Innovative materials

Tailor Made Concrete Structures – Walraven & Stoelhorst (eds)

Design of two reactive powder concrete bridges

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ABSTRACT: Ductal® is a reactive powder concrete that exhibits exceptional mechanical and durability properties. VSL has been involved with the development of this technology into structural solutions over the last ten years. Recently, concepts of two different bridges exploring the capabilities of Ductal® to the fullest have been developed. One of these is the BrennerPass footbridge located in Europe, a cable stayed structure that supports a light rail track. The other series of bridges is located in New Zealand and provides access to a variety of train stations. The design and fabrication of these two bridges is described in this paper.

1 BRENNERO FOOT BRIDGE, A CONCEPT DUCTAL® APPLICATION

Crossing Europe from Modena in Italy, to Munich in Germany, the E45 highway passes through the Alps in the region of the Brenner, a major European mountain pass.

To highlight the importance of the Brenner Pass, a rest area including a museum has been proposed. The museum is on one side of the highway with a parking area on the other, connected by a footbridge that is used by a cable car: the Brenner Pass Footbridge.

Figure 1. Photo of the Brenner Pass.

1.1 *Environmental conditions*

The environment imposes some tough conditions including large temperature variations during the day and throughout the annual seasons. The highway in this area is salted systematically every winter, making the environment aggressive to builts infrastructure and similar to those at the sea. Located over a highway, the footbridge condition must be absolutely controlled, with maintenance procedures to be kept to an absolute minimum.

1.2 *Ductal®: a suitable performance material*

The idea of utilizing Ductal®, an ultra-high performance concrete on this project was realized by the performance requirements and necessary durability. Offering extremely high resistance to chemical agents compared (Roux et al. 1996) with ordinary concrete or steel construction materials, Ductal® is a clear choice. The other aspect that led to the decision to consider Ductal® as preferred material for the bridge concept is its ability to be used in ambitious architectural designs (Ricciotti 2001, Blais et al 1999, Acker & Behloul 2004).

Ductal® was originally developed by Rhodia, Lafarge and Bouygues (Richard & Cheyrezy 1995) and is in the class of reactive powder concretes (RPCs). The constituents of RPC are cement, fine sand, silica fume, silica flour, superplasticiser, water with a

Table 1. Typical mechanical properties of Ductal®.

Compressive strength	160–200 MPa
Flexural strength	15–45 MPa
Young's Modulus	50 to 60 GPa
Density	2.4 to 2.5 ton/m^3
Fluidity ASTM	170–260 mm

Table 2. Durability properties of Ductal®.

Total porosity & microporosity	2–6% and <1%
Permeability (air)	2.5×10^{-18} m^2
Water absorption	<0.2 kg/m^2
Chloride ion diffusion	0.02×10^{-12} m^2/s
Electrical resistance (fibres)	137 kΩ.cm
Abrasion resistance	1.3

Figure 2. Render of initial concept of Brenner Pass Footbridge.

low water-cement ratio, and may include either high-strength steel fibres or non-metallic fibres. Some mechanical (Gowripalan & Gilbert 2000) and durability properties of Ductal® are listed in the two tables below.

1.3 *Innovative material, innovative design*

The design of the Brenner Pass footbridge was influenced by the flexibility Ductal® offers. Several options for the geometry were investigated.

Initially supported by an arch, the first concept, made entirely made of Ductal® consists of several different shapes, making it a challenging project to fabricate (Fig. 2).

A second option consisted of a monolithic asymmetric deck, supported by cables to an arch. Two geometries of arch where looked at; a parabolic geometry and circular geometry. Both combined with either a pure Ductal® arch (Fig. 4), or composite Ductal® slab with steel webs (Fig. 3). As presenting better durability performances, this latter solution was preferred.

1.4 *Integrating the rails to the platform?*

The Brenner Pass Footbridge was to carry a cable car developed by LEITNER traditionally rolling on rubber wheels over a steel track. Due to the high performance

Figure 3. Render of concept with circular composite arch.

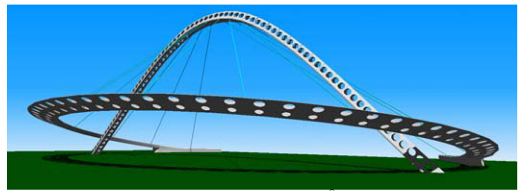

Figure 4. Render of concept with Ductal® parabolic arch.

