Designing bridges for manufacture and assembly: joining technologies for precast concrete components

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Synopsis
In this article, Charlotte Murphy, winner of the Institution's Pai Lin Li Travel Award 2017, discusses her research into joining techniques for precast concrete bridge deck components in the USA, and considers what lessons could be applied in the UK to facilitate the use of off-site manufacturing.

LAING O'ROURKE

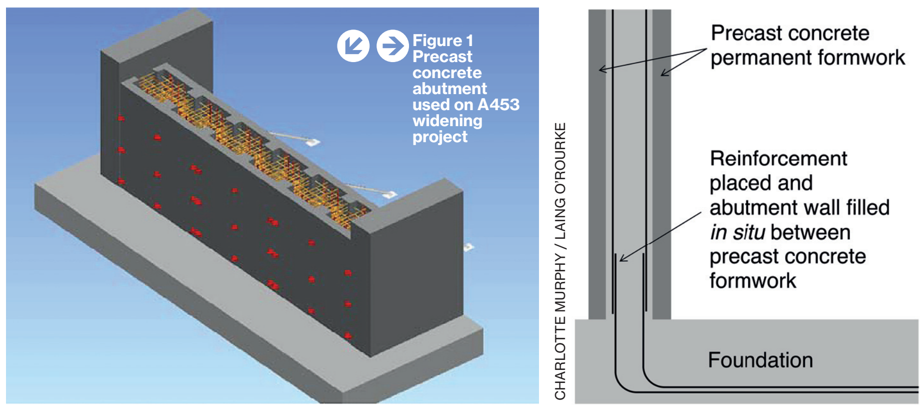

Figure 1 Precast concrete abutment used on A453 widening project

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Introduction

The benefits of off-site manufacture in the construction industry are well known: improved safety, a reduced on-site construction schedule, higher-quality results, reduced waste and reduced impact of construction on communities[1]. The UK has a growing pipeline of megaprojects (e.g. HS2, Transpennine Route Upgrade, Lower Thames Crossing, Hinckley Point C nuclear power station). Adopting more off-site manufacture techniques will deliver this much-needed critical national infrastructure sooner and more safely.

UK government policy is encouraging off-site construction. The *Analysis of the National Infrastructure and Construction Pipeline*, published in December 2017, states that UK government departments 'will adopt a presumption in favour of off-site construction by 2019 across suitable capital programmes, where it represents best value for money'[2].

When construction is moved off site, the two key challenges become: a) how are components transported to site; and b) how are components joined together on site so as to be durable and safe? This article addresses the second challenge – joints – by investigating the design, specification and construction of short-span (<40m) concrete highway bridges.

Off-site construction is coming. As an industry, are we ready for it?

Why do we need better joints?

Current methods

In bridges, there are two ways to join precast concrete components together: a conventional *in situ* lap joint and reinforcement bar couplers. Both of these techniques require an *in situ* concrete pour.

Lap joints can be prohibitively large, as the width of the *in situ* part of the joint must be at least as great as the reinforcement lap joint required. Formwork is also required at the joint, generating the need for on-site labour, time and materials. Feasibility studies have demonstrated that it is only possible to precast 60% of a concrete bridge deck due to the space required for *in situ* lap joints between components, and thus many of the advantages of precasting are lost.

Reinforcement bar couplers remove the need for a lengthy lap joint. However, they demand a high degree of construction tolerance and require space within the joint to allow them to be tightened.

Non-sustainable solutions

Due to the limited joining techniques available, recent projects adopting precast concrete construction have predominantly used precast concrete solely as permanent formwork. Using precast concrete as permanent non-participating formwork is an inefficient use of materials and leads to higher embodied energy in our structures.

Figure 1 shows a precast abutment solution used on the A453 road-widening project by contractor Laing O'Rourke[3]. Laing O'Rourke has created its own precast factories and, in doing so, has been pushing the industry forward. However, due to a lack of approved precast concrete joining techniques, structural connections need to occur within *in situ* concrete pours.

