Ultra-High Performance Concrete – Technology for Present and Future

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Abstract. Ultra-high performance concrete (UHPC) is an advanced cementitious-based composite material that offers new opportunities for infrastructure works, building constructions and many niche markets. In the last two decades UHPC has been used for both structural and non-structural precast components in many countries. However, this outstanding technology has struggled to become a main-stream for everyday use due to lack of design codes and due to initial high investment costs of manufacturing facilities. Moreover, the high UHPC material cost makes it hard to compete with conventional designs optimized for other materials. Most projects in these countries have been motivated by government agencies as demonstration projects intended to encourage further implementation. However, for most of the countries, the follow-up implementation has been slow. Both private and governmental bodies are increasing their directives for the attention and initiative towards exploiting UHPC as a future concrete construction material, in the belief that UHPC technology embraces a more complete solution for sustainable construction with favourable life cycle values.

This paper briefly presents various examples on the application of UHPC technology in the context of Malaysia and Singapore. Examples include past successful and present projects and other potential applications of UHPC technology that are either in the design stage or are envisioned. The examples include the ten equal spans, total 420-metre-long Kg Baharu-Kg Teluk Bridge and the 2016 PCI award winning single span 100-metre-long Batu 6 Bridge. Other examples are internet transmission towers, portal frame structures, retaining walls, light-weight precast bathroom units, external walls for precast-prefinished-volumetric-construction, and others.

Keywords: Bridge · Retaining wall · Tower · Fibre · Ultra-high · Performance · Concrete

1 Introduction

Ultra-high performance concrete (UHPC) is an advanced cementitious-based composite material that offers new opportunities for current and future construction developments, ranging from building components, bridges, architectural features, repair and rehabilitation, vertical components such as towers for windmills or utilities, oil and gases industry applications, off-shore structures, hydraulic structures, overlay materials and many others.

In its current form UHPC has been used for bridges and bridge components in various countries, including Australia, Austria, Canada, China, Czech Republic, France, Germany, Italy, Japan, Myanmar, Netherlands, New Zealand, Slovenia, South Korea, Switzerland, Vietnam and the United States. Many UHPC related projects in the above-mentioned countries have been motivated by government agencies as demonstration projects intended to encourage further implementation. For the most part, follow-up implementation has been slow.

In the authors' opinion, the world already has sufficient knowledge and technical know-how to utilise this UHPC technology at large scale, but very often resistance comes firstly from the high initial investment cost of the material and facilities and, secondly, the lack of design codes combined with a risk adverse profession. In that, this outstanding technology has struggled to become a main-stream technology for everyday use and so it is not due to technical reasons, but these other reasons.

This paper will briefly present various examples of the application of UHPC technology in the context of the Malaysian and Singaporean experience. The examples focus on previously successful projects, as well as present projects and other potential applications.

In Malaysia, use of UHPC started as an organized effort based on a solid foundation. The effort has resulted in excellent and sustainable results. The technology has been shown to be commercially and practically viable. The results so far have seen the completion of over 90 bridges, and contracts for 20 more. A search of the literature identifies completion of about 200 pedestrian and vehicular bridge projects. These projects include utilization of UHPC in one or more components of the bridges. Both private and governmental bodies are directing increasing attention and initiative towards exploiting UHPC as the future concrete construction material, in the belief that UHPC technology embraces the complete solution for sustainable construction with favourable life cycle values.

In Singapore, use of UHPC was initiated by Tiong Seng Group (TSG), a publicly listed company of more than 50 years (formed in 1959). TSG has grown to become one of the major leading market players in the Singapore construction industry, with a reputation for spearheading new and innovative construction methods and products. With TSG's continuous drive for innovation, they came across Dura®'s UHPC material, which led to the formation of a strategic partnership between the two parties in 2014. Thus, began TSG efforts in the adoption of UHPC in the Singapore market. Since then, the partnership had reaped results with

TSG successful applications of the UHPC material in the building industry that goes beyond usage in the infrastructure sector.

2 The Malaysia Dura Experience

Introduction of UHPC in Malaysia started in 2006. The company Dura Technology Sdn Bhd (DTSB) was founded by Dr Voo and his colleague Leong C.N., after Dr. Voo completed his PhD at UNSW Sydney, Australia. In contrast to Malaysia, the use of UHPC in Australia has stagnated since the construction of its first bridge, the Shepherd Gully Creek Bridge, completed in 2005. The Australian experience has paralleled that in the US and Canada where small demonstration bridges were not followed by the acceptance hoped for. Dura's pioneers started with an intensive research program from 2006 to 2010. The program was supported by the Malaysian Public Works Department (JKR), the Irrigation and Drainage Department (JPS) and the Ministry of Rural and Regional Development (KKLW). It's aim was building "*longer span and lighter and easier to construct*" bridges without piers in the waterway, or as few piers as possible, especially in the rural development program where materials sources, site accessibility and conventional construction with large cranes are major constraints. The research program yielded the following important optimization results:

(1) UHPC mix designs were simplified using mostly local source materials. Further, a source of relatively low cost but high strength micro steel fibres, with tensile strength over 2700 MPa, were identified. As a result, a UHPC mix with 2% by volume of steel fibre that had a material cost of USD 2600/m^3 was reduced to about USD 600/m^3 [1]. Most importantly, the resulting concrete met all the engineering properties requirements for use of UHPC in major bridge members and systems. They include minimum characteristic compressive strength of f_{Uck} = 150 MPa, characteristic flexural strength of f_{cfk} = 20 MPa, and characteristic ultimate bending tensile strength of f_{Utuk} = 7.7 MPa [2].

