MALAYSIA, TAKING ULTRA HIGH PERFORMANCE CONCRETE BRIDGES TO NEW DIMENSIONS

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Abstract

This paper presents the current state of practice in the utilization of ultra-high performance fibre reinforced concrete (UHPFRC) bridge construction in Malaysia. Since 2006, Dura Technology Sdn Bhd (DTSB) has pioneered research in the optimal uses of UHPFRC in bridge construction through its *Sustainable Bridge Construction Initiative*. At the time of date writing of this paper, a total of 93 UHPFRC bridges have been constructed, with 87 of these bridges for vehicular traffic and 6 for pedestrians. There are a further 12 bridges that are in construction and 5 in the tender stage and more than 10 in design stage. The typical types and shapes of the UHPFRC bridge beams used in Malaysia is presented. Two case studies are also presented; the first is on the ten equal spans, 420-metre-long, Kg Baharu-Kg Teluk Bridge. The second case study is an up-coming project on the Tanjung Kuala Gum Gum Bridge at Sabah. If completed as planned in 2020, this bridge will have a total length of 577 metres, with nine equal 50.5m spans and one centre span of 120m.

Résumé

Cet article présente l'état actuel des pratiques dans l'utilisation de béton fibré à ultra-hautes performances (BFUP) pour la construction de ponts en Malaisie. Depuis 2006, Dura technology Sdn Bhd (DTSB) a innové en matière de recherche dans l'utilisation optimale du BFUP dans la construction de ponts au travers de son projet « initiative de construction de ponts pour la croissance verte ». Au moment où a été écrit cet article, 93 ponts en BFUP ont été construits au total, dont 87 pour le trafic automobile et 6 pour les piétons. Il y a en outre 12 ponts en construction, 5 en cours d'appel d'offre et plus de 10 en cours d'étude. Les formes et types de poutres de ponts en BFUP employés en Malaisie sont présentés. Deux études de cas sont détaillées ; la première est un pont de 420 mètres de long divisé en 10 travées égales : le pont Kg Baharu-Kg Teluk. La deuxième étude de cas est un projet imminent pour le pont Tanjung Kuala Gum Gum à Sabah. S'il est achevé comme prévu en 2020, ce pont aura une longueur de 577 mètres avec 9 travées égales de 50.5 m et une travée centrale de 120 mètres.

1. INTRODUCTION

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

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

In the authors view, there is already sufficient knowledge and technical know-how to utilise this technology at large scale; often the resistance is 1) in the initial high investment cost of facilities and 2) the lack of design codes, which require designers and end users to carry higher insurance risk. This outstanding technology has struggled to become a main-stream for everyday use, not for technical or commercial reasons but due a general aversion to risk of new technologies in the engineering profession and by regulatory authorities – and a lack of investment of asset owners in promoting development in new technologies.

Notwithstanding the above criticisms on our profession, it is recognised that private and governmental bodies are directing increasing attention and initiative towards exploiting UHPFRC as a future construction material, in the belief that UHPFRC technology embraces the complete solution for sustainable construction with favourable life cycle values. In Malaysia, use of UHPFRC started as an organized effort based on a solid foundation that has resulted in excellent and sustainable results. The technology has been shown to be commercially and practically viable [1-3]. The result so far has seen the completion of over 90 bridges and with contracts on a further twenty. In a search of the literature, the completion of about 200 pedestrian and vehicular bridge projects are identified, globally. These projects include utilization of UHPFRC in one or more components of the bridges.

2. THE DURA EXPERIENCE

Introduction of UHPFRC in Malaysia started in 2006. The company Dura Technology Sdn Bhd (DTSB) was founded by Dr Yen Lei Voo and, his colleague, Wilson Leong C.N. after Dr. Voo completed his Ph.D. at UNSW Sydney, Australia, under the direction of the second author. Dura's pioneers started with an intensive research program from 2006 to 2010; the program was strongly supported by the Malaysian Public Works Department (JKR); Irrigation and Drainage Department (JPS) and Ministry of Rural and Regional Development (KKLW). The program aimed at building "longer span" 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 outcomes:

(1) UHPFRC mix designs were simplified. The constituent materials were reduced to ordinary Portland cement, silica fume, sand, superplasticizer and water. Further, relatively low cost but high strength steel fibres with tensile strength over 2700 MPa were identified. As a result, the UHPFRC mix with 2 % by volume of steel fibre that

normally has a material cost of USD 2600/m^3 was reduced to about USD 600/m^3 [3]. Most importantly, the resulting concrete met all the engineering properties requirements for use of UHPFRC in major bridge members and systems. They include a characteristic compressive strength of $f_{ck} \geq 150$ MPa, characteristic flexural strength of $f_{cfk} \geq 20$ MPa and characteristic bending tensile strength of $f_{Utuk} \geq 7.7$ MPa [4].