Fig. 1 shows that the precast concrete permanent formwork does not participate in the bending capacity of the section. To withstand wet concrete loads and transportation loads, the precast concrete formwork panels contain significant reinforcement. Once the *in situ* pour has taken place, the precast panels are structurally redundant. The embodied energy in a precast concrete formwork panel is significantly higher than that in reusable timber formwork.

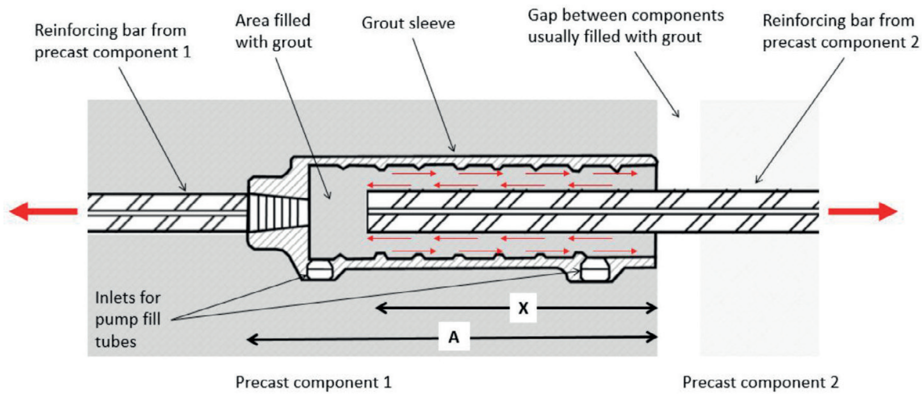

Figure 2 Load transfer through grouted splice coupler

These types of precast assembly deliver time savings on site and reduce site labour requirements, but they are not a fully off-site manufactured solution. Large wet concrete pours are still needed on site and steel fixing work is required as with traditional construction.

Productivity

While industries such as manufacturing have delivered a seven-fold increase in productivity since the 1950s, productivity in the construction industry has remained flat[4]. Firms are striving to improve construction efficiency through off-site manufacture, as the Laing O'Rourke example above demonstrates. However, the scope to dramatically improve productivity is limited when novel methods need to be individually approved. This slows the development of more efficient solutions.

To conclude, the methods for joining precast concrete components used in the UK at present will not allow a widespread increase in off-site manufacture. To unlock the benefits of precast concrete construction in a sustainable and structurally efficient manner, new joining methods capable of securing approval are required.

Enabling technologies

Other countries, most notably the USA, have different approved joining methods for precast concrete components.

Post-tensioning

Precast concrete bridge deck components are often joined using post-tensioning in the USA. This requires no wet concrete on site (only grout) and can lead to rapid installation and connections. However, these types of connection have not been investigated in detail due to historical post-tensioning problems. In the UK, the temporary ban on the use of grouted post-tensioned cables between 1992 and 1996, after failures of bridges built in the 1960s[5], has reduced clients' confidence in the technology. Introducing post-tensioned connections in UK highway bridges would be a significant cultural challenge given the well-embedded prejudices to be assuaged.

Examples of two well-established US techniques are given below, together with a summary of the principal issues which would need to be overcome in order to secure UK approval.

Grouted splice couplers

Grouted splice couplers are a type of reinforcement bar coupler. They provide some significant constructability advantages over the reinforcement bar couplers currently used in the UK. Grouted splice couplers provide reinforcement continuity by load transfer through a high-strength grout. There is no mechanical connection between the two bars that are being joined. The force transfer mechanism for a generic grouted splice coupler is shown in Figure 2.

There are several suppliers of grouted splice couplers in North America: e.g. nVent LENTON and NMB Splice Sleeves. Grouted splice sleeve products are supplied with a specific grout and tend to be high-early-strength mixes.

The minimum embedment length (depicted as 'X' in Fig. 2) for the LENTON Interlok to achieve full tensile transfer for a 32mm bar is 200mm. For a 32mm bar, the overall length of the splice coupler (depicted as 'A' in Fig. 2) is 275mm and the diameter of the grout sleeve is 76mm[6]. These relatively compact dimensions allow grouted splice connections to be easily fitted inside precast concrete components and do not impose strict limits on the minimum spacing of reinforcement.