(2) A large, 12 m^3 single shaft ribbon blender was used for mixing powder and highly viscous materials. The precast concrete product was sized so that it could be produced with only one batch of UHPC; piece weights were limited to about 20 tonnes. There is no waiting for the next batch, and no concern for differential setting time, thermal gradient, or shrinkage between batches. There are other benefits to making relatively small pieces, such as:

    (a) The UHPC is mixed in one cycle using the large mixer.
    (b) The precast elements can be made in a small, indoor facility.
    (c) The precast elements can be shipped in enclosed trucks and shipping containers.
    (d) The precast elements can be handled at the jobsite with small equipment.

(3) Use four standardized cross-sectional shapes (refer to Fig. 1):
   (a) Type 1: Decked bulb tees – integral beam-deck system with in-situ UHPC in-filled stitch.
   (b) Type 2a: Spliced segmented U-girders – precast/prestressed U-beam casted with in-situ conventional reinforced concrete (RC) deck.
   (c) Type 2b: Monolithic pretension or spliced segmental I-beams (length less than 24m) – precast/prestress I-beam casted with in-situ conventional RC deck.
   (d) Type 3: Segmental box-girder shapes for relatively long spans. The longest span achieved, so far, for the third shape is 100 m.
   (e) Type 4: Spliced segmented U-trough girder – normally for single lane traffic bridge construction.
(4) Use straight pre-tensioning where possible. Although, most applications involve spliced post-tensioned beams with straight bottom flange post-tensioning. The segment interfaces are match cast, with dry or epoxy joints.
(5) Employ strict quality control measures. Each batch is tested for 1 and 28 day average cube compressive strength, with minimum requirements of 70 MPa and 165 MPa, respectively, and for average flexural strength at 28 days, on a notched specimen, of 25 MPa. Testing is performed in accordance with [3] and [4] for compressive strength and flexural strength, respectively.

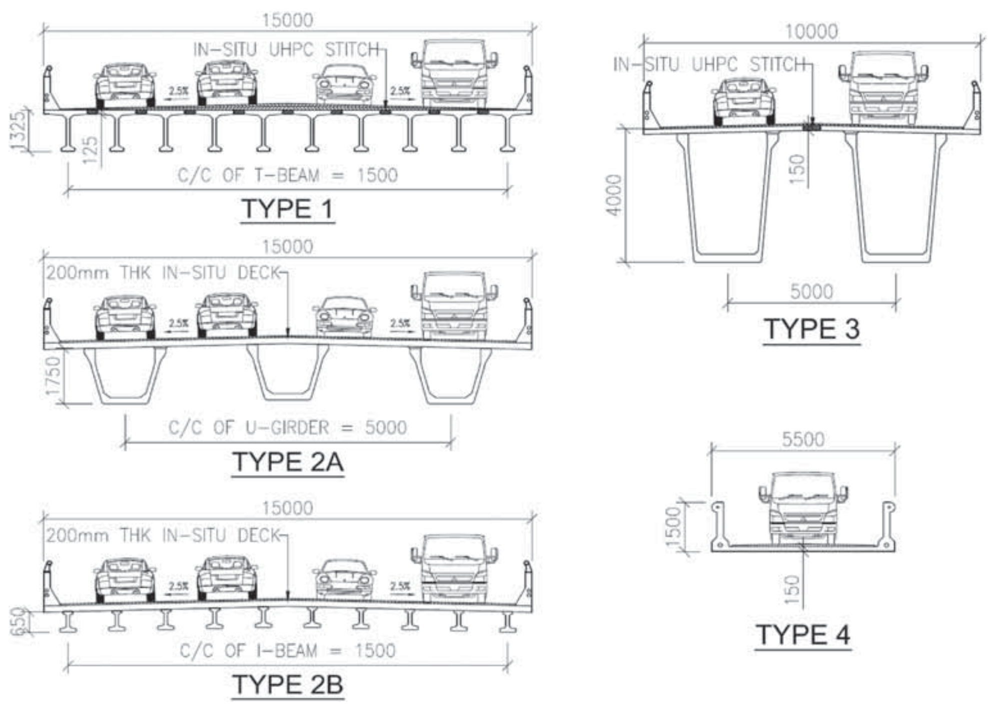
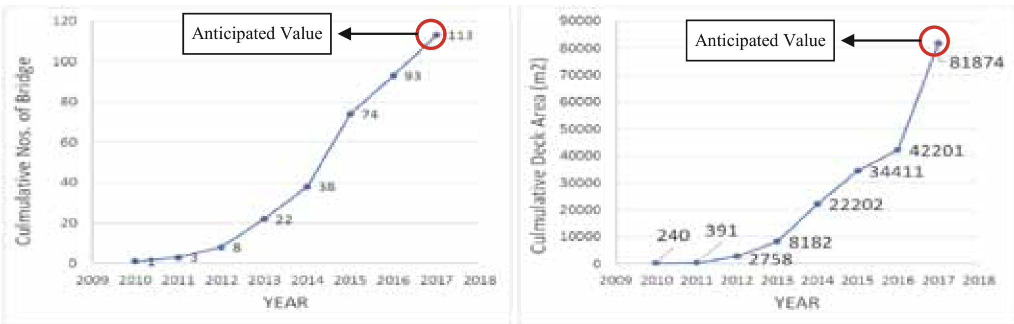


Fig. 1. Four different types of Dura® UHPC bridge girders.