(2) It was decided to have a large geometrical volume mixer, 12 m^3 and above, with sufficient capacity for a single batch for any element cast. It was also decided not to precast a product where size requires more concrete than allowed in one mixing cycle. The corresponding product weight would be about 20 tonnes (a comfortable limit for transport and site carnage). This way, there would be no waiting for fresh concrete delivery and no concern about cold joints. Also, steam curing processes eliminates concern about such factors as differential setting time, thermal gradient and differential shrinkage in the final product. Thus, highly consistent products are produced.

(3) Use four standardized cross-section shapes (Figure 1):

   a. Type 1: Decked bulb tees – integral beam-deck system with in-situ UHPFRC in-filled stitch.
   b. Type 2a: Spliced segmented U-girders – precast / prestressed U-beam casted with in-situ conventional RC deck.
   c. Type 2b: Monolithic pre-tensioned or spliced segmental I-beams (length of 24 metres and less) – precast / prestressed I-beam constructed with a conventional in-situ reinforced concrete deck.
   d. Type 3: Segmental box-girder shapes for relatively long spans. The largest span achieved for the third shape, so far, has been 100 metres.
   e. Type 4: Spliced segmented U-trough girder – normally for single lane traffic bridge construction.

(4) There are significant, counter-intuitive, benefits to making relatively small pieces. They can be made in small indoors facility. They can be shipped in multiple ways including enclosed trucks and shipping containers. They can be handled at the site with small equipment.

(5) Use straight pre-tensioning where possible. Most applications involve spliced post-tensioned beams, with straight bottom flange post-tensioning. The segment interfaces are match cast, with dry or epoxy joints.

(6) Employ a strict quality control procedure that requires each batch to be tested for 1 and 28 day average cube compressive strengths of 70 MPa and 165 MPa, respectively, and average flexural strength at 28 days of 25 MPa, on a notched specimen. The testing is performed in accordance with [5] and [6] for compressive strength and flexural strength, respectively.

(7) Simplify design of most bridges by eliminating the need for time dependent stress-redistribution analysis, since creep and shrinkage of this material are negligible after a period of steam curing. Noting though that creep growth of camber and deflection may still need to be considered by the designer in construction geometrics.

