EXAMPLES OF CREATIVE SOLUTIONS IN RECENT CONCRETE BRIDGE CONSTRUCTION

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SUMMARY

Innovation and creative solutions in the concrete industry are often driven by bridge projects because of the desire for an aesthetically pleasing and durable structure that is achievable technically and financially. A classic example of innovation is the use of prestressed concrete to reach further across the divide and enhance durability. Likewise, the use of high strength concrete as a material has mainly been adopted in conjunction with bridge construction. Often these inventive, engineering achievements in designing bridges can be put to use in more common concrete projects.

Three case studies are presented highlighting creative solutions in relation with choice of structural system, development of a new arch bridge construction method and mitigation of ship impact forces.

The first case study explores the conceptual and technical design of the Gilman Drive Bridge in La Jolla California. Aesthetically, the concrete arch bridge design is a departure from the standardized box girder bridge commonly used on the California freeways.

The second case study discusses an innovative method for concrete arch bridge construction from both a technical standpoint and a product development standpoint. The concept alleviates the need for temporary falsework to support the arch during construction.

The third case study explores the innovative use of reinforced concrete buffers to resist the forces generated by accidental ship collision. Choosing, unconventionally, to use buffers reduces the design forces and consequently minimize foundation size and construction cost.

INTRODUCTION

Innovation and creative solutions in the concrete industry are often driven by bridge projects because of the desire for an aesthetically pleasing and durable structure that is technically and financially viable. Three case studies are presented highlighting creative solutions in relation with choice of structural system, development of a new arch bridge construction method and mitigation of ship impact forces.

The first case study explores the conceptual and technical design of the Gilman Drive Bridge in La Jolla California. The concrete arch bridge, currently under construction, crosses the extremely busy Interstate 5 and will connect the eastern and western sides of the University of
California, San Diego campus. Aesthetically, the arch bridge design is a departure from the standardized box girder bridge commonly used on the California freeways. Technically, the bridge is based on conventional cast-in-place concrete technology fused with originality in the structural system.

The second case study discusses an innovative method for arch bridge construction from both a technical standpoint and a product development standpoint. The concept that alleviates the need for temporary falsework to support the arch during construction. Adjacent to the bridge site, precast concrete elements are post-tensioned together to form the compression arch. The complete arch spans are then lifted in place and provide a stable platform for further construction. The arch bridge concept, patented under the name of ‘Pearl-Chain Bridge’, was developed through an experimental program and a focused marketing effort, and has been used for a river crossing in Denmark.

The third case study explores the innovative use of reinforced concrete buffers to resist the forces generated by accidental ship collision. The Mersey Gateway Bridge, UK, crosses the Manchester Ship Canal and its pier foundations near the ship canal are vulnerable to ship collision. Proposing to use buffers to reduce the design forces and consequently minimize foundation size and construction cost, required rigorous design, analysis and structural testing to demonstrate the feasibility and overcome technical, as well as legislative hurdles.

**CREATIVE USE OF A CONVENTIONAL BRIDGE CONSTRUCTION METHOD FOR AN UNCONVENTIONAL BRIDGE**

The UCSD Gilman Bridge, currently under construction, will be a key element in the transportation plan for the University of California, San Diego (UCSD) campus. Figure 1 shows an aerial view of the general area and the bridge site. Interstate 5 separates the west and east sides of the UCSD campus, and, currently, the only connection is the Voigt Drive overcrossing. The Gilman Bridge will connect the southern ends of the West and East sides of campus and will complete the campus internal loop road concept. Funding for the project comes from three principal sources, UCSD, California Department of Transportation (Caltrans) and the San Diego Association of Governments (SANDAG).

UCSD’s current push for the Gilman Drive connection began in the late 2000’s and was rooted in the university’s growth and the need for integration of the bridge with the arrival of the San Diego Trolley System extension (developed by SANDAG) to the UCSD campus.

![Figure 1. Project overview, West and East Campus](image-url)
The bridge financing, design and construction was to be managed UCSD. Subsequently ownership and maintenance was to be passed to California Department of Transportation (Caltrans). Caltrans acceptance of the bridge type, construction schedule and geometry would be essential. UCSD selected Moffatt & Nichol as the prime consultant to develop the project and design a practical and cost-effective bridge for the site.