These measures have resulted in highly successful and rapidly growing UHPC bridge systems. The optimization resulted in initial cost that is actually lower than the initial cost of conventional concrete construction. This fact alone has been a tremendous breakthrough, considering the relatively limited experience with this new technology. With further experience and refinements, the initial cost is expected to become even more favourable. The literature indicates that life expectancy of UHPC is close to 500 years, which far exceeds the range of 75–100 years life expectancy targeted by the design community.

Figure 2 show progression of bridge construction with UHPC in Malaysia since 2010. It started with one bridge with deck floor area of a mere 240 m^2 [5]. The number of completed bridges in each year since has been 2, 5, 14, 16, 36 and 19 in 2011, 2012, 2013, 2014, 2015 and 2016, respectively. The current year, 2017, is anticipated to break previous records. The deck area is expected to be about double that of the accumulated value to the end of 2016.

Figure 3(a) shows the type of UHPC bridge girders used in Malaysia. In terms of popularity, UHPC precast girder composite with in-situ RC deck bridges (i.e. Type 2) is the most commonly used (72% of applications) due to the construction cost being more competitive compared to conventional designs. Half of the superstructure concrete volume is constructed with conventional cast in-placed reinforced concrete (i.e. the bridge deck), so the relatively high UHPC material cost is partially absorbed by the lower conventional concrete material cost. Besides, the bridge owners and designers felt more comfortable in accepting "*one small change at a time*" – that is beam replacement only, instead of replacing the whole superstructure with a new material that currently does not have a national design code. In terms of constructability, bridge Type 2 is an easier option in that the weight is lower and the cast in-placed concrete is easier to shape and level to angle of inclination of the bridge deck cross-fall.



(a) (b)

Fig. 2. Quantity of DURA® UHPC bridges built in Malaysia from year 2010 to 2016 in term of (a) number of bridges and (b) deck floor area.

Figure 3(b) shows the type of prestressing used for the UHPC beams. All the segmental beams come with post-tensioning and is 68% of total applications. Segmental beams are normally used for longer span bridges (length > 25 m),

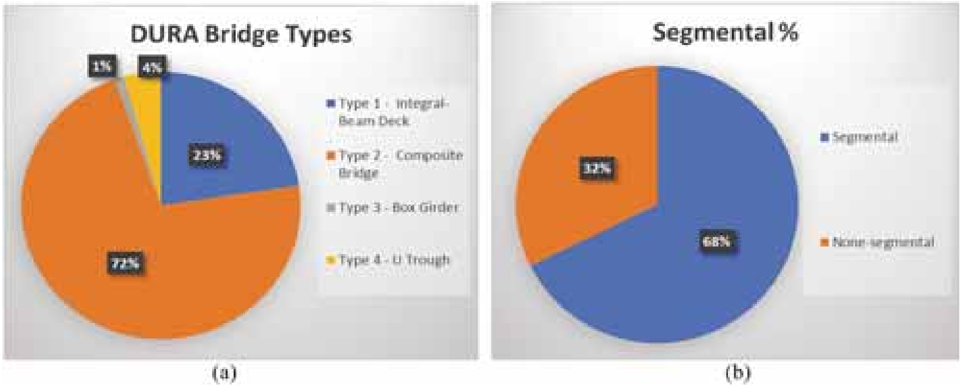


Fig. 3. Percentage on (a) UHPC bridge girders type and (b) segmental or none segmental.

or when transportation and weight of lifting are an issue. Pre-tensioning is used on monolithic beams, which normally are of shorter lengths (not exceeding 24 m).

3 Case Studies in Malaysia

3.1 Multi-span Bridge: Kampung Baharu-Kampung Teluk Bridge (KB-KT)

The Kg Baharu-Kg Teluk (KB-KT) bridge is understood to be the current record holder as the world's longest multiple-span road bridge superstructure constructed using UHPC precast/prestressed girders. It has a U-shape cross-section and the bridge crosses an estuary located at Ayer Tawar, Manjung, Perak (GPS Location: 4.30526°N; 100.6838°E). The construction cost was Ringgit Malaysia RM16.3 million (USD$3.62 million in Jan 2017). This cost includes the foundation piles, substructure, superstructure, temporary works, bridge fixtures, earthworks, and pile cap protection works.

Figure 4 shows the completed KB-KT bridge. The bridge superstructure consists of 20 UHPC precast U-beams (i.e. Type 2a). The typical cross-section of the superstructure is given in Fig. 5. Each beam has a total precast length of 41.5 m and is constructed from six segments (two pieces of 4.75 m long end/anchorage segments and four pieces of 8 m long standard intermediate segments). Each segment is 2.0 m deep, 3.0 m wide at the top and 1.4 m wide at the bottom flange. The segments were match-cast in the factory and delivered to site for assembly and post-tensioning. The total weight of the fully assembled girder is approximately 95 tonnes, including the weight of the tendons and grout. Unlike conventional precast concrete girders, this U-beam does not have vertical shear reinforcement in its 125 mm thin webs. The only conventional reinforcement used is the anti-bursting reinforcement located at the anchorage zones and the reinforcement

Fig. 4. Completed 420 metres long KB-KT bridge.

