by drilling and filling with epoxy but the prestressing force of the external tendon is mainly anchored by friction. Concrete surfaces are scabbled to enhance the roughness of the contact surface between old and new concrete and to improve the load transfer in shear. Roughening is achieved by one pass of three pins scabbler completed by 10mmx10mm diagonals shear keys done with a V grinder.

Friction type design between concrete elements is covered by American Codes (clause 5.8.4 shear friction of AASHTO) or by European Codes. American Code is less conservative than European Code in a sense that it takes into account a cohesion factor capturing the aggregate interlock effect at interface between concrete elements on top of the pure friction effect that is directly proportional to the clamping force applied. Friction coefficient proposed by AASTHO is ranging from 1.0 for concrete surfaces intentionally roughened to 6mm amplitude to 0.6 for clean concrete surfaces not intentionally roughened.

Blocks are designed with a formwork tube to allow for the free passage of external tendon through the block as a provision for future tendon replacement if required. Formwork tubes are made of OD 139.7x5 galvanized steel tube for the bent sections and OD 160x14.6 HDPE tube for the straight sections. Steel tubes are bent with a curvature radius of 4500mm. Diabolos are fitted at the ends of the formwork tubes inside the formwork to provide flared ends necessary to deal with the possible angular misalignment of the tendon. A ground Penetration Radar was used to locate the existing reinforcement and internal prestressing tendons in the web walls such as to avoid cutting any of them while coring through the webs.

**Pier Diaphragm strengthening**

Two external tendons are coming across the pier diaphragm on each side of the web wall with the bottom tendon being very close to the top corner of the opening through the pier diaphragm. The diameter of the core implied that some of the passive reinforcing bars had to be cut. To compensate the loss of capacity due to reinforcement cutting, and to provide extra capacity in order to carry the additional vertical loads arising from external tendon stressing, a steel frame was systematically installed in the inside of the pier diaphragm opening (see Fig 6).
Fig. 6. Westgate Bridge -Access ramp and strengthening frame in the pier diaphragm

Duct installation

Ducting was made of 110 PN10 HDPE duct with expansion oversleeves made of 125 PN8 HDPE duct. Oversleeves were 1.5m long and connected to the main run of the duct by electrofusion coupler at each end. One end was welded before tensioning and the other end after stressing, to allow for duct movement during tensioning.

Fig. 7. Westgate Bridge –duct and oversleeve profile after tendon stressing
The duct was supported at 3m spacing. Alignment of the duct was visually made to minimize excessive sagging before tensioning. Anti vibrations clamps weren’t requested. Duct was supplied in 12m long elements and butt welded on site (mirror welding).

**Threading of the strands**

Threading of the strands posed a great challenge given the length of the longest tendons T1 at 235m. Full prefabrication of tendon and winching into position was considered, however for practical and safety reasons another solution was found and adopted. Normally, strand pushing is limited to around 150m depending on the duct profile however machinery was developed to be able to push the full 235m. This was considered to be a major achievement of the project.

**Stressing of the tendon**

Tendons had to be stressed simultaneously on both sides of the web wall with two jacks to limit local bending of the web wall.

![Fig. 8. Westgate Bridge - End block tendon Stressing](image-url)
After the first stressing, elongations were found to be longer than expected due to a low friction coefficient (around 0.10/rad). As a result, the double end stressing prescribed by the design was deemed to be unnecessary and all the tendons including the longest tendons were single end stressed.

**Grouting**

The grout mix was prepared at ground level and then pumped up into the box girder. Mix used was Freyssigrount which is a proprietary high performance grout.

Given the potential issues mentioned previously in this paper, grout performance is of vital importance for the external tendon durability. Hence a high bleed resistance, low shrinkage and high fluidity grout mix was used, above the normal requirements from Vicroads. Grout mix adopted complied with RTA specification B113, with a bleed of less than 0.5% using a modified wick test to ASTM C940.

Also, the grout was injected uphill through the post tensioning anchorages and air vents were systematically provided 1 m after each high point in the direction of the flow. Prior to injecting the grout, duct was air tested to detect any leak and to check the strength of the ducting including all its welded connections.

**Conclusion**

The strengthening works of Westgate Bridge were a challenge in many ways. In the centrepiece of the bridge (cable stayed steel box girder), 400,000 bolts were installed along with 1600 tonnes of steel fabricated into 80,000 pieces.

In the concrete approach viaducts, massive scaffolding including a moveable underdeck gantry was erected to apply the carbon fibre on the outside of the box girder. 10,000 square meters of carbon fibre fabric, 65 tonnes of adhesive and 20 tonnes of epoxy resin went into the Westgate Bridge, which is reportedly the largest bridge-rehabilitation project ever undertaken with composites.

Inside the box girder, Freyssinet Australia efficiently carried out the installation of 300 tonnes of external post tensioning tendons which provides most of the structural capacity upgrade for the concrete approach viaducts. Other major work completed by Freyssinet Australia included repositioning of the Eastern Viaduct to the west via horizontal jacking from the Eastern Abutment. The jacking works were completed in a single night including packing plates installation.
It shall be noted that some bridges using the same external post tensioning technology as Westgate Bridge (bare strands injected with cements grout), experienced external tendon failures. Investigations revealed that the failure was due to the corrosion of the strands under tension and to the composite behaviour of the grouted bundle of strands. Two ways forward shall be considered.

First, the corrosion of the strands is mainly triggered by air entrapment in the duct close to the high points of the tendons, instability of the grout during installation and poor grouting technique and equipment. These two pathologies can be addressed by using an adequate grout mix (mix complying with latest requirements of RTA specifications B113 or mix with Thixotropic properties) and appropriate grouting procedure (air test of the duct, air vent adequately located, completed by vacuum injection if necessary). This state of the art has been used by Freyssinet Australia on the Westgate Bridge.

Secondly, other technologies exist for external prestressing, such as bare strands injected with flexible product (grease or preferable petroleum wax) or greased and sheathed strands injected with cement grout.

Complexity and durability of external post tensioning systems highlight the significance of the following:

- Consider all the options available for external post tensioning tendons.
- Pay attention to the detailing of the external post tensioning components.
- Use appropriate grout mix and injection method.

References