The grout sleeve can either be gravity filled, if the component containing the sleeve is on the bottom, or pump filled. Grout tubes to either end of the grout sleeve are cast into the component and grout is pumped in one hole. When grout flows out of the other hole,

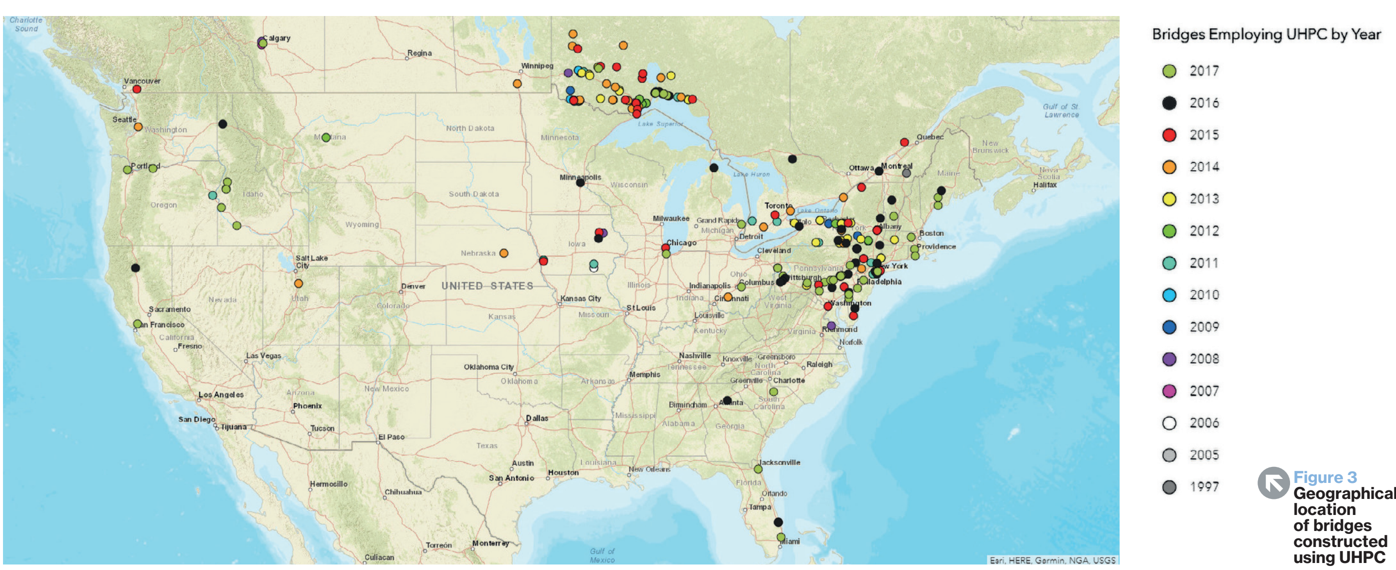

Figure 3 Geographical location of bridges constructed using UHPC

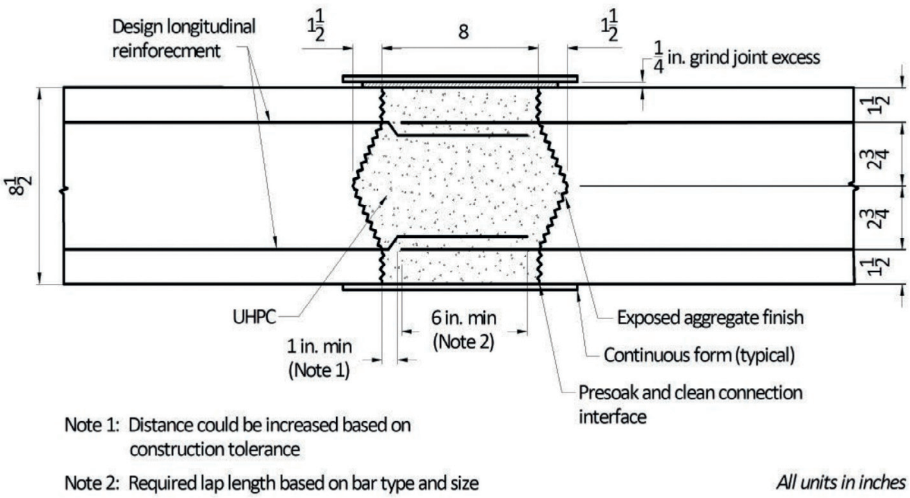

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Figure 4
FHWA TechNote recommended UHPC deck panel connection

the coupler is full. The pump fill mechanism gives the grouted splice couplers versatility in the applications they can be used in.