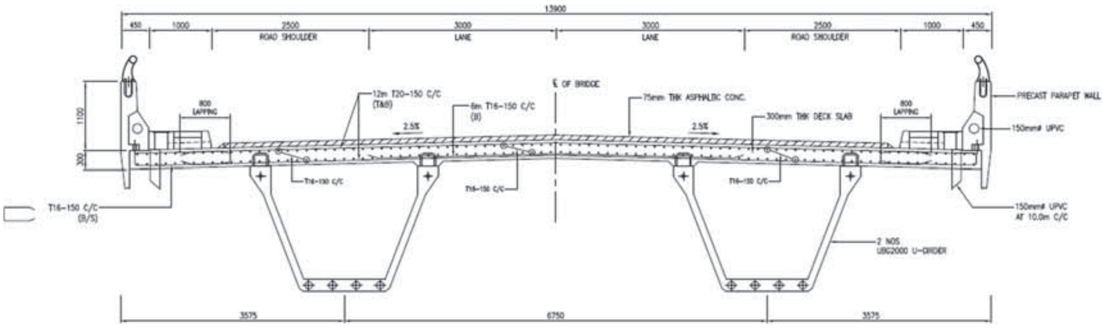


Fig. 5. Typical cross-section of KB-KT Bridge.

for transfer of longitudinal shear at the connection of the flanges and the Grade 40 in-situ deck slab.

The steel fibre reinforced UHPC used was produced by DTSB. The mechanical properties obtained from control specimen testing are summarized in Table 1. Each segment was cast using a separate batch of UHPC materials, with control samples collected from each batch. In total, 120 sets of samples were collected, one set for each pour or each segment. Each set of control samples consisted of a minimum of nine by 100 mm cubes and three 100 mm × 100 mm × 500 mm prisms. The cube compressive strength (f_{cu}) was determined using [3]. QA test results show that the UHPC used achieved a cube compressive strength of between 64 MPa and 100 MPa at 1 day, and 150 MPa to 188 MPa at 28 days. The average cube compressive strength for 1-day and 28-day were 89 MPa and 167 MPa, respectively. The characteristic compressive strength for 1-day and 28-day were 78 MPa and 154 MPa, respectively. The flexural strength (or modulus of rupture) was determined using [4]. The QA test results show the average and characteristic flexural strength after 28 days was 29.1 MPa and 24.5 MPa, respectively. Three cylinders of 100 mm diameter by 200 mm high from random units were tested for modulus of elasticity (E_o) and Poisson's ratio (v). The experimental results show that the UHPC had an average elastic modulus of E_o = 50.7 GPa and Poisson's ratio v = 0.2. The E_o values were determined according to [6]. Both the longitudinal and transverse strains were captured using electronic strain gauges. The construction sequence of the bridge can be obtained from DTSB [7].

Table 1. Mechanical property of UHPC used for KB-KT bridge.

Properties	Unit	Min	Max	Mean	S. D.	Characteristic
1 Day Compressive Strength, $f_{cu,1d}$	MPa	64	100	89[1]	6.6[1]	78
28 Days Compressive Strength, $f_{cu,28d}$	MPa	150	188	167[1]	7.7[1]	154
Flexural Strength, $f_{cf,28d}$	MPa	23.9	36.5	29.1[2]	2.8[2]	24.5
Modulus of Elasticity, E_o	GPa	50.0	51.7	50.7[3]	N/A	N/A
Poisson's Ratio, v		0.19	0.21	0.2[3]	N/A	N/A

1. Out of min 360 cube samples
2. Out of 360 prism samples
3. Out of 3 cylinder samples

3.2 Single Span: Batu 6 Bridge

The Batu 6 Bridge is understood to be the current longest single span road bridge where the superstructure is constructed entirely using UHPC. This bridge has recently obtained the Precast/Prestressed Concrete Institute PCI 2016 Design Award for being the best *International Transportation Structure*. The bridge has a box girder cross section and it crosses Sungai Perak, located at Batu 6, Gerik, Perak (GPS Location: 5.4504°N, 101.1866°E).

The construction cost was Ringgit Malaysia RM6.3 million (USD$1.4 million). The cost includes the piling foundation, substructure, superstructure, temporary works, road and bridge fixtures, solar-powered street lighting, earthworks, 600 m long by 5 m wide approach road works and slope protection works.

Figure 6 shows the completed Batu 6 Bridge. The bridge superstructure consists of 40 precast UHPC segments. Each segment is 4 m deep, 2.5 m long and 5 m wide. The segments were match-cast in the factory and delivered to site for assembly and post-tensioning. The total weight of the full-span girder is approximately 670 tonnes, excluding the weight of the tendons and grout. Unlike conventional precast concrete girders, this box girder does not have vertical shear reinforcement in its 150 mm thin webs. The webs are locally thickened over a small region at the matched joints to accommodate the shear keys. Each of the 36 typical segments weigh 16.5 tonnes. The two end segments each weigh 20 tonnes. The second-to-the-end segments weigh 18 tonnes. With 30 tonnes of prestressing cable, 10 tonnes of grout, 52 tonnes for the wearing surface and 30 tonnes for railings and ancillary fixtures, the total weight of the bridge is about 780 tonne. The only conventional reinforcement used is the anti-bursting reinforcement located at the anchorage zone and the reinforcement for transfer of longitudinal shear at the connection of the flanges and the UHPC deck slab that was cast in a second pour.

Fig. 6. 100 m long single span Batu 6 Bridge.