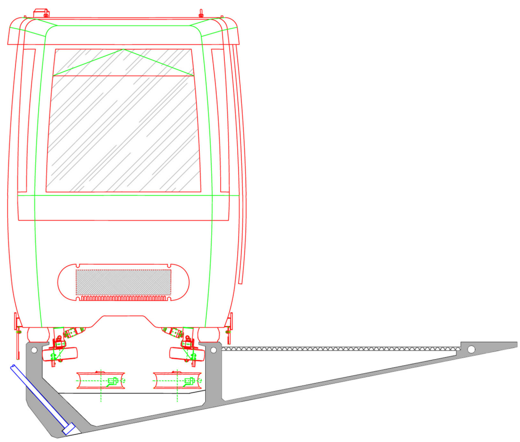

Figure 5. Integrated rails to the platform.

of Ductal®, VSL proposed a solution that integrates as interdependent, the rails and the platform into a monolithic component.

Despite such a solution offering the best performances in terms of acoustic comfort and durability, the design raised questions of installation accuracy not commonly inquired in pure civil engineering domain. The preferred solution was thus to adapt to the Ductal® structure, to use the original steel rails that are traditionally used on these cable car systems.

1.5 *Cable support for deck*

The deck is supported by 12 stay cables, each unit consisting of 4 galvanized individually sheathed and

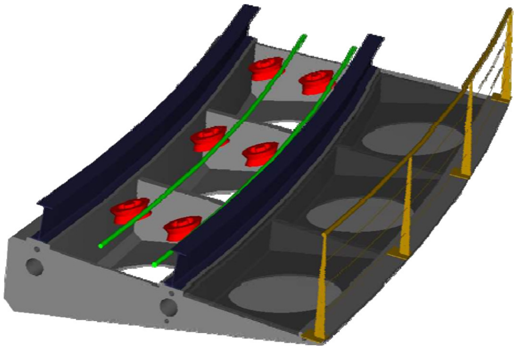

Figure 6. Preferred solution using steel rails.

waxed mono-strands, encapsulated inside an HDPE stay pipe. Anchor head are fabricated on the base of the VSL SSI2000 concept, without guide deviator, integrating a rubber type damping device.

2 DESIGN CONSIDERATIONS

2.1 *Short overview of dynamic aspects*

In addition to mentioned environmental considerations, wind load, and especially aerodynamic interaction between the wing-shape-suspended-deck and the wind, which can be very strong in this area, cannot be neglected. The option of making provision of stabilizing cables or members, to connect the bottom side of the deck to the arch abutments, was kept in mind.

The impact of the cruising cable car on the bridge was a critical issue that needed to be investigated through direct temporal integration onto a 3D finite element dynamic model. In fact, the lightness of the structure combined with its relative wide span made the question of dynamics crucial.

2.2 *Complex geometry*

Corresponding apparently to a cylindrical geometry, the circular deck presents some critical particularities. The slope of the path curve is a constant 12°, inserting it into a helical shape and not into an inclined plan. In addition, the heel of the cable car must be horizontal along the entire path.

2.3 *Anticipation of static deformations*

The weight of the loaded cable-car is not insignificant compared to the dead load on the bridge and its stiffness. Consequently, sensitive deformations occur when the cable-car passes. These deformations have to be anticipated by an initial shape of the deck, in order to ensure the cable car heel is horizontal during its cruise.

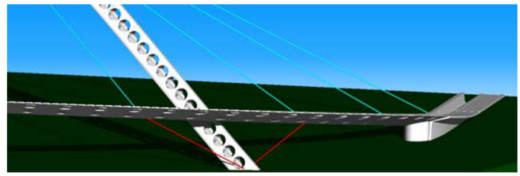

Figure 7. Stabilizing members below the deck at arch abutments.

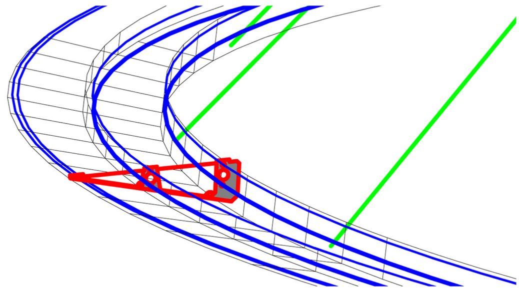

Figure 8. Post tensioning path and stay cables.

3 PRECAST FABRICATION

3.1 *Post-tensioned pre-cast elements*

All elements for the Brenner Pass Footbridge are intended to be precast. The elements are air cured for two days and then heat treated at 90°C for 48 hours to achieve their definitive performance, then brought to site for assembly. Elements are match cast and post-tensioned using a wet joint.