Use on projects
Grouted splice couplers are an approved product in many non-seismic US states and are a well-established method of joining precast concrete bridge elements. They are mainly used in column-to-foundation, column-to-pier cap and abutment-to-foundation connections. Depending on the grout used, they can reach the design strength within 12 hours.

Ongoing research
Current research is predominantly focused on seismic performance to prove ductile behaviour is maintained under earthquake loading. The University of Reno, Nevada and the University of Utah are leaders in this type of research and both have full-scale testing facilities. The research is funded by the Federal Highway Administration (FHWA), as well as state departments of transportation (DOTs). Further research is also being conducted to determine the effect of the position of the bar within the splice sleeve on the performance of the joint. Larger-radius grout sleeves are being investigated to further reduce construction tolerance requirements on site.

Concerns for UK use
There are three main concerns about the use of such couplers in the UK and, as yet, these concerns have not been overcome to the satisfaction of UK approvers.

Durability – the joint interface between two components is filled with grout, but it is a weak point from a durability perspective. Shrinkage of the grout and cracking could create a direct route for water to penetrate to the reinforcement. These products have been developed in the USA where the design life of highway structures is rarely over 50 years. Research would need to be carried out to prove that these products could achieve a 100- to 120-year design life, as required by various UK and European codes.

Structural behaviour – during design, grouted splice couplers are considered to behave no differently than if the structure was built with conventional *in situ* construction. However, this is not the case for shear transfer between components. In *in situ* construction, shear transfer would predominantly be through aggregate interlock of the concrete. Shear transfer through a joint using grouted splice couplers is through friction between the components and the shear resistance of the reinforcement. Though there have been no shear failures in the USA, the difference between the two shear transfer mechanisms should be noted by designers.

Quality assurance – pump-filled grouted splice couplers are assumed to be full when grout flows smoothly out of the second hole. Although there is no evidence under laboratory conditions that this is not the case, there is no practical way to ensure that every coupler has been completely filled. There is currently no CARES product approval for grouted couplers in the UK, although UK CARES is reviewing the process[7]. It is also not possible to inspect the condition of the joints subsequent to construction.

Ultra-high-performance concrete field-cast connections

The FHWA defines ultra-high-performance concrete (UHPC) as[8]:

'... a cementitious composite material composed of an optimized gradation of granular constituents, a water-to-cementitious materials ratio less than 0.25, and a high percentage of discontinuous internal fibre reinforcement. The mechanical properties of UHPC include compressive strength greater than 150MPa and sustained post-cracking tensile strength greater than 5MPa. UHPC has a discontinuous pore structure that reduces liquid ingress, significantly enhancing durability compared to conventional concrete.'

UHPC has a modulus of elasticity of up to 70GPa, meaning that it is nearly twice as stiff as normal-strength structural concrete. The most commonly used UHPC in the USA is Ductal®, supplied by Lafarge. UHPC typically costs \$2600/m^3, which is roughly 20 times the cost of a conventional concrete[9]. The high cost has limited the use of UHPC to situations where its benefits are vital. It is predominantly used in connections between precast concrete components, as the quantities of UHPC required are small.

Use on projects
The majority of research into the use of UHPC in bridges has been commissioned by the FHWA, which has produced TechNotes that serve as preliminary design guides. UHPC has not yet been included in AASHTO (American Association of State Highway and Transportation Officials) or other US design codes. Where it has been used, the state DOT has allowed the design to be undertaken to the FHWA TechNote. The use of UHPC is rising fast, with 212 bridges in total, 40 of which were constructed in 2017. Figure 3 shows that the northeastern states are adopting UHPC more readily than the rest of the country[11].