The creative process leading to selection of the appropriate structural concept was framed by the following constraints:

- Structure feasibility
- Appropriateness for site
- Owner preferences (UCSD)
- Caltrans approval
- Ease of construction
- Construction cost

Tony Sanchez, chief designer on the bridge, explained that it was quickly determined that a concrete structure using conventional California-style cast-in-place prestressed concrete construction would have the best chance of getting Caltrans approval. Further, use of the most common construction method would likely attract multiple bids from local contractors and result in lower bid cost. Four structurally feasible concepts were proposed by the consultant to carry the roadway approximately 122 m (400 ft) from abutment to abutment (Sanchez et al.). Figure 2 shows renderings of the concepts.

Concept 1 was a standard two-span straight concrete box most commonly occurring bridge type encountered in California. Simple to design and economical to construct but, as stated by the consultant: “ordinary in appearance and lacks architectural features that would differentiate it from thousands of other bridges along California freeways” (Sanchez et al.).

Concept 2 was a variation of Concept 1 using a haunched girder to improve structural efficiency and also improving aesthetics. The bridge deck depth intuitively accentuates the accumulation of force near the supports. This concept usually is favoured for longer spans and is relatively uncommon in California. The consultant stated that “concepts 1 and 2 make sense structurally and functionally, the support in the median reduces the elegance. In fact, the depth of the crossing and the inclination of the slopes suggest that a bridge that clear-spans the freeway could architecturally be superior”.

Concept 3 was a three-span frame bridge with inclined legs. The inclined legs were architecturally pleasing and gave the bridge an interesting appearance. The consultant concluded “The concept has the advantage of shorter spans while keeping the legs away from the traffic. Structurally, the bridge acts as a frame making the columns carry a significant amount flexure from being integral with the bridge deck.”

Concept 4 was an arch. It was a further refinement of Concept 3 achieved by curving the inclined legs inwards to form an arch. The thickness of the arch increases from the base towards the middle and the thickness of the deck increases towards the arches. “As the member geometry responds to the internal forces, the structural efficiency is increased and the visual appearance is improved”, stated the consultant. “The arch is the most graceful and robust form used for bridges since ancient times. Furthermore, the site is well suited to support and arch structure with steep slopes on the sides and competent ground to resist the arch thrust.”
UCSD’s immediate favorite was Concept 4 because it was seen as an innovative and creative institution and had “landmark quality”. Supporting the selection of the arch concept for detailed studies was that three similar structures were designed and built (and currently owned) by Caltrans in the 1970’s over major freeways in the region and that these bridges have performed remarkably well in comparison to conventional bridges of same age. This made the design team confident that the arch concept would be viable and receive approval by Caltrans. It was also determined that the structure could be constructed using conventional cast-in-place concrete construction and that the cost would not be significantly more than a conventional two-span box girder bridge. Major dimensions and structural form were determined by the consultant while the outer geometric lines were refined by Safdie Rabines Architects. A three-cell box was chosen for the superstructure.

Critical to the structural integrity of the arch are firm supports on either side of the freeway. Geotechnical investigations revealed competent sandstone formations on both sides. However, a weaker material overlaid the sandstone on the west side. The initial solution was to use a spread footing cast directly on the sandstone on the East side, and on the west side use a spread footing on slurry backfill to transfer the arch thrust to the sandstone. Detailed computational analyses showed that, although the formation had enough strength to support the arch thrust, the relatively low stiffness of the upper sandstone layer would lead to undesirable foundation movements, thus a risk that the arch would deform unfavourably and develop high bending stress. The low foundation stiffness was mitigated using micropiles to transfer the load to stiffer strata as shown in Figure 3. The consultant decided to add inclined concrete struts between the foundations and the bridge ends, as illustrated in Figure 3. Each strut effectively reduces the horizontal component of the arch thrust from self-weight by 20% and allows for a steeper and practically achievable micropile inclination of about 45 deg. The inclined struts also improve the robustness of the bridge to environmental loads by adding redundancy to the system. Seismically, the arch bridge concept turned out to be rather robust. A push-over analysis revealed that no yielding would occur anywhere in the bridge for the design level earthquake.
The selected bridge solution has a total length of 124 m (406 ft). The superstructure is supported by four arch legs, with a pair on either side of the bridge; each leg pinned at the foundation. The arch spans 96 m (315 ft) and rises 11 m (36 ft) at the crown. Each footing is supported by 48 micropiles nearly 18 m (60 ft) long. Inclined struts link the footing to the superstructure.

The owner (UCSD) was attracted by the architectural qualities of an arch that complements the site and symbolises creativity. Choosing a conventional concrete construction method would attract multiple bidders and should assure a reasonable cost in comparison with the standard bridge type. It should also assure Caltrans acceptance of the bridge as the future owner and operator. The US$ 10 million cost (Sanchez et al.) of the arch bridge (bridge items only) was about 25% higher than the cost of a conventional bridge (Concept 1). In the big picture, it is estimated that the total project cost of the concrete arch bridge, including road realignment, bridge items, design fees, project management, etc., came in with a 5% cost premium when compared to a conventional bridge solution.

DEVELOPMENT OF THE PEARL-CHAIN BRIDGE CONSTRUCTION CONCEPT

The Pearl-Bridge concept is an innovative method for arch bridge construction that alleviates the need for temporary falsework to support the arch during construction. Adjacent to the bridge site, precast concrete elements are post-tensioned together to form the compression arch. The complete arch spans are then lifted in place and provide a stable platform for further construction. The concept was conceived in 2009. Following six years of development, the first Pearl-Chain Bridge was completed in 2015. Product development and commercialisation of the concept was done through the start-up company ‘Abeo’ founded in 2010 (http://www.abeo.dk). Prof. Kristian Hertz, Department Civil Engineering, Technical University of Denmark holds the patent for the concept.

Figure 4(a) shows an assembly of 8 precast concrete elements. The individual elements are straight, have sloped ends to form the desired curvature and incorporate ducts for post-tensioning cables. End elements incorporate post-tensioning anchorages. Intermediate elements may be solid or may have block-outs filed with lightweight concrete. The elements are placed on the side, aligned to the correct geometry and post-tensioned together to form an arch span. The exact geometry is achieved using non-shrink mortar in the joints. Each assembly is subsequently hoisted into place on the foundation as shown in Figure 4(b). Multiple parallel assemblies make up the width of the structure and finally form the completed compression arch (Figure 5(a)). Then precast edge elements are placed and attached to the arch as shown in Figure 5(b).
Figure 4. (a) Arch segment assembly, (b) arch span erection

Figure 5. (a) Completed compression arch, (b) assembly of precast edge elements

Figure 6. (a) Deck lean concrete fill, (b) Completed bridge

Figure 7. (a) First assembly, 3 elements, (b) Full-scale load test
Figure 6(a) shows the bridge deck with lean concrete fill, ready for casting the concrete deck slab. Temporary cable ties are required during the construction phases to balance the arch thrust. Post-tensioning cables embedded in the deck slab balance the arch thrust in the service condition. Figure 6(b) shows the completed bridge with spans of 7 m, 14 m and 7 m.

The Pearl-Chain Bridge concept has advantages, disadvantages and limitations as any other construction type. Advantages are aesthetically pleasing, cost savings on temporary formwork and support, consistent quality of precast concrete elements, flexible geometry, and construction speed. Disadvantages include the need for temporary control of the arch thrust, multiple element joints, span limitation due to crane capacity.

Nicky Viebæk (previously project manager for Abeo) explained in a recent conversation that there were many technical challenges during development of the concept, but that the biggest challenge really was to market the product and get the first real bridge built. Nicky explained that, technically, there were three main questions: Does the concept of tying together slender precast elements lined up on the side actually work? What is the real capacity of a Pearl-Chain arch? Does the site assembly of the arch and other components actually work? While theory shows that all should work out nicely, Abeo set out to demonstrate the concept physically. The first step was to tie three elements together and show that the assembly could be picked up by a crane (Figure 7(a)). The second step was to investigate the connections between element and between the ends and the supports. A Ph.D. student was recruited to build and test assemblies with various connection details and mortar types (Halding et al.). Third step was to tie multiple assemblies together transversely and to conduct a full-scale load test. The load test, shown in Figure 7(b), revealed a load carrying capacity in excess of what was predicted.

The fourth step, to get an actual bridge built, turned out to be the most challenging step and took several years of conversation with the bridge construction industry. Nicky Viebæk explained that an entrepreneurial mind-set is necessary to convince a conservative industry to use a new construction concept. It is essential to step out of the, often skeptical, ‘engineering mind-set’ and think more about business, market surveys, production and sales, and think positively and respond to intuition. Naturally, most contractors prefer to use tried and true methods and are risk adverse. It is particularly difficult to promote new concepts if multiple entities are involved with independent contracts, and who all add a ‘risk premium’ due to uncertainty, thus compromising the cost competitiveness. Finally in 2015, Abeo convinced the Danish precast concrete manufacturer, Perstrup, to enter into a consortium, which proceeded to successfully plan, design and construct the first Pearl-Chain Bridge, the Vorgod River Bridge shown in Figure 6(b). According to Nicky Viebæk, it took several years of conversation with the prestressing contractor to convince it that the structural system was not just a ‘pipe dream’. It is a safe and sound structural system that fulfils all code requirements and a simple and viable construction method. Nicky stressed that a key element to get the first bridge built was a comprehensive market survey presented to the contractor. It showed the potential regional market for Pearl-Chain bridge construction for both road and rail bridges, and was an incentive for the contractor to think of the project as the first bridge of many, not just a ‘one-off’ bridge. Abeo was subsequently acquired by the mother company of Perstrup, IBF (www.ibf.dk), to further market the concept.

**HARNESSING SHIP IMPACT FORCES ON BRIDGE FOUNDATIONS**

The Mersey Gateway Project is a 9 km road and bridge link going across the Mersey River between the towns of Widnes and Runcorn. Section 3 of the link, 'The Mersey Gateway Bridge' shown in Figure 8, consists of a main cable stayed bridge crossing River Mersey and approach viaduct bridges. The unique three-pylon cable-stayed bridge has pylons up to 125 m high and is 2.250 km long with a 1 km long cable supported section. The main bridge deck
is constructed from pre-stressed and reinforced concrete suspended from the pylons via high strength steel cable stays. The decks of the concrete approach viaducts were constructed using two 1700 tonne, 157 m long self-propelled launching gantries (movable scaffolding systems) enabling rapid and safe construction of a complete 70 m long span in a single pour. COWI, UK was engaged by Merseylink Civil Contractors Joint Venture to deliver the design. The bridge is currently under construction.

Figure 9 shows the busy Manchester Ship Canal and the approach viaduct bridge. Because of the modular nature of the approach viaduct construction with 70 m spans, it was desirable to place the bridge columns near the edges of the canal. Consequently, accidental ship impact would have to be considered in the pier foundation design. An equivalent static force of up to 42.5 MN was found when considering typical ship load-indentation characteristics and rigid foundation response (CEN). Such force would require 16-20 piles of 1.2 m diameter. Lars Lundorf Nielsen, Project Director with COWI A/S, explains that this would require very large and deep pile caps that would conflict with the geometric constraints of the canal and would require a departure from the standardized foundation construction scheme.
Alternatively to the equivalent static calculation, COWI proposed to base the foundation design on absorption of the ship kinetic energy through plastic deformation (AASHTO). It was proposed to use a buffer solution that would allow energy absorption through ship indentation, buffer deformation and foundation displacement. The principle is illustrated in Figure 10. As the ship hits the foundation the indentation of the ship, \(x\), increases until a maximum force arises, \(F_{\text{max}}\), at an indentation of \(x_{\text{def}}\). At the same time the foundation displaces, \(\delta\), until the same maximum force \(F_{\text{max}}\) is reached at a structure displacement of \(\delta_{\text{max}}\). During the process, the ship indentation follows the vessel load-indentation curve and the structure the load-displacement curve. In Figure 10(b) the foundation capacity can be represented by \(F_u\) (yielding of piles). The sum of the hatched areas under the ship and foundation load-deformation curves represents the energy dissipated and equates the original ship kinetic energy. Inserting a buffer between the ship and the foundation modifies the structure load-displacement curve. When the yield force of the buffer is lower than the foundation capacity, \(F_u\) represents the buffer capacity. If the buffer displacement capacity is sufficiently large, damage to the foundation can be avoided. Once the collision force attains the buffer yield force, the buffer will be permanently deformed and may need replacing.

A concrete friction type buffer was designed and tested (Figure 11). The buffer relies on concrete-to-concrete shear friction between a conical cylindrical wedge and a reinforced concrete ring. As the cylinder is pressed through the ring, hoop forces arise in the ring as the ring reinforcement resists expansion, and shear friction results. As the ring reinforcement reaches yield, the buffer force should remain constant. Figure 12 shows the force-displacement response of a typical test specimen. A clear yield plateau is visible. In this case failure was caused by ring reinforcement fracture. The area under the curve represents the energy dissipation.

Figure 10. (a) Ship-foundation collision, (b) load-deformation response curves for ship and foundation structure (Bennedsen et al.)

Figure 11. Concrete buffer

Figure 12. Typical buffer force-displacement response (Bennedsen et al.)
Clearly, the response depends on the buffer geometry, inclination of the cone, concrete type, strength and friction coefficient, and ring reinforcement strength and ductility. All of these parameters were studied [6] and predictive equations were established and validated with the load tests.

Figure 13 shows site installation of a buffer. A total of eight buffers were placed between the front wall that distributes the ship impact force and the pile cap. It was found that the buffer design would about halve the impact force on the foundation such that a pile group of 8 piles would be sufficient. Lars Lundorf Nielsen explains that it was a rather comprehensive task to get approval from the independent checker and the canal owner because of the departure from the conventional design approach. Naturally, the contractor was pleased with the design. The biggest challenge was documentation of the design calculations. It was necessary to produce calculations for both upper and lower bound limits of critical parameters such as the friction coefficient, reinforcement strength, etc., in order to demonstrate that 1) the ship impact energy could be absorbed (lower bound) and 2) that the pile group did not see excessive forces (upper bound).

CONCLUSIONS

Three case studies on creative solutions in concrete bridge construction show how a goal can be achieved through careful planning, analysis, visual presentations and market analysis. They should not be seen as one-time, isolated incidents. We need to learn how to make these creative concrete solutions more common so that these examples are not singular. The case studies are examples of engineers seeking real solutions to real problems. They set a precedent for more aesthetically pleasing structures that are cost effective and structurally sound. The engineer must think outside of the box to expand the potential of concrete construction and engage a risk adverse construction industry.

The Gilman Bridge project shows how overcoming uncertainties can promote creative concrete solutions. Notably, no such bridge had been built in California in recent times, there was limited contractor interest and experience, and the construction viability was questioned. The consultant demonstrated the superior aesthetic qualities of the arch solution with a visual presentation of four bridge concepts. A proposal was made to use the conventional cast-in-place prestressed concrete construction method that would support construction viability and open up for the possibility of multiple and competitive bids. Currently under construction, the result will be an aesthetically pleasing concrete arch bridge with a nominal cost difference. This is not just creative thinking; it is also sound engineering practice.

The Pearl Chain Arch Bridge project shows how a yet unproven construction method was developed and eventually came to fruition. Early on it was evident that product development required not just technical justification but also a strong marketing effort. It was important to show that there is a potential market for the bridge type. The greatest challenge was to get the first bridge built. Eventually a prestressing contractor was convinced that the construction
method was not just a fantasy or fanciful hope. It is a safe and sound structural system, and a simple, viable construction method that has a market potential.

With the Mercey Gateway Bridge ship collision protection project, creativity was used on many levels to protect pier foundations against ship impact. Reinforced concrete proved to be a successful material for friction buffers that could protect pier foundations against ship impact. This unconventional concrete buffer protection strategy resulted in a 50% reduction of impact force and a substantial cost saving. The creative process relied in designing the protection concept, developing a new and unproven concrete buffer type and obtaining approval from the independent checker, the canal owner and the bridge owner. This project sets a precedent for using concrete buffers to control ship impact forces and will hopefully inspire better performing and cost saving structures.

Concrete is a well-known material that has been widely used in engineering. Through innovative thinking and precedent setting projects, creative solutions in concrete will expand.

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