ULTRA-HIGH PERFORMANCE DUCTILE CONCRETE: THE DELIVERY FROM RESEARCH INTO PRACTICE

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Abstract: With the opening of Shepherd's Gully Bridge 150 km north of Sydney in 2005, Australia was amongst the leaders in the world in the utilisation of ultra-high performance concrete (UHPC) for road bridge construction. Ten years on, not one more bridge has been constructed and the uptake of UHPC technologies has been, at best, limited. In contrast, Malaysia's first bridge was opened in 2010 and in the time since a further 47 bridges have been completed, with many more under construction and on the drawing boards. Road bridges with spans as little as 12 metres and large as 58 metres are operational and of 100 metres are being built. Around the globe, UHPC is seeing slow, but steady, take up in many countries with more than 100 operational bridges worldwide. The question is asked "why has Australia gone from leading the world in the application of UHPC technology to watching from a distance" and "what is the future of UHPC for developing sustainable and resilient infrastructure"? This paper provides examples of two Malaysian UHPC bridges, the 51.0 metre span UHPC-composite deck Rantau Negeri Sembilan Bridge completed in December 2013 and the 100 metre span integral-deck precast segmental box girder bridge completed May 2015.

Keywords: Ultra-high performance, ductile, fibre, segmental, bridge, sustainable.

1. Introduction

One of the major breakthroughs in concrete technology of the 1990s was the development of ultra-high performance fibre reinforced concrete (UHPFRC), also known as the reactive powder concrete (RPC), by Richard and Cheyrezy (1994, 1995). Compressive strengths and flexural strength of over 180 MPa and 40 MPa, respectively, have been reported. Since then, extensive research studies have been undertaken by academics and engineers alike with the view to industrialise this technology as an alternative for sustainable construction. While its take-up in practice has received gradual acceptance in many countries, this has not been the case in Australia. In the years 2004 and 2005, Australia was amongst the world leaders in development of UHPFRC for road bridge construction, through VSL Australia and their product Ductal. In the time since, and despite significant potential, the uptake of the technology has stalled, if not stopped in Australia.

The first major structures adopting UHPFRC technology were footbridges. In 1996, the 60-metre single span Sherbrooke Pedestrian Bridge was constructed, crossing the river of Magog, province of Quebec, Canada (Lachemi et al., 1998). The walkway deck, serving as the top chord to the truss, consists of 3.3 metre wide by 30 mm thin UHPFRC slabs. The web members are of a composite design involving UHPFRC placed in thin walled stainless steel tubing. April 2002 saw the construction of the Seonyu Footbridge (the Footbridge of Peace) in Seoul, South Korea (Behloul and Lee, 2003). Constructed by Bouygues Construction, the bridge is an arch with a 120 metre span supporting a 30 mm thick RPC deck. The structure required about one-half of the quantity of concrete that would have been used with traditional construction. At a similar time to the construction of the Seonyu bridge was the 50 metre footbridge constructed in Sakata (Sakata-Mirai footbridge), which is located in the north-western region of the island of Honshu, Japan (Tanaka et al., 2011). Other examples from Japan include the 36.4 metre span segmental construction Akakura Onsen Yukemuri Bridge (completed in 2004), the 64.5 metre span Hikita Footbridge (completed in 2007), the 81.2 metre span Mikaneike Footbridge (completed in 2007) (Tanaka et al., 2011, Musha et al., 2013). In the time since the construction of the Seonyu and Sakata-Mirai footbridges, UHPFRC bridges for pedestrian traffic have been constructed in France, New Zealand, Spain, Germany and elsewhere (Toutlemonde and Resplendino, 2011).

Internationally, private and governmental bodies are increasing their attention and initiative towards utilising performance advantages of UHPFRC, together with its being demonstrated as one solution towards more sustainable construction (Ng et al., 2012; Voo and Foster, 2010). UHPFRC is a highly workable material that may be used to form complex shapes, with reduced mass and reduced material. Figure 1 shows a 2.5 metre high UHPFRC retaining wall segment; Figure 2 shows the UHPFRC façade elements of the Museum of European and Mediterranean Civilisations, Marseille, France and constructed in 2013.