The mechanical properties obtained from control specimen testing are summarized in Table 2. QA test results show that the UHPC achieved a cube compressive strengths of between 82 MPa and 95 MPa at 1 day, and 165 MPa to 185 MPa at 28 days. The characteristic compressive strength for 1-day and 28-days were 78 MPa and 163 MPa, respectively. The QA test results show the characteristic flexural strength after 28 days was 24.4 MPa. Three cylinders of 100 mm diameter by 200 mm high were tested for modulus of elasticity (E_o) and Poisson's ratio (v). The experimental results show that UHPC has an average elastic modulus E_o = 45.6 GPa and Poisson's ratio v = 0.2. The construction sequence of the bridge can be obtained from [8].

Table 2. Mechanical property of UHPC used in Batu 6 Bridge.

Properties	Unit	Min	Max	Mean	S.D.	Characteristic
1 Day Compressive Strength, $f_{cu,1d}$	MPa	82	95	85[1]	4.4[1]	78
28 Days Compressive Strength, $f_{cu,28d}$	MPa	165	185	173[1]	6.2[1]	163
Flexural Strength, $f_{cf,28d}$	MPa	26.6	31.2	29.1[2]	2.8[2]	24.4
Modulus of Elasticity, E_o	GPa	44.8	46.8	45.6[3]	N/A	N/A
Poisson's Ratio, v		0.19	0.21	0.2[3]	N/A	N/A

1. Out of min 240 cube samples
2. Out of 360 prism samples
3. Out of 3 cylinder samples

3.3 Internet Transmission Tower

The Malaysia Ministry of Science, Technology and Innovation (MOSTI) funded DTSB with a *Technofund* grant for an industrial research project entitled "*Development and construction of the Malaysia first internet transmission tower using UHPC*".

In the Malaysian government's 2014 budget, one of the major announcements was the implementation of the High-Speed Broadband (HSBB) project under the National Broadband Initiative. To expand coverage in major towns, the 2nd phase

(a) (b) (c)

(d) (e) (f)

Fig. 7. Lifting/assembling of (a) first bottom-segment; (b) second middle-segment; (c) third top-segment. (d) Fully assembled UHPC prestressed/precast tower with (e) ladder and working platform installed. (f) Full-scale cyclic loading test on the segmental epoxied joint at the structural laboratory of Universiti Putra Malaysia.

of HSBB will be implemented in collaboration with the private sector, involving a RM 1.8 billion (USD$400 million) investment. This is expected to provide more coverage in urban areas, benefiting 2.8 million households. Internet speed will be increased to 10 Mbps. There will also be more internet coverage to rural areas; thus, the need for a durable, sustainable and cost effective towers or poles in order to accomplish the plan.

In Malaysia, internet transmission towers are usually constructed from galvanised steel poles or steel frames. The objective of this initiative is to develop, plan and construct a new generation of durable and affordable transmission tower systems using UHPC. The UHPC tower can be constructed in a purely dry way, the precast UHPC segmental tubes are assembled with each other in a modular form. Figure 7(a)–(e) shows the UHPC tower being assembled using one unit 45 tonne mobile crane.

The tower was built at the factory of DTSB as a demonstration and also for non-destructive health monitoring test purpose. The total weight of the tower is 11 tonnes and it is 30 m high. Each tower consists of three 10 m long precast/pretension tapered tubular ring-like pipes, with the connected ends thickened for bolting. The ring section has a uniform thickness of 50 mm. The UHPC tubes are placed on top of each other with a layer of epoxy applied to the joint interface. They are then tightly fastened using stainless steel bolts and nuts.

An extra tower was made for proof load testing. The experiment was conducted at the structural laboratory of Universiti Putra Malaysia (UPM) under the direction of Dr Farzard Hejazi. The study included finite element modelling of the tower and the following experimental testing: (i) non-destructive health monitoring; (ii) destructive cyclic-dynamic load test; and (iii) destructive static load test (refer to Fig. 7(f)).

3.4 UHPC Portal Frame Building

In 2008, a portal frame building named *Wilson Hall* (named for the co-founder of Dura C.N. (Wilson) Leong) with a roof coverage area of 2,860 m^2 was built using the prefabricated system of UHPC technology. The width and length of the building is 67 m and 42.7 m, respectively. Each UHPC portal frame was spaced at 12.2 m centres and the building consists of eight pieces of UHPC precast/prestressed columns, internal rafters, cantilever rafters and connections (shown in Fig. 8). This building was a first look at an alternative to conventional steel I-beams/columns for portal frame construction. More detail of the design of the fame is given in [9].

Fig. 8. UHPC portal frame (before completion at year 2008).