UHPC's strength allows the lap length for reinforcing bars to be reduced to just 10 times the bar diameter. For a 20mm diameter reinforcement bar, the width of the joint would need to be 200mm. UHPC is used in the shear connections between bridge decks and girders and in the splice joint between precast concrete components. The FHWA TechNote diagram of a joint suitable for full-depth precast concrete deck components is shown in Figure 4[8].

All joints contain a shear key so that the bond interface between the precast component and the UHPC does not need to be relied upon. Nonetheless, the bond between the precast concrete components and UHPC is very strong and, as the cyclic bending test in Figure 5 shows, cracking does not occur along the joint interface. The high

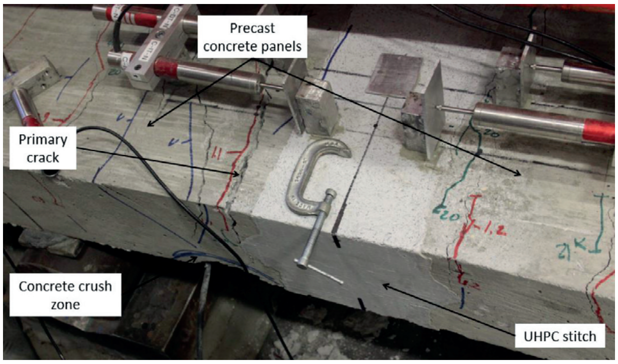

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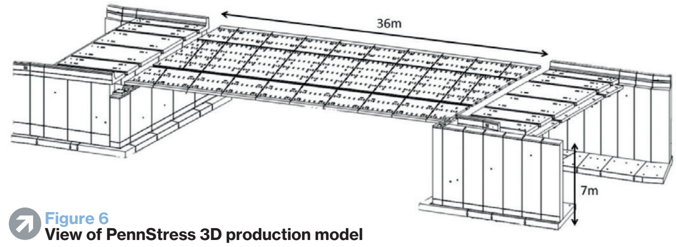
Figure 5
Failure surface of precast concrete deck components joined by UHPC *in situ* stitch



PENNSTRESS

Figure 6
View of PennStress 3D production model

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Figure 7
Completed bridge

bond strength is due to the small particle size of UHPC, which allows it to penetrate into the pours of the precast concrete. Failure of the joint occurs by crushing of the precast concrete adjacent to the joint.

Globally, the behaviour of the bridge deck is considered to be the same as for traditional *in situ* construction. The UHPC joints are designed to develop the yield strength of the deformed steel reinforcement bars extending from the prefabricated concrete elements. This ensures that the joint is always stronger than the surrounding precast concrete components.

Early-age-strength mixes of UHPC can reach design strength within eight hours, meaning that a bridge deck can be installed and ready to use in less than 24 hours. A drawback of UHPC is that it requires a labour-intensive process on site. The UHPC must be mixed on site, joint surfaces require wetting before the UHPC is poured, high-quality (and sometimes top-of-joint) formwork is required as UHPC has high flowability. In addition, UHPC cannot flow long distances as this can cause the steel fibres to align and the material will no longer be isotropic. UHPC is a high-tech material and, without correct application, it may not perform as intended.

Ongoing research

Research to improve the constructability of joints is ongoing. Key areas of research are joints that do not require formwork and shear connection joints that do not require reinforcement. Using the high-strength properties of UHPC to transfer the shear, instead of shear studs, would remove the risk of a component clashing with a shear stud on site.

To diversify the market and to bring down the cost, the FHWA is carrying out research to develop design guidance for non-proprietary UHPC mixes. The FHWA is also investigating the cost of constituent ingredients and assessing the effect on material properties if quantities of the most expensive ingredients are reduced or replaced with a cheaper alternative.

Concerns for UK use

Again, there are three main concerns about the use of such joints in the UK. To date, these concerns have not been overcome to the satisfaction of UK approvers.