The first road bridges to be constructed using UHPFRC technology appeared in 2005, with four bridges constructed at around the same time (Voo et al. 2014). One of these was the 16 metre span, 21 metre wide, precast pre-tensioned I-girder bridge at Shepherd's Gully Bridge (Figure 3) located 150 km north of Sydney and constructed by VSL Australia (Foster, 2009, Rebentrost and Wight, 2011). The girders for these bridges were fabricated by VSL using the facilities of the Heavy Structures Laboratory at UNSW Australia. At this time, Australia was at the cutting edge of research into use of UHPFRC with doctoral theses by Voo (2004), Warnock (2005), Ngo (2005) Malik (2007) and Menefy (2007). The significance of such technology lies not only in the great enhancements in concrete strengths, leading to lighter weight construction and more efficiency of materials, but also in the contribution to sustainability through lower carbon footprints (Voo and Foster, 2010).

Figure 1. Precast UHPFRC 2.5 metre high retaining wall segment.

(a) (b)

Figure 2. (a) Museum of European and Mediterranean Civilisations - Marseille, France; (b) UHPFRC façade:

(a) (b)

Figure 3. Shepherds Gully Bridge, NSW, Australia constructed 2005: (a) 15 metre span 4 lane road traffic bridge (b) underside showing I-girders.

In 2008, the world's first segmental UHPFRC composite deck road bridge was constructed; a single-span 46.0 metre ground support equipment (GSE) bridge was built over a road connecting the south and north apron in the extension of the Tokyo International Airport project. At the time, the road bridge was the largest UHPFRC road bridge in the world (Tanaka et al., 2011).

While construction of UHPFRC bridges in Australia has stalled, since 2006 Dura Technology Sdn Bhd (DTSB) has been pioneering research on the optimal uses of UHPFRC in bridge construction in Malaysia. During several years of research and development, DTSB has been collaborating with the Malaysia Works Ministry to design and build UHPFRC bridges, with a particular emphasis for bridges in rural areas where sourcing materials, site access and construction method are major constraints when using the conventional technology. From 2010 to now a total of 47 UHPFRC bridges have completed; a further 13 are in advanced stage of construction and another 15 are in the early stages of production. By the end of 2015, 75 bridges are due to be completed; 58 of these bridges are of segmental construction and 17 are pre-tensioned girders having spans of less than 22 metres.

In most cases UHPFRC precast bridge construction can be demonstrated to realise the following advantages (Voo and Foster, 2010, Voo et al., 2014):

- immediate and life-cycle cost saving;
- enhancement in design/service life of structures;
- low maintenance due to their high durability;
- reduced overall construction time and risk;
- reduced consumption of raw material;
- lighter superstructure dead weight permitting smaller and lighter substructure and foundations;
- reduced man-power and smaller plant;
- higher quality than in-situ wet work and precast high performance concrete structures; and
- lower impact on the construction site due to shorter-duration of temporary works.

In this paper, firstly, the mix design and mix performance properties of the Malaysian UHPFRC are outlined; next, two of the more than 40 bridges that have been completed are briefly discussed, the first the Rantau, Negeri Sembilian bridge, the largest single span composite deck UHPFRC bridge constructed to date, and the second the 100 metre span Batu 6 bridge, the world's longest UHPFRC single-span box-girder road bridge.

2. DURA Ultra-High Performance Fibre Reinforced Concrete

There are many variations in mix design of UHPFRC with a number of commercial products in the marketplace (eg. Ductal, BSI, Taktl, myUHPC, Forida, etc). The mix design used in the beams in all bridges designed and constructed by DURA is given in Table 1; the material used to produce UHPFRC consists of Type I Ordinary Portland cement, densified silica fume containing more than 92% silica dioxide (SiO2) and with a surface fineness of 23,700 m2/kg and washed-sieved fine sand with a particle size range between 100 μm and 1000 μm. A polycarboxylic ether (PCE) based superplasticizer is used. Two types of steel fibres are utilised in the mix; both manufactured from 2500 MPa high carbon steel wire. Type I steel fibre are straight in shape and are supplied with dimensions of 20 mm length by 0.2 mm diameter. Type II steel fibre is hooked-end and have dimensions of 25 mm long by 0.3 mm diameter. One percent of each fibre type is used; a total of 2%, by volume. Benchmark values for the specification of the UHPFRC are a 28 day characteristic cube compressive strength of 150 MPa and flexure strength of not less than 20 MPa; heat curing is applied for a period of 48 hours at a temperature of 90ºC. The mechanical properties of the DURA UHPFRC are presented in Table 2.