Contrary to classical post-tensioning work, the Brenner Pass footbridge post tensioning forces would be “tuned” according to the desired geometry. Not only the stay cable would adjust the geometry setting, but also the post tensioning located inside the ducts located on the longitudinal beams integrated to the deck elements (Fig. 8).

By setting the force in the post-tensioning it is possible to control the rotation of the cross section around an orthoradial axis. The stay cable force influences the vertical position of the deck. Consequently, the post-tensioning is not grouted, and the PT strands are, same as for the stay cable, individually sheathed waxed galvanized mono-strands.

3.2 *Elements of arch*

The arch design concept is based on the use of two different elements. One, repeated 30 times realizes the

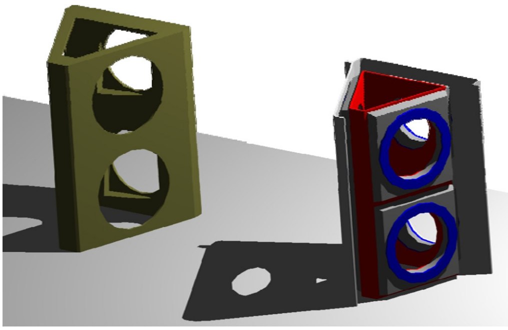

Figure 9. "Jamb" element of the arch and associated concept formwork.

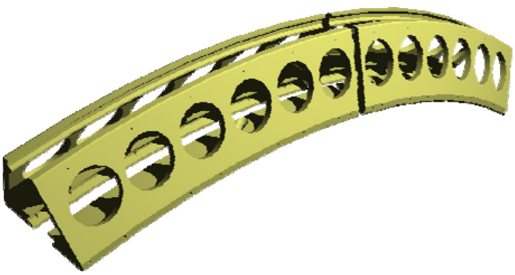

Figure 10. "Top key" elements of the arch.

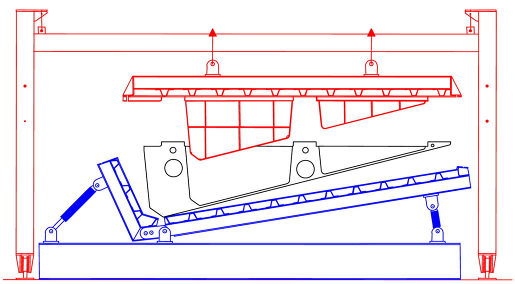

Figure 11. Formwork with geometry control.

jambs of the arch, the other, repeated 4 times, contains the stay cables anchorages recesses, and is located as the top closure of the arch.

3.3 *Deck elements*

Due to the complex geometry, the deck elements cannot be superimposed. The same formwork cannot be reused to cast all elements, without specific adaptations. The torsion of the deck elements vary according to its polar position along the path. Such a characteristic can be fabricated by using a deformable formwork positioned onto jacks (Fig. 12).

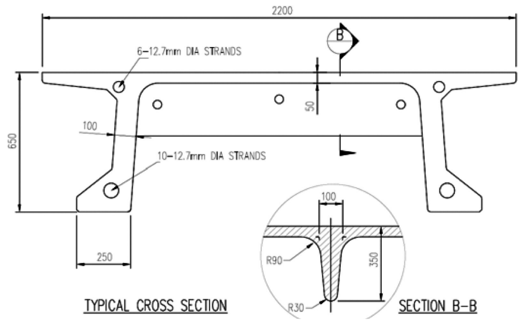

Figure 12. Typical cross-section of Ductal® Beam.

4 CONSTRUCTION METHOD

The BrennerPass footbridge is prefabricated using elements described previously. All elements are adjusted to give the final geometry. Post-tensioned is installed to ensure sufficient capacity for shear and bending.

4.1 *Erection of the arch*

After the formation of both abutments, the first element assembled on site is the arch. After erection of both jambs, the complete pre-assembled top element is lifted up to its final position and connected. Once achieved, the arch is stabilized by two back stays, anchored inside the abutments.

4.2 *Erection of the deck*

The deck is assembled onto temporary scaffolding that forms a temporary bridge over the highway. This allows the realization of the work without disrupting the traffic. All deck elements are supported by the scaffolding, adjusted in relative position, and joined. Once all the elements are in position, post-tensioning cables are installed. The post-tensioning force is defined according to the desired geometry.