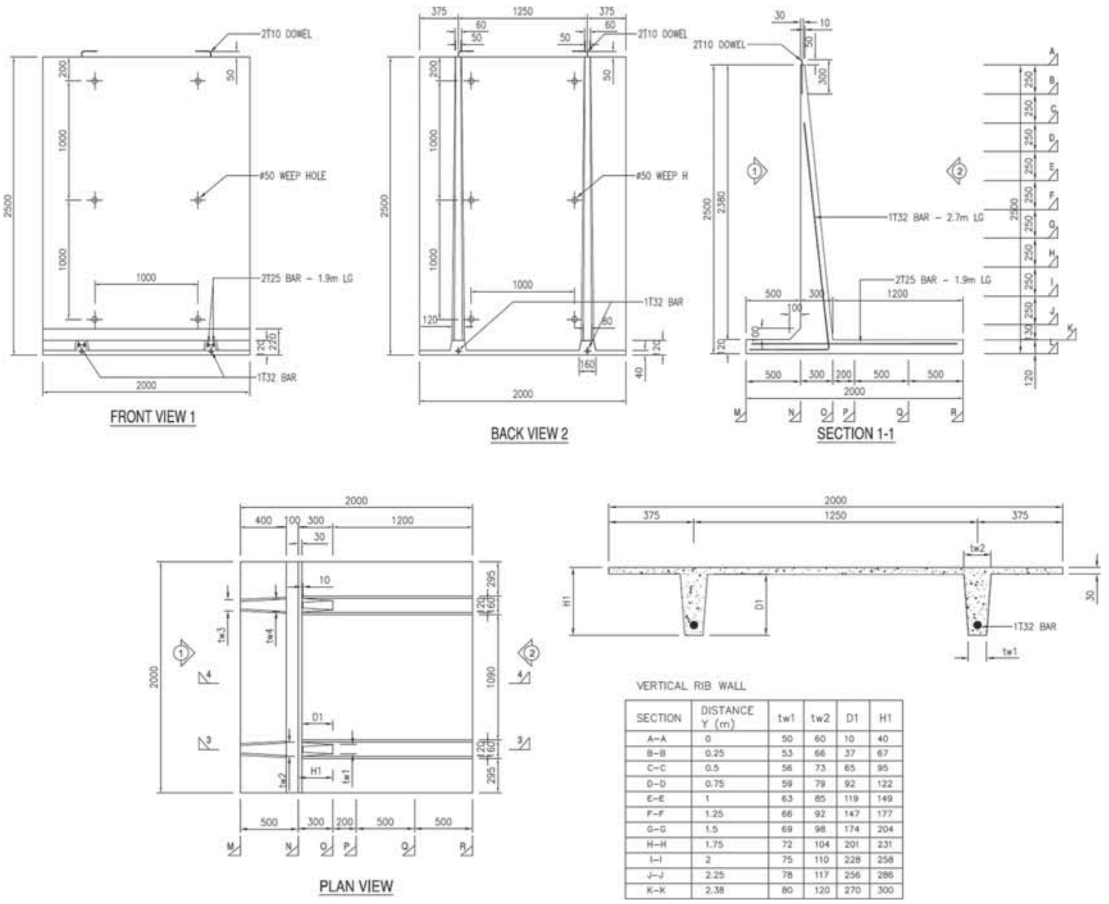
3.5 Cantilever Retaining Wall

UHPC is ideal for precast short retaining wall construction (for height < 3 m) due to its ultra-high strength-ultra-light-weight features. Figure 9 shows the detail of a 2.5 m tall UHPC L-shaped cantilever retaining wall. The wall has a width of 2.0 m per piece and a base length also of 2.0 m. Each of the wall segments weighs 1200 kg (i.e. 600 kg/m). Unlike conventional RC walls, the UHPC wall does not contain any transverse reinforcement or crack control bars in any part of the wall section. The only conventional steel reinforcement used is a small amount of longitudinal bars in the counterfort thickening (or ribs) and the adjacent base region. This is to resist the critical design moment resulting from the imposed loadings.

Figure 10(a) and (b) shows the lightness, and toughness, of UHPC L-shaped retaining walls, as they are stacked on top of each other without compromising quality. In 2013, the Irrigation and Drainage Department of Malaysia (JPS) constructed a 120 m long river protection structure at Sungai Ara, Perak using the UHPC retaining wall described. It took just two weeks to complete the entire construction work, including site clearing works, preparation of the granular base, placing and assembling of the walls and back filling of the earth. The UHPC retaining wall system provided for a speedy construction solution.

3.6 Anti-climb Free Standing Wall

One of the notable properties of UHPC is its high flowability and its ability for self-compaction. Coupling these with its superior mechanical properties, such as flexural-tensile strength, makes it an ideal material for the manufacturing of thin and light-weight precast wall panels, without conventional steel reinforcement. Unlike conventional RC wall panels, there is no concern of corrosion as there are no conventional steel bars in any parts of the structure.



SECTION	DISTANCE Y (m)	tw1	tw2	D1	H1
A–A	0	50	60	10	40
B–B	0.25	53	66	37	67
C–C	0.5	56	73	65	95
D–D	0.75	59	79	92	122
E–E	1	63	85	119	149
F–F	1.25	66	92	147	177
G–G	1.5	69	98	174	204
H–H	1.75	72	104	201	231
I–I	2	75	110	228	258
J–J	2.25	78	117	256	286
K–K	2.38	80	120	270	300

Fig. 9. Detail of UHPC retaining wall.

Figure 11(a) shows a 56 m long free standing anti-climb protective wall that was constructed in 2008. Each precast panel is 7 m high and has a width of 2 m. The self-weight is 2400 kg per piece. The face is 30 mm thick, with two 75 mm wide tapered flanges and a 100 mm thick base plate (Fig. 11(b)).

The wall panel has multiple applications such as use as protection against the environment, privacy, acoustic emissions, etc. The benefits of the UHPC, wall when compared to conventional RC walls, is its high durability and being impermeable, making it suitable for use in aggressive environments such as marine exposure or chemically active plants. Installation is by conventional drop-in anchors or pre-positioned bolts, with base levelling grout, if needed. No scaffolding or formwork is required for the installation, reducing construction site activities, improving safety and eliminating in-situ casting work. It is many times lighter than conventional RC wall systems and is guaranteed to be geometrically stable, due to steam-curing. The off-form finish on the faces provides for a smooth surface.