Table 1. Mix design of standard DURA UHPFRC.

Ingredient	Mass (kg/m^3)
DURA-UHPFRC Premix	2100
Superplasticizer	36-40
High strength steel fibres	158
Free water	168
3% moisture	32
Targeted W/B ratio	0.16
Total air voids	< 4%

Table 2. Material characteristics of DURA UHPFRC.

Characteristics	Standard	Value
Specific density, δ	BS1881-Part 114 – 1983	2350 – 2450 kg/m^3
Cube compressive strength, f_{cu}	BS EN 12390-3-2009	Min. 150 MPa (characteristic) Min. 160 MPa (mean)
Creep coefficient at 28 days, ϕ_{cc}	AS1012.16 – 1996	0.2 – 0.5
Post-cured shrinkage	AS1012.16 – 1996	< 100 $\mu\varepsilon$
Modulus of elasticity, E_o	BS1881-Part 121 – 1983	40 – 50 GPa
Poisson's ratio, ν		0.18 – 0.2
Split cylinder. cracking strength, f_t	BS EN 12390-6 – 2000 ASTM C496 – 2004	5 – 10 MPa
Split cylinder ultimate strength, f_{sp}		10 – 18 MPa
Flexural strength or Modulus of rupture, $f_{cf,3P}$	BS EN 14651-2005 (Three-point test on notched specimens)	20 – 35 MPa
Rapid chloride permeability	ASTM C1202 – 2005	< 200 coulomb
Chloride diffusion coefficient, D_c	ASTM C1556 – 2004	0.05 – 0.1 x 10^{-6} mm^2/s
Carbonation depth	BS EN 14630 – 2006	< 0.1 mm
Abrasion resistance	ASTM C944-99 – 2005	< 0.03 mm
Water absorption	BS1881-Part 122 – 2011	< 0.2 mm
Initial surface absorption	BS1881-Part 208 – 1996	< 0.02 ml/(m^{2}s) (10 min) < 0.01 ml/(m^{2}s) (120 min)

3. Rantau, Negeri Sembilan Bridge

The first example presented is the Rantau, Negeri Sembilan Bridge, which on 20 May 2013 became the world's longest single span UHPFRC-composite deck bridge, breaking the record of its predecessor, the 50 metre Kampung-Linsum bridge (see Voo et al., 2011). The project cost was MYR6.5 million (A$2.1 million), which includes the construction of the new four lane road, river protection works, road furniture, earthwork, 400 metre by 16 metre wide approach pavement works, in addition to that of the bridge structure. The four lane wide bridge consists of five DURA UBG1750 beams with a conventional concrete cast in-situ deck (Figure 4). Being one of the busiest road accesses between the towns of Seremban and Port-Dickson, on the day of launching the existing road, and bridge, could not be closed to traffic for periods of more than 15 minutes at a time. The seven segments (2 × 5.8 metres and 5 × 8.0 metres) making up the 51.6 metre long beams were delivered from the factory to a site adjacent to the construction, where they were assembled and stressed together. The girders were next transported the short distance to the new bridge site, utilising the existing bridge, and were lifted by two 500 tonne mega cranes in a single lift and placed on their abutments (Figures 5a and 5b). The whole launching process took just five hours to complete. There were no major disruptions to the heavy traffic and by 5 pm normal activity around the site was resumed and launching was complete. The composite deck slab was subsequently cast and the completed bridge is shown in Figures 5c and 5d.

The 18.3 metre wide Rantau, Negeri Sembilan Bridge remains the largest single span composite-deck bridge in plan area constructed to date; the longest span is held by the 58 metre span single lane Kampung Merdeka Bridge, completed in June 2015. The largest multi-span bridge is the 5 span, 200 metre long by 17 metre wide CFS Bridge, completed February 2015.

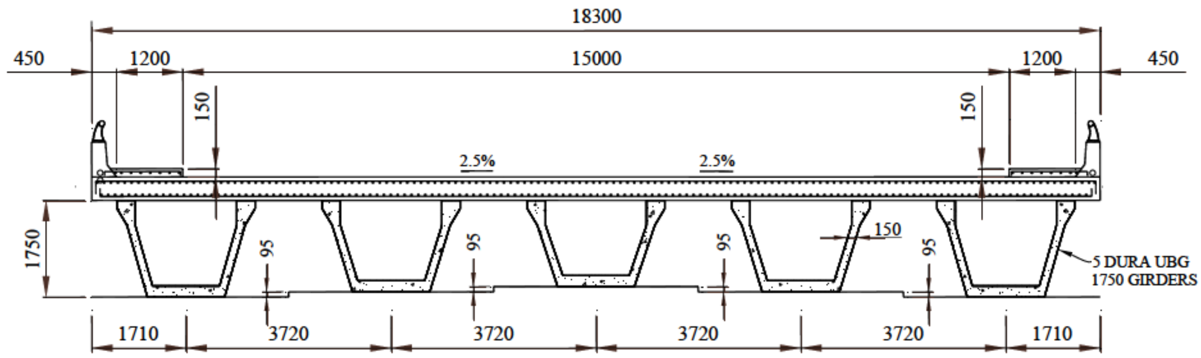

Figure 4. Rantau-Siliau Bridge cross section.

Figure 5. Rantau-Siliau Bridge. U-shaped UHPFRC girder with composite conventional strength concrete deck at different stages of construction: (a) and (b) during launching; (c) and (d) after completion.

4. Batu 6 Bridge

The second example presented is the 100 metre span, integral-abutment box girder Batu 6 Bridge, located at Batu 6, Gerik, Perak, Malaysia. The construction cost was RM6.3 million (A$2.2 million), which includes the foundation/piling, substructure (included wing-wall and approach slabs), superstructure, temporary works, road furniture, earthwork, 600 metre long by 6 metre wide approach road works and slope protection. The bridge was due for completion in February 2015; however, on December 22nd 2014, just one day before the planned pouring of the first of the integral abutments, the pour that would join the bridge to its foundations, saw the worst floods in Malaysia in decades with more than 100,000 people displaced.

The bridge is constructed of 40 – 4.0 metre high precast segments (Figures 6 and 7a), with each segment matched cast in the factory and delivered to site for placement and tensioning. The thickness of the webs between segment ends is 150 mm; the webs are locally thickened at the matched joints to accommodate the shear keys. The 36 middle segments each weight 16.5 tonnes, the segments second from the end 18 tonne and the end segments 20 tonne. With 26 tonnes of prestressing cable, 52 tonnes for the wearing surface and 20 tonnes for railings and ancillary fixtures, the total weight of the bridge is 770 tonne. For construction of the bridge falsework and positioning of the segments, crane access was available from one bank only and required the largest crane available; a 550 tonne crawler crane with a boom length of 108 metres. Even then, the last end segments at Abutment B could not be lifted into position and an innovative strategy was needed. To this end, a rail system was developed on the falsework to locate the precast segments to the accuracy needed for threading of the tendons. Figures 7b – 7d show the placement of the UHPFRC precast box segments. The 40 segments were placed over a period of 18 days (including two rest days). On day 11 of placement, five segments (12.5 metres of bridge) were positioned and aligned in a single day.

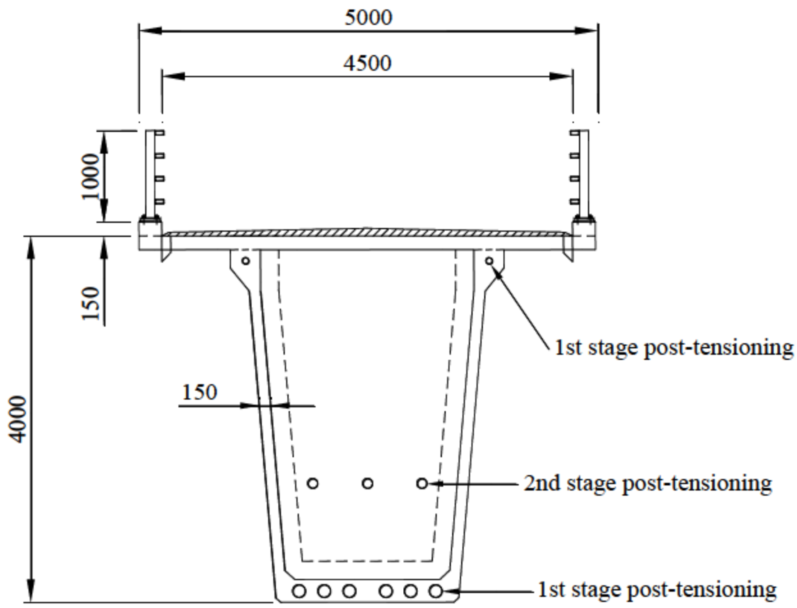

Figure 6. Batu 6 Bridge cross section.

The stage 1 prestressing work began on day 19 and the bridge was stressed on day 33 (29 November). On days 34 to 38 the strand ends were cut and grouting was completed (Figure 7e); the average prestress on the section (P/A) is 17.1 MPa compression, the stress at the top and bottom of the section at mid-span is 19.3 MPa (compression) and 15.0 MPa, respectively. The calculated theoretical hog was 34.8 mm; the measured hog was 50 mm. After 7 days, the hog had reduced due to creep by 7 mm to 43 mm, consistent with predictions. Stage 2 stressing will be undertaken after completion of the integral abutment works.

Figure 7. **Batu 6 Bridge: (a) factory cast segments; (b)-(d) placing of segments; (e) after stage 1 stressing; (f) during flood; (g) shifting of girder on abutments downstream; (h) after completion of Abutment A.**

On 29 December 2014, from an unplanned release of water from Bersia Dam, the river Perak rose to a level of 3.0 metres above the soffit of the 4.0 metre tall girder (Figure 7f). This placed an extreme lateral pressure on the member, a load for which it had not been designed! The bridge, which had its first stage stressing a month before, carried the load without damage but had moved on its abutment 1.2 metres downstream, with the edge of the girder moving to within 50 mm of the edge of the abutment, and had tilted by 5 degrees (Figure 7g); it had come precariously close to topping into the river! On 20 January 2015 the flood waters had subsided to below the soffit of the girder and planning for restoration works began.

On 12 February the construction authority gave approval for the proposed remediation plan and work began shortly after. The girder was first lifted using hydraulic jacks and Teflon bearing plates were placed between the girder and the pile cap. The bridge was then repositioned by jacking laterally against a temporary structure that had been constructed around the pile caps for this purpose. The casting of integral Abutment A was undertaken over the days between 30 March and 3 April, 2015 (Figure 7h) and Abutment B is between 13 to 17 April. With the completion of construction in May mid-2015, the 100 metre span Batu 6 Bridge became the world's longest single span UHPCFRC integral-box road bridge (Figure 8).

Figure 8. 100 metre span Batu 6 Bridge – completed May 2015.

5. Concluding Remarks

With the opening of Shepherd's Gully Bridge near Newcastle, Australia was at the lead of industrialisation of the latest in research in cementitious materials technology and in the utilisation of ultra-high performance concrete for road bridges – ten years ahead, not one more bridge has been constructed. The question that should be asked is: "where will we be in 2025"? In contrast, based on research begun in Australia and with Australian research training, Malaysian engineers built their first UHPC bridge in 2010; in the short time since, 47 more bridges, road and pedestrian, have been built. Similarly in other parts of Asia (particularly Japan) and in Europe (particularly France) some remarkable structures are being developed utilising UHPC technology.

In 2005 the German Government, through the German Research Foundation, invested €12 million (A$16.7) in a programme that involved 34 research projects at more than 20 research institutes (Schmidt, 2012). Similarly, in 2007 the Korean Institute of Construction Technology (KICT) invested WON$12 billion ($A14 million) into research into UHPC for cable-stayed bridges in their Super 200 program (Kim et al., 2012). The US Federal Highway Administration (FHWA) began investigating the use of UHPC in 2001, with the first structure, the 33 metre Mars Hill road bridge in Iowa, constructed in 2006 (Graybeal, 2011). This compares to a general lack of investment in cementitious materials technology research throughout Australia by government, industry and, indeed, universities. Will we be looking for inspiration from overseas for the years ahead; will again Australia be at the lead or remain followers? It is time that that a new paradigm is found that unlocks the talent invested in Australian research institutions and brings the benefit more directly to Australian industry and the Australian economy.

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