5 NEW ZEALAND FOOTBRIDGES

An important part of the station redevelopment being undertaken by the Auckland Regional Transport Network Ltd is a series of new footbridges, providing ramp access for pedestrians to cross the railway tracks. To-date, five (5) stations have had the footbridges replaced, the first being Papatoetoe Station which is described in the following paragraphs. A second footbridge at Penrose Station also in Auckland has recently been completed using the same Ductal® superstructure element. The bridge has a total length of 265 m consisting of 15 spans of mostly 20 m, and was opened to the public in March 2006. The third major upgrade was completed at Papakura station in August of 2007.

Figure 13. Demoulding of match-cast segments.

Figure 14. Segments in transport.

5.1 *Ductal® advantage*

The station at Papatoetoe was the first station to have the new footbridges. The conforming design for the Papatoetoe pedestrian bridge was a conventional prestressed concrete structure until a New Zealand contractor saw an opportunity to reduce the weight and cost by using a Ductal® solution proposed by VSL. The main advantage of the alternative solution is the significant weight reduction, resulting in reduced design earthquake actions imposed by the New Zealand design code and cost savings in the substructure and erection.

5.2 *Footbridge layout and geometry*

The Papatoetoe Footbridge has a total length of 175 m consisting of ten simply supported spans, with the majority of spans being 20 m long. There are two shorter spans of 8.2 and 10.2 m. The bridge spans are formed using two precast Ductal® segments. The deck is 50 mm thick, contains no ordinary reinforcement, and has two symmetrical legs with large circular holes that provide architectural interest and reduce weight (Fig. 13). Ribs protrude 350 mm below the top of the deck slab at 2.7 m centres along the beam to add torsional rigidity. The tension steel is provided by ten DIA 12.7 mm post-tensioned strands in the bottom of each leg and six strands at the top to balance stresses. Both tendon profiles are straight and

Figure 15. Ductal® span with railing attached being lifted.

Figure 16. Penrose Footbridge during construction.

anchored directly against the Ductal® without the need for further anchorage reinforcement.

5.3 *Precast element fabrication*

Production of the Papatoetoe bridge beams (Fig. 14) commenced in December 2004 and was completed over a ten week period. To achieve the required architectural shape and surface finish, a special steel formwork was utilised, comprised of a fixed internal form and two side forms that shape the exterior surface and web penetrations. The larger elements were match cast in two segments to allow later transportation on standard 40-foot containers (Fig. 15).

5.4 *On-site works*

The Ductal® beams were post-tensioned on site after delivery to New Zealand. Prior to erection a topping surface made of ordinary concrete was applied to the superstructure. This surface was graded in accordance with accessibility guidelines and has a varying thickness. Steel hand rails were secured directly to the Ductal® superstructure (Fig. 16). A more detailed account of the design is given in (Wight et al. 2007) and of the construction account in (Rebentrost 2005).

6 CONCLUSION

The Brenner Pass Footbridge gathered all characteristics of a project that perfectly explores the unique properties of Ductal®. Performances requirements in term of durability, mechanic behavior or maintenance, combined with a very specific design where characteristics that would exclude the use of steel or classical concrete. Unfortunately, for political reasons, the whole project was deferred.

The New Zealand Footbridges did however succeed and clearly demonstrated the use and economies of state-of-the-art concrete technologies combined with intelligent design (Fig. 17).

REFERENCES

Richard, P. & Cheyrezy, M. 1995. Composition of reactive powder concrete. *Cement and Concrete Research*, 25(7).

Roux, N. Andrade, C. & Sanjuan, M. A. 1996. Experimental Study of Durability of Reactive Powder Concretes. *Journal of Materials in Civil Engineering*, 8(1).

Blais, P.Y. & Couture, M. (1999) Precast, Prestressed Pedestrian Bridge – World's First Reactive Powder Concrete Structure. PCI Journal, Sept.–Oct.

Acker, P. & Behloul, M. (2004). Ductal® Technology: A Large Spectrum of Properties, A Wide Range of Applications. *fib Symposium*, Avignon, France.

Gowripalan, N. & Gilbert, R. I. (2000) Design Guidelines for Ductal® Prestressed Concrete Beams. Design Guide, *School of Civil and Environmental Engineering, The University of New South Wales*, Sydney, Australia.

Ricciotti. (2001). Bridge to the Future. ASCE Civil Engineering Magazine, 71(1).

Rebentrost, M. 2005. Design and Construction of the First Ductal® Bridge in New Zealand, *New Zealand Concrete Industry Conference*, Auckland, New Zealand.

Wight, G. Rebentrost, M. & Cavill, B. 2007. Designing Bridges with Ductal® Reactive Powder Concrete, *23rd Biennial Conference, Concrete Institute*, Adelaide, Australia.