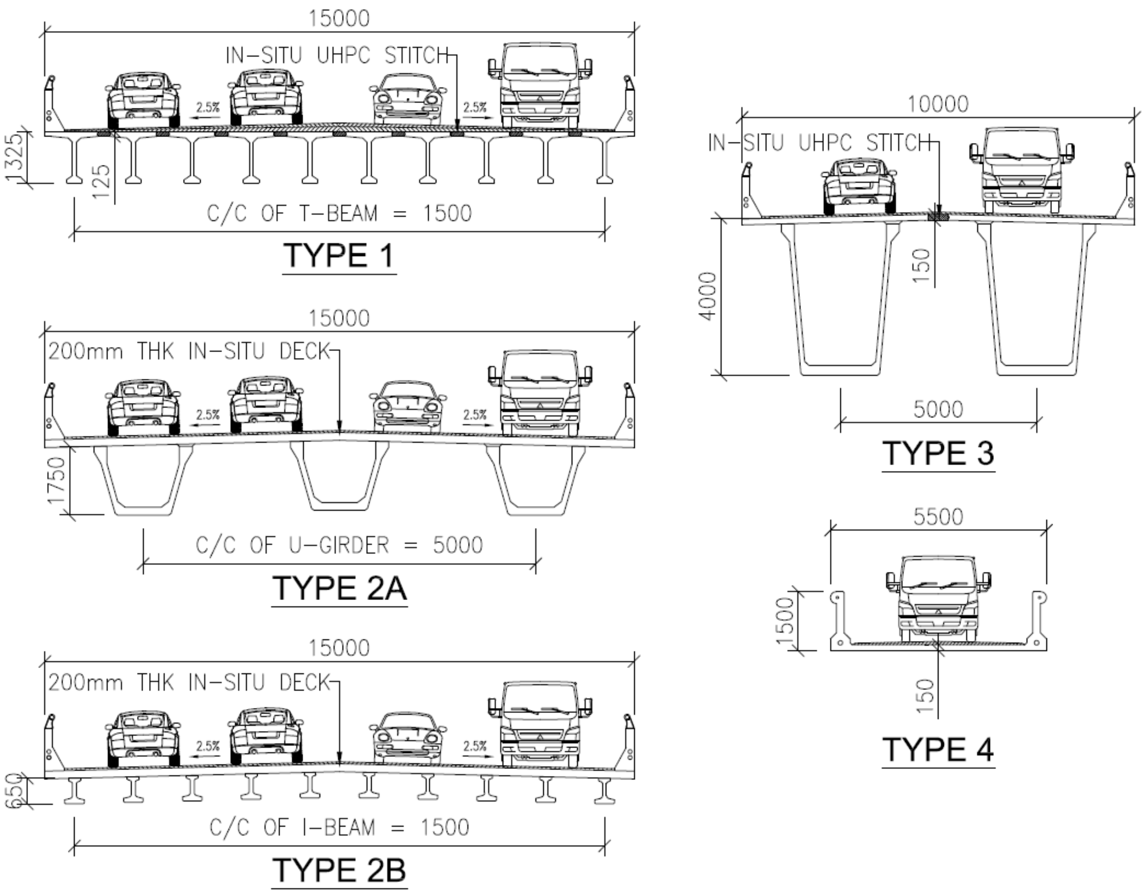


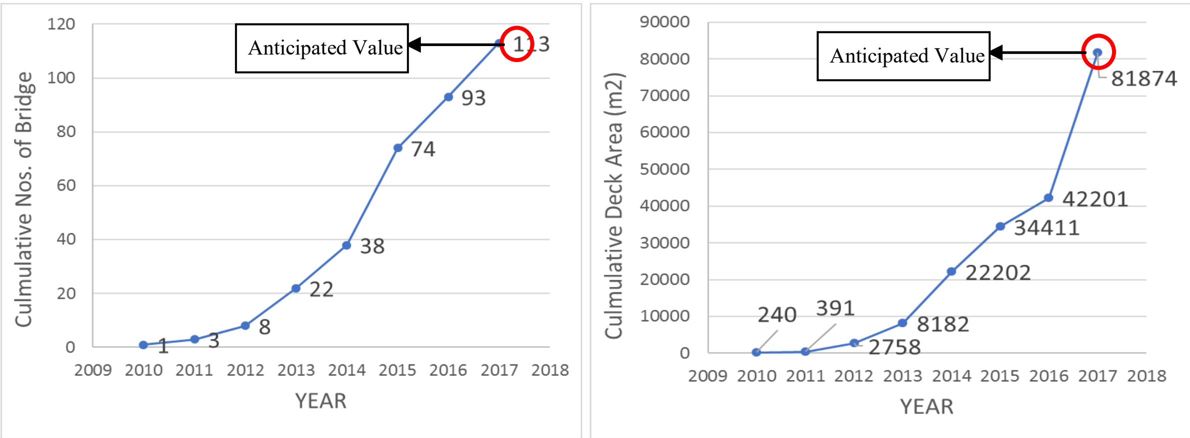
Figure 1: Four different types of DURA® UHPFRC bridge girders.

These measures have resulted in highly successful and rapidly growing UHPFRC bridge systems. The optimization resulted in initial cost that is lower than the initial cost of conventional concrete construction. This 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.

In regards to durability and sustainability, the literature indicates that life expectancy of UHPFRC is potentially more than 300 years [1, 7, 8]; far exceeding the 100-year life expectancy targeted by the bridge design community.

Figure 2 shows progression of bridge construction with UHPFRC in Malaysia since year 2010. It started with one bridge with deck floor area of merely 240 m^2 [9] It has progressed exponentially. The number of completed bridges increased to 2, 5, 14, 16, 36 and 19 in 2011, 2012, 2013, 2014, 2015 and 2016, respectively. In 2017 it is expected to continue to break these previous records and the deck area is expected to double over that of 2016.