Structural behaviour – the effect of having a deck made out of normal-strength and normal-stiffness panels connected by a grid of high-strength and high-stiffness UHPC has not been investigated. Research has focused on the performance of the joint and not the bridge deck as a whole. Although no problems have occurred to date in the bridges that have been constructed, the potential difference in structural behaviour between a conventional *in situ* bridge deck and a UHPC-connected precast concrete deck should be investigated.

Early-age thermal cracking – early-age thermal cracking in UHPC has not yet been investigated in detail. UHPC connection studies have not seen evidence that early-age thermal cracking is a concern. This is most likely due to the presence of the fibres and their ability to restrain cracks. However, there have been instances of larger specimens of UHPC exhibiting early-age cracking. UHPC's use in joints means that the pours are restrained. There is likely to be a critical size of pour where early-age thermal cracking begins to occur; however, there is no guidance on the maximum sizes of such joints.

Long-term performance – fatigue and durability tests have been conducted on UHPC joints. However, knowledge of behaviour only extends to the results of the tests that have been conducted. As UHPC is a new material with very different properties to conventional concrete, it is difficult to predict what issues may develop in the future.

Joints in action

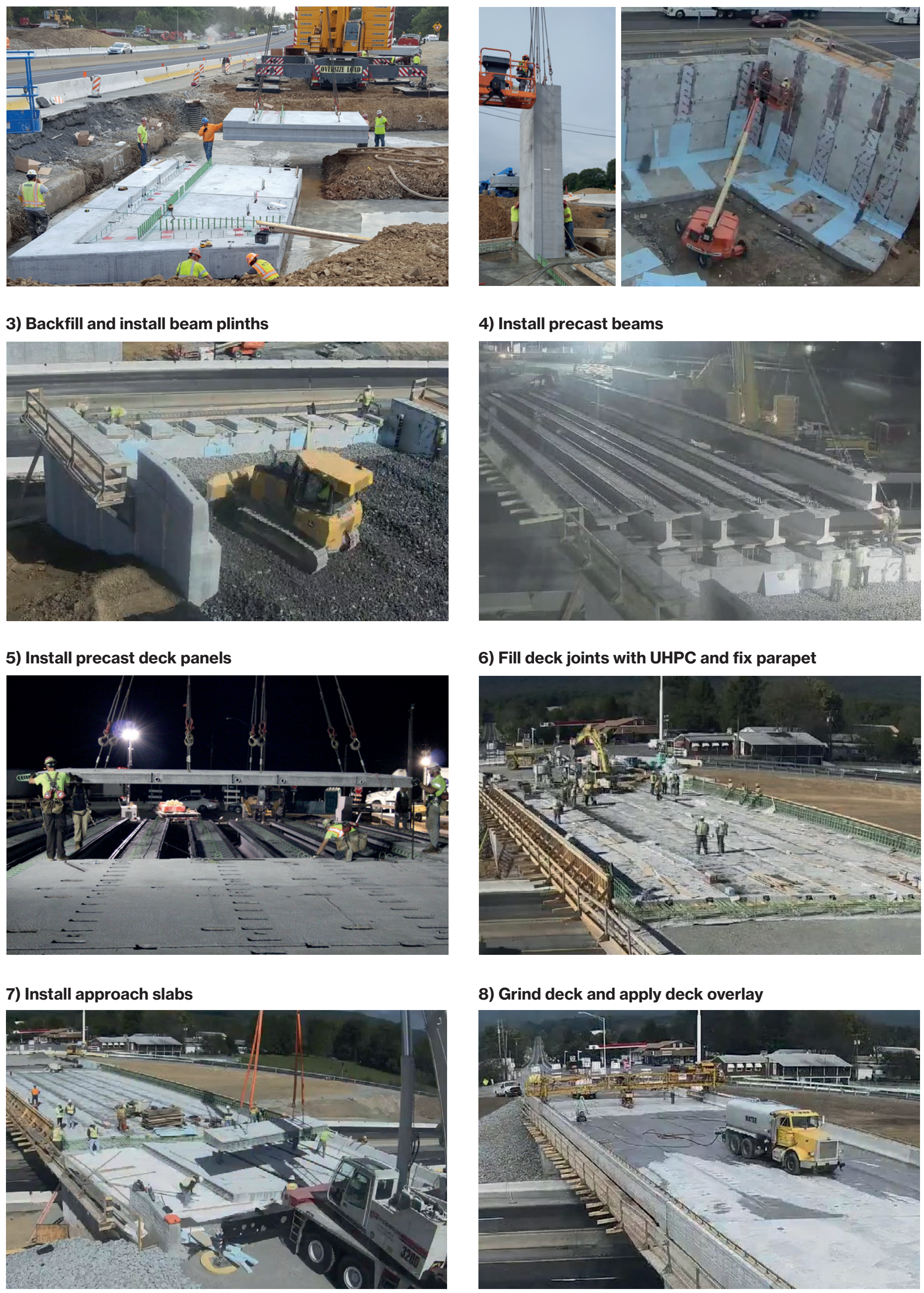
In 2016, 9.1% of bridges in the USA were classed as structurally deficient. This equates to approx. 56 000 bridges. A bridge is classed as structurally deficient if it requires significant maintenance or replacement and the owner must place limits on the weight of vehicles permitted to cross the bridge. Many of the nation's bridges are approaching the end of their design life and the rehabilitation cost is estimated at $123bn[4].