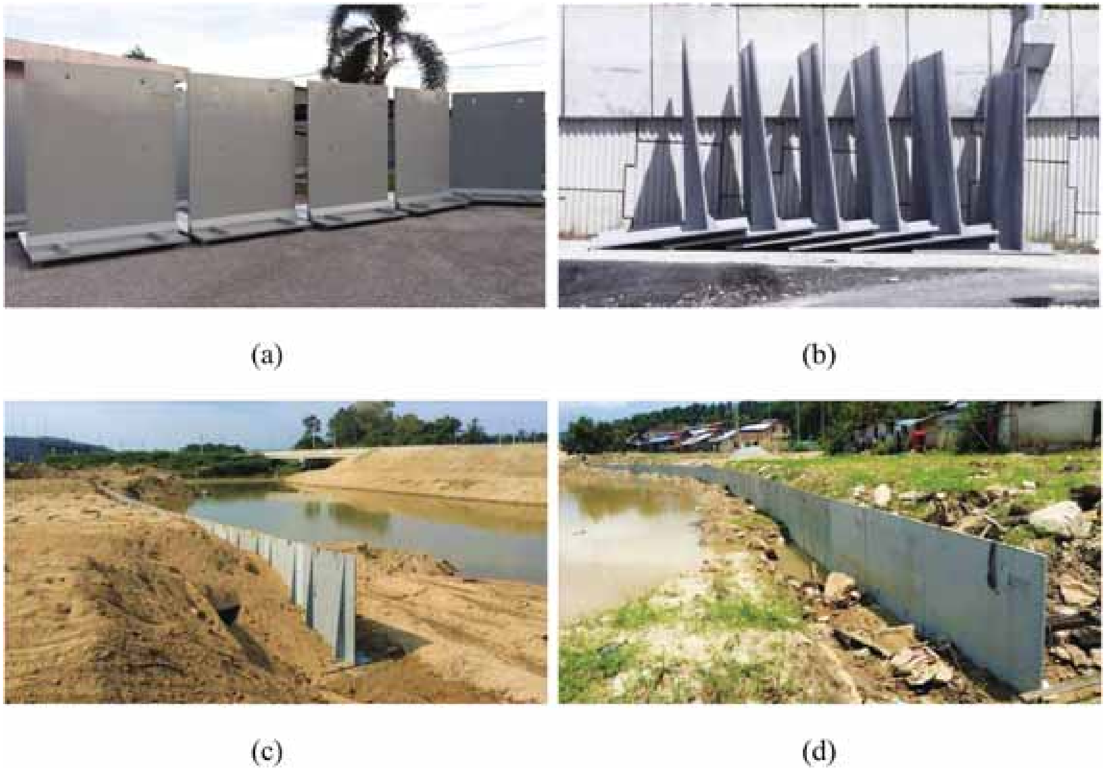


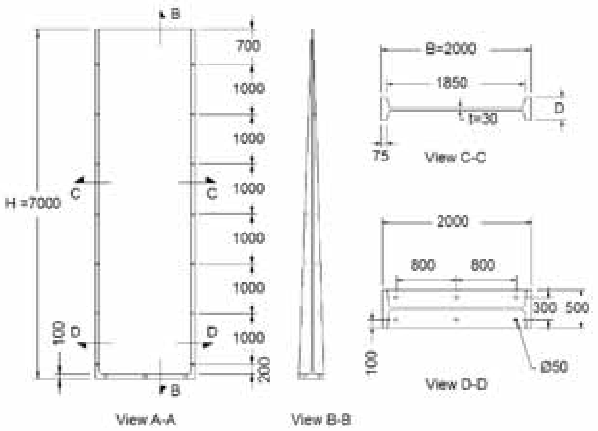
Fig. 10. (a) and (b) UHPC retaining wall at storage yard; (c) and (d) 120 m long retaining wall installed for slope and river protection.

3.7 Monsoon Drain

Figure 12(a) shows a 180 m long by 1.5 m high L-shape retaining wall that was used in the construction of a 90 m long monsoon drain for a housing development project in Ipoh, Perak. The L-shaped wall comes with thin panels of 30–50 mm thick (see Fig. 12(b)). Unlike conventional RC L-shaped precast walls, which weight 1200 kg per lineal metre, and are provided in one metre lengths, the UHPC retaining wall is made in 3 m lengths per piece (Fig. 12(c)) and have a self-weight of just 260 kg per lineal metre of wall; that is a factor of five times lighter than the conventional solution. Prior-to construction of the wall, the local council requested a load proof test of the wall panel to meet a service surcharge loading of 10 kPa, and a 15 kPa surcharge at ultimate. The wall was tested with back filled soil up to 1.5 m and an additional surcharge load of 25 kPa; that is, 66% greater than the strength limit requirement and still it did not fail! Thus, the wall performance was demonstrated to satisfy both design service and strength requirements.

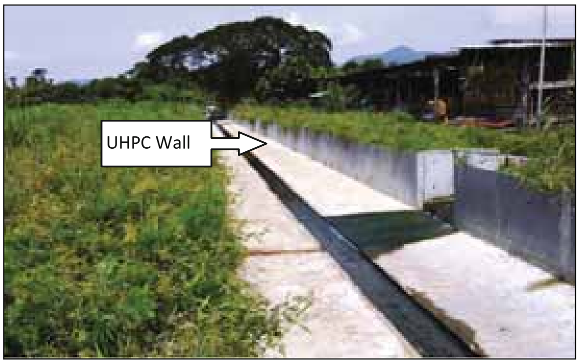
Figure 12(d) shows a comparison of an environmental impact calculation (EIC) for the UHPC retaining wall system, compared to the conventional L-shaped RC wall shown in Fig. 12(c); further details of the EIC are given in [10]. In terms of material consumption, the UHPC retaining wall has 73% less material than the conventional wall. In terms of the environmental indexes, the UHPC wall has one-half the embodied energy and one-half the CO_2 emissions than the conventional solution. In terms of the 100-year global warming potential (100-year GWP), the UHPC solution provides a reduction of 43%. This it is an example of how innovative design with UHPC supports sustainable construction solutions.

(a)

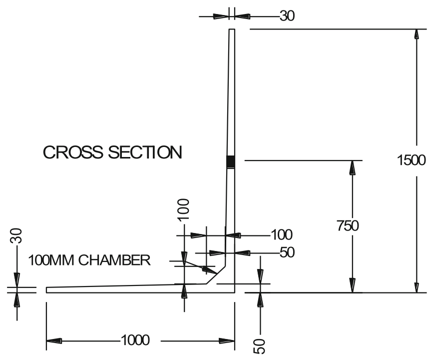


(b)

Fig. 11. (a) UHPC anti-climb wall and (b) detail of wall panel.

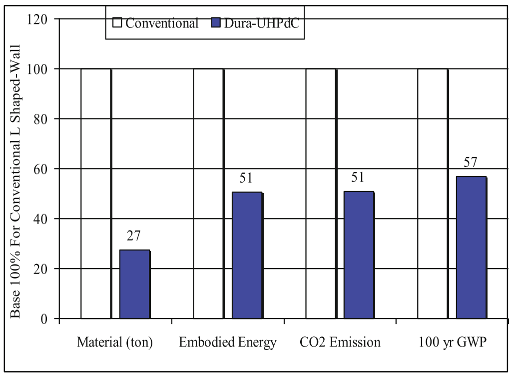


(a)



(b)

(c)



(d)

Fig. 12. (a) 90 m long monsoon drain using UHPC retaining wall; (b) cross-section detail; (c) comparison of conventional precast L-shape retaining wall with UHPC wall; and (d) environmental impact calculations of UHPC retaining wall.

4 Case Studies in Singapore

4.1 Precast Bathroom Unit (PBU)

Tiong Seng Group (TSG) developed a proprietary Lithe^{TM} Prefabricated Bathroom Unit (PBU) system utilising Dura UHPC. The PBU is pre-assembled off-site complete with finishes, sanitary wares, pipes and fittings, before installing into position. TSG's PBU system is lighter than most systems on the market. This greatly enhances the manoeuvrability of the unit without the need for specialised lifting equipment. The light weight of the Lithe PBU also decouples the installation of the unit from the building's structural works schedule, allowing installation to be executed as a non-critical path item. This leads to substantial time and manpower savings over the construction schedule.

To-date, more than 4500 UHPC PBUs have been installed in various high end residential projects in Singapore. Figure 13 shows a complete PBU display at an exhibition showroom during the *BuildTech Asia 2016* exhibition in Singapore.

Fig. 13. PBU display at an exhibition showroom.

4.2 External Wall for Precast Pre-finished Volumetric Construction (PPVC)

After the PBU, TSG next exploded UHPC in the design and manufacturing of precast pre-finished volumetric construction (PPVC) in Singapore, where PPVC refers to a construction methodology of modularising entire building units, complete with finishing and with construction off site. This encouraged the industry to incorporate the concept of *Design for Manufacturing and Assembly* (DfMA), where the product is designed such that as much work as possible of the manufacturing is done away from the construction site, in a controlled environment. Tiong Seng went on to develop their own proprietary Lithe^{TM} PPVC system incorporating the usage of Dura UHPC as external walls for the system. UHPCs unique property of being highly impervious to water penetration makes it an ideal material for external walls. Figure 14 shows the lifting of a PPVC module, demonstrating its light-weight and ease of assembly.

Fig. 14. Lifting of PPVC unit.

5 Conclusions

This paper presents on the 10 year journey of UHPC constructions in Malaysia and Singapore. So far, more than 90 UHPC bridges have been constructed, with a further 20 at various stages of tender, design or construction. One of the key advantages of UHPC is its high strength to weight ratio. This makes it an ideal material for prestressed construction solutions. Due to this lightness and strength, UHPC members can be made in a modular form needing smaller equipment and machinery and reduced temporary works. This is particularly beneficial in remote and rural areas where heavy construction equipment is in short supply.

In addition to bridges, the paper presented on a range of novel applications, such as walls, telecommunications polls, portal frame and prefabricated bathroom units. In each case, light weight and speed of construction are fundamental to commercial success. In the case of prefabricated bathroom units, the ability to take the units off the critical path leads to substantive savings in construction time and costs.

Lastly, it is recognised that while UHPC is no longer a new material, national building codes and standards have yet to be developed. This is an impediment to a greater take up of this outstanding technology and should be a priority for both national standards organisations as well as international bodies such as *fib*.

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