Figure 3a shows the type of UHPFRC bridge girders used in Malaysia since 2010. In terms of popularity, UHPFRC precast girder composite bridges with in-situ RC deck (Type 2) are the most commonly used (72 % of the applications), as the construction cost is competitive with conventional designs. Half of the superstructure concrete volume is constructed with conventional cast in-place reinforced concrete (i.e. the bridge deck), so the relatively high UHPFRC material cost per unit volume is partially absorbed by the lower conventional concrete material cost. Besides, bridge owners and designers are more comfortable to accept "*one small change at a time*" – that is beam replacement only, instead of replacing the whole superstructure with a new material, for which there is no national design codes available. In terms of constructability, Type 2 is an easier option than conventional RC designs due to the lower weight of the UHPFRC girders, than conventional RC girders, and in that RC deck concrete is easier to shape to the level and angle of inclination of bridge deck cross-falls.



(a) (b)

Figure 2: DURA® UHPFRC bridges built in Malaysia from year 2010 to 2016 and anticipated values in 2017: (a) number of bridges constructed; (b) deck floor area.

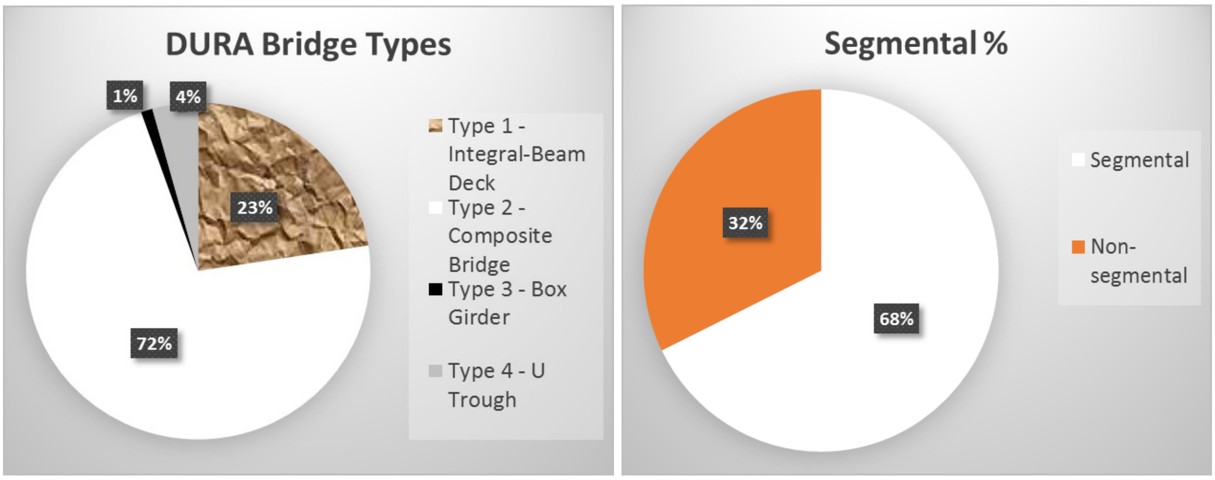


Figure 3: Percentage of (a) UHPFRC bridge girder types constructed and (b) segmental or non-segmental.

Figure 3b shows the type of prestressing used for the UHPFRC beams. Segmental beams represent 68 % of the bridges and are normally used for longer span bridges, or when transportation and weight of lifting are an issue. Pre-tensioning is used on monolithic beams, which normally are of a shorter length (maximum 24 metres).

3. KG. BAHARU-KG TELUK BRIDGE (KB-KT)

The 420 metre long Kg Babaru-Kg Teluk (KB-KT) bridge is one of the world's longest multiple-span road bridge superstructure currently constructed using UHPFRC precast, prestressed girders. It has a U-shape cross-section and the bridge crosses an estuary, located at Ayer Tawar, Manjung, Perak (GPS Location: 4.30526ºN; 100.6838ºE). The construction cost was Ringgit Malaysia RM 16.3 million (USD 3.62 million in January 2017). This cost includes the piling foundation, substructure, superstructure, temporary works, bridge fixtures, earthwork, and pile caps protection works.

Figure 4 shows the completed bridge. The bridge superstructure consists of 20 UHPFRC precast U-beams (Type 2a). The typical cross-section of the superstructure is shown in Figure 5. Each beam has a total precast length of 41.5 metres and it comes with six segments – two pieces of 4.75-metre-long end/anchorage segments and four pieces of 8.0 metre long standard intermediate segments. Each segment is 2.0 metres deep, 3.0 metres wide at the top and 1.4 metres 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 full-span girder is about 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 for transfer of longitudinal shear at the connection of the flanges and the Grade 40 in-situ deck slab. The construction sequence of the bridge is given in [11].

The steel fibre reinforced UHPFRC used was produced by DTSB. The mechanical properties obtained from control specimen testing are summarized in Table 1. As outlined above, strict quality assurance (QA) requirements for UHPFRC products are set by DTSB. Each segment was cast using a separate batch, with control samples collected from each batch. A total of 120 sets of samples were collected, one set for each pour (i.e. each segment).

Figure 4: completed 420-metre-long KB-KT Bridge.

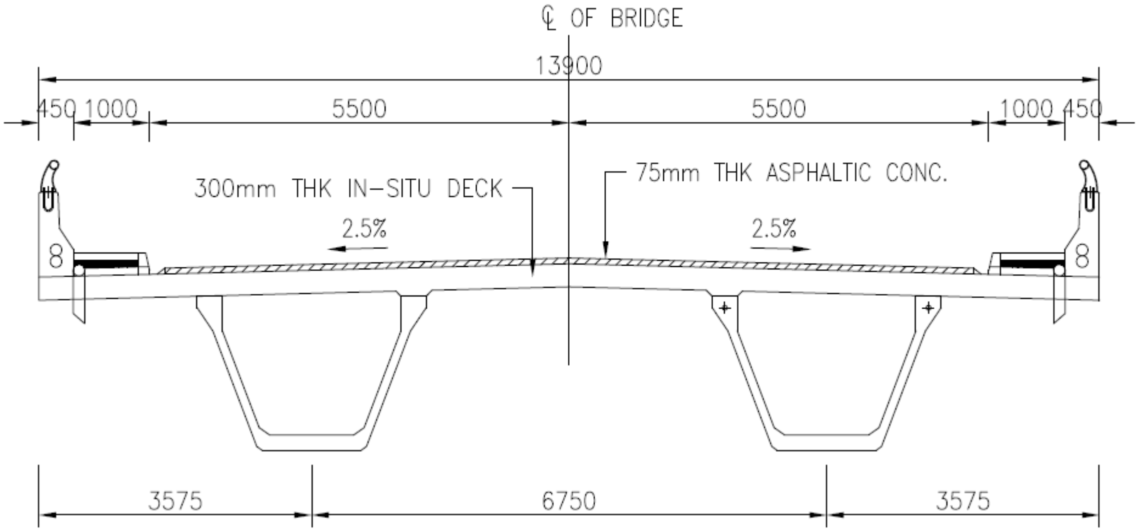


Figure 5: Typical cross-section of KB-KT Bridge.

Each set of control samples consisted of a minimum of nine by 100 mm cubes and three 100 mm x 100 mm x 500 mm prisms. The cube compressive strength (f_{cu}) was determined using [5]. A summary of the test results for the UHPFRC used on the KB-KT Bridge is given in Table 1.

The QA test results from 360 1-day tests and 360 28-day cube compressive strength tests showed strengths between 64 MPa to 100 MPa at 1 day, and 150 MPa to 188 MPa at 28 days. The average cube compressive strength for 1-day and 28-days were 89 MPa and 167 MPa, respectively. The characteristic compressive strength for 1-day and 28-days were 78 MPa and 154 MPa, respectively.

The flexural strength (or modulus of rupture) was determined using [6]. The QA results from 360 tests show the average and characteristic flexural strength after 28 days were 29.1 MPa and 24.5 MPa, respectively.

Three cylinders of 100 mm diameter by 200 mm high from randomly cast batches were tested for modulus of elasticity (E_o), in accordance with [10], and Poisson's ratio (ν), with electronic strain gauges used to obtain both the longitudinal and transverse strains. The experimental results gave an average elastic modulus E_o = 50.7 GPa and Poisson's ratio ν = 0.2.

Table 1: Mechanical property of UHPFRC used for KB-KT Bridge.

Property	**Min**	**Max**	**Mean**	**Std. Dev.**	**Characteristic**
1 Day Comp. Strength, $f_{cu,1d}$ (MPa)	64	100	89	6.6	78
28 Days Comp. Strength, $f_{cu,28d}$ (MPa)	150	188	167	7.7	154
Flexural Strength, $f_{cf,28d}$ (MPa)	23.9	36.5	29.1	2.8	24.5
Modulus of Elasticity, E_o (GPa)	50.0	51.7	50.7	–	–
Poisson's Ratio, ν	0.19	0.21	0.2	–	–

4. TANJUNG KUALA GUM GUM BRIDGE (TKGG)

The Tanjung Kuala Gum Gum (TKGG) Bridge is currently being studied for construction with UHPFRC. At the time of writing of this paper, the TKGG Bridge is in the open tender stage. Construction of the bridge is expected to commence on September 2017 and the project is given a duration of 36 months to be completed. The TKGG Bridge has a total length of 577.4 metres and it crosses an estuary, located at Sandakan, Sabah (GPS Location: 5.968077ºN; 117.908522ºE). If constructed in UHPFRC, it will become the longest multiple-span road bridge constructed in Malaysia using this material, surpassing the 420-metre-long KB-KT Bridge by over 150 metres. Figure 6 shows the proposed longitudinal profile of the TKGG Bridge. The bridge consists of nine equal 50.5 metre spans and one centre span of 120 metres (at the middle span). The UHPFRC U-girders used for the 50 metre and 120 metre spans have proposed beam depths of 2.0 metres and 5.0 metres, respectively.

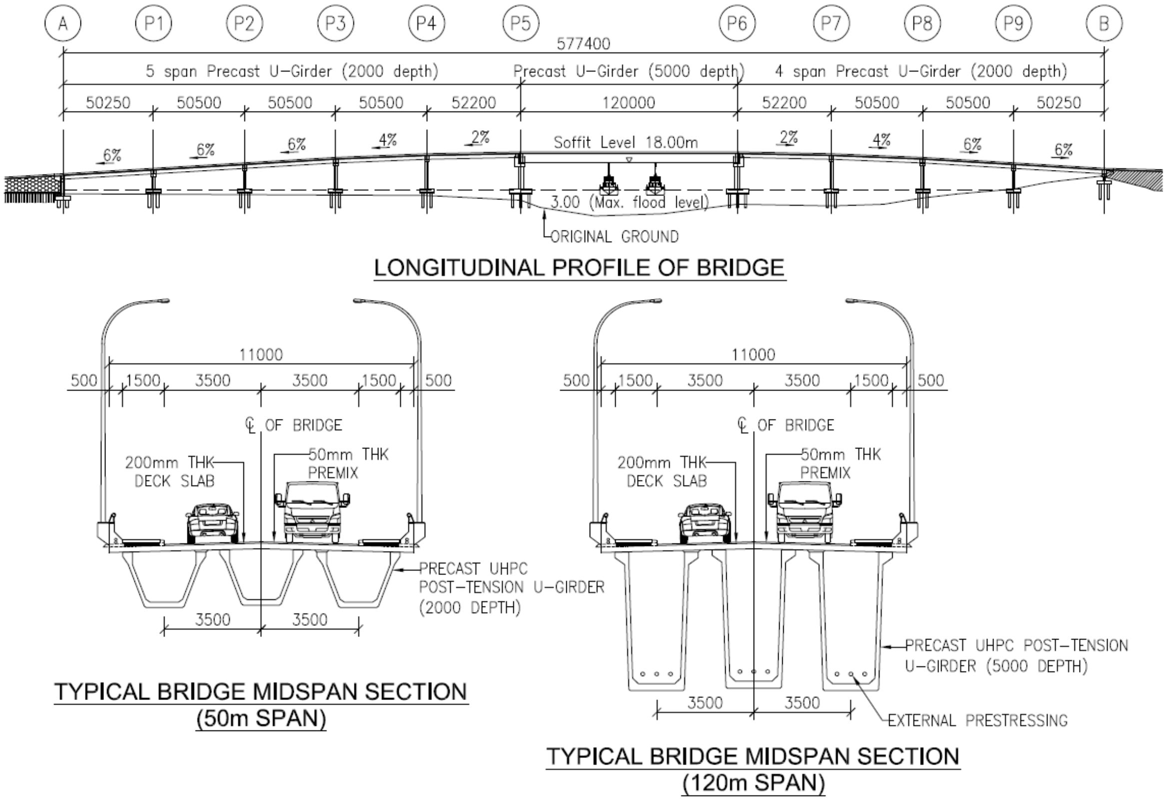
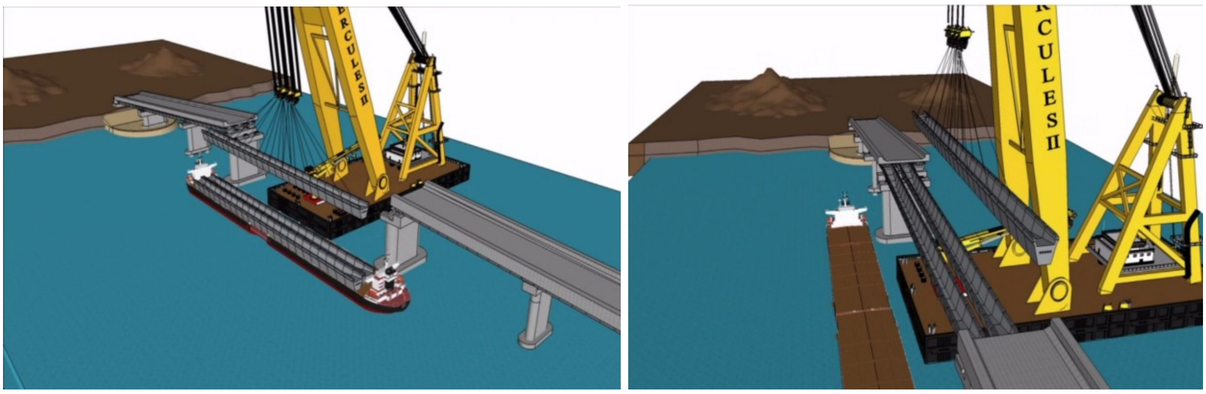


Figure 6: Longitudinal layout and typical cross-sections of proposed TKGG Bridge (dimensions in mm).

A total of twenty-seven numbers of 50-meter-long U-girders are needed; the U-girders have the same cross section as the KB-KT bridge (Figure 5). Each 50-metre beam will have seven segments (two pieces of 5.0-metre-long end/anchorage segments and five pieces of 8.0-metre-long standard intermediate segments. Each segment is 2.0 metres deep, 3.0 metres wide at the top and 1.4 metres wide at the bottom flange. The total weight of the full-span girder is approximately 125 tonnes, including the weight of the tendons and grout.

Three 120-metre-long U-girders are also needed. These super U-girders will have a new cross-section, customised for the project. It is proposed that each 120-metre beam will be constructed of 48 segments (two pieces of 2.5-metre-long end/anchorage segments and forty-six pieces of 2.5-metre-long intermediate segments). Each segment would be 5.0 metres deep, 3.0 metres wide at the top and 2.0 metres wide at the bottom flange. The segments are to be match-cast in the factory and delivered to site for assembly and post-tensioning. The total weight of the full-span girder is approximately 700 tonnes, including the weight of the tendons and grout.

The biggest challenge during the construction of this bridge is how to assemble and position the 120-meter-long U-girders. The designer envisions a simple launching method that significantly reduces the launching period and can minimize construction cost and the need for massive temporary works and usage of machinery and equipment. Figure 7 depicts the three 120-metre-long super U-girders pre-assembled and post-tensioned on a barge. A minimum 3600 tonne capacity floating crane barge will be used to lift and position the U-girders onto the pier cross-heads. The approach bridge from the left and right hand sides will be constructed first. Lifting of the super U-girders will be done at the final stage.



(a) (b)

Figure 7: (a) 120 m span U girders assembled on barge and (b) lifting using barge crane.

5. CONCLUSIONS

This paper outlines the history of the development of bridge construction in UHPFRC in Malaysia and summarises some of the important lessons learned along the way. One of the most important lessons is that both designs and construction methods and processes must be optimised for this relatively new material, as those optimised for conventional materials and construction processes may not be optimal for construction with UHPFRC.

Two examples were presented of precast post-tensioned bridges; the first being the completed 420-metre-long Kg. Baharu-Kg Teluk Bridge and, the second, the proposed Tanjung Kuala Gum Gum Bridge – two of the world's longest bridges in UHPFRC. While the material is slowly gaining acceptance around the globe for use in bridge design and construction, DSTB Malaysia is continuing to strengthen its resolve in evolving the materials properties, and element designs and construction techniques to ensure the costs associated with commercialisation are not just competitive against conventional materials and designs, but are seen for the superior performance, longevity and environmental sustainability that the material offers.

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