To tackle this problem, the FHWA has set up the Accelerated Bridge Construction (ABC) scheme. This is a nationwide initiative that uses innovative planning, design, materials and construction methods to enable rapid bridge construction.

The FHWA has its own research centre, the Turner-Fairbank Highway Research Center in Virginia, where it conducts research into new materials and construction techniques. The FHWA also funds the Accelerated Bridge Construction University Transportation Center (ABC-UTC), which is an organisation of research partner universities, led by Florida International University.

The key outputs of these research groups have been a number of guidance documents and TechNotes to advise designers and contractors on how they can incorporate ABC techniques. A major strength of the ABC

Figure 8
Construction of bridge 6



1) Install precast spread footing
2) Install abutment walls and waterproof joints
3) Backfill and install beam plinths
4) Install precast beams
5) Install precast deck panels
6) Fill deck joints with UHPC and fix parapet
7) Install approach slabs
8) Grind deck and apply deck overlay

initiative is that it does not aim to provide a standard set of solutions. Instead, it provides guidance on how to use the tools that it has developed so that the designer can apply them in specific situations where they provide a benefit.

State DOTs can apply for extra infrastructure funding when construction uses ABC techniques. This incentivises the use of ABC technologies, helps state DOTs deliver more projects and helps develop ABC skills. The following case study demonstrates the impact ABC construction can have.

Interstate 78 bridge replacements

Interstate 78 (I-78) is a major route within Pennsylvania, connecting Harrisburg, the state capital, with New York City. Despite the road's importance, many of the bridges crossing I-78 have insufficient under-clearance for large trucks. Over 34% of travel along Pennsylvania's Interstate roads is truck traffic, more than double the national average. There is a regular problem with larger trucks colliding with low bridges on Interstate routes.

In 2014, Pennsylvania Department of Transportation (PennDOT) put out a contract for the replacement of six bridges between crossings 16 and 23 on I-78. Each bridge spans approx. 36m over the interstate and carries a lane of traffic in each direction. In a bid to drive forward total precast construction, PennDOT mandated that the roads over I-78 could be closed for a maximum of 40 days each and imposed heavy penalties if these times were not met. These 40 days included the decommissioning of the existing bridge, the construction of the new bridge and all associated road alterations.

The contract was awarded to HRI, Inc, a leader in highway works within Pennsylvania. HRI, Inc appointed PennStress as its precast subcontractor. Michael Baker International was appointed by PennDOT as the designer and on-site supervisor. In two years, the team replaced all six bridges. All were built within budget and all but one opened on time (the bridge that was behind schedule opened three days late).

This contract was not only remarkable in its ambitions, it was also a fantastic learning opportunity for PennDOT and the companies involved. Because the six bridges were all contained within one contract and the same team of people followed the project through, the lessons learned on each bridge were carried forward to the next bridge. The author observed the construction of the sixth bridge and the site ran like clockwork with shifts frequently finished early.

Although each bridge was a simply supported single-span bridge, none of the six bridges were exactly the same. Bridges had different spans, skews, widths and foundation types. This project has moved the construction industry one step closer to a streamlined manufacturing process. The precast parts of each bridge were different shapes, yet the manufacturing and construction methodologies were the same for all the bridges. The project shows that the benefits of a repeatable process can be realised while still delivering bespoke products.

Bridge 6 was constructed 84% from precast concrete components. The precast abutment components are 7m tall (Figures 6 and 7) and the largest weighs 54 tonnes. The joints between the abutment and footing components are formed using grouted splice couplers and shear keys. Installing the footing components and the abutment components (Figure 8) each took one day – tasks that would take weeks using conventional construction methods. The full-depth precast deck is made of 31 panels, stitched together using UHPC.

Each of the six bridges contained around 120 components. Due to good quality control, 3D clash detection and dry fits at the precasting plant, there were no issues with the fit of components. Total precast solution (TPS), as this is known, is growing rapidly in the USA and projects like this are no longer 'one-offs'. The construction contract for this bridge was $4.1M. Currently, TPS is about 20% more expensive than conventional construction. However, when the cost to the public due to road closures and detours is included, TPS solutions become cost-effective.

What can the UK learn?

The I-78 case study, and many more examples across the USA, have demonstrated that a step-change in construction is achievable and is delivering benefits across the Atlantic. The rapid development and deployment of new structural joints into highway bridges in the USA is predominantly down to the FHWA's investment. Such case studies demonstrate how fast developments can happen when there is adequate research funding and owners are prepared to champion the technology.

The fact that the USA is made up of 50 states with independent DOTs has been a key driver in the speed of advancement. Some states are trail-blazers, some will adopt once technology is proven elsewhere and some will not approve the new technology. In the UK, there are far fewer major bridge-owning authorities, and these authorities tend to be risk-averse. The organisational set-up in the UK reduces the chance of new technologies succeeding.

Margins in the UK construction industry are low and few projects are large enough to support an R&D programme to develop and approve new joining techniques. UK bridge-owning authorities should learn from the FHWA to drive the development of new industry technologies, otherwise progress will remain slow.

A further advantage of the I-78 example is that it was a single contract for all six bridges, with the same team being employed throughout the programme. This enabled each bridge to learn lessons from its predecessor and for a factory-style streamlined approach to be created that made the processes both quicker but also reliably so.

The two key enabling technologies identified, grouted splice couplers and UHPC, are not solutions that most bridge engineers would readily deploy on UK structures today. Additional research that builds on what has already been achieved in the USA should be conducted before these products can satisfy UK design standards, most importantly to prove that they can achieve a 120-year design life. France now has a National Annex for UHPC, so things are moving forwards in other countries subject to the Eurocode regime, with its much longer life for civil structures.

A concern, and an area for future research, is that these bridges were designed as conventional *in situ* bridges. Joints are designed to ensure that there is no reduction in capacity, but the designs in the USA have assumed that using these joints is structurally no different to *in situ* construction. Although this assumption has not yet resulted in a problem, it is something that should be investigated. These are relatively short-span simply supported bridges. If this approach is taken forward to more complex structures, then unexpected behaviours could be seen.

Despite the concerns raised, all the precast components in the I-78 example are participating structurally in the completed bridge. This is much more efficient in terms of materials than the precast concrete solutions that are being developed in the UK. These joining technologies allow the development of more sustainable solutions.

Conclusions

The UK construction industry has not improved its productivity since the 1960s. New procurement policies will be introduced for the public sector in 2019 that will incentivise off-site manufacture techniques. Current approved joining methods do not enable efficient precast concrete structures and are resulting in the development of non-participating precast formwork solutions that have higher embodied carbon.

The FHWA in the USA has invested in research into precast concrete joining techniques that are facilitating rapid bridge construction – enabling it to offer a much better service to its customers. Although these techniques still require development, they have moved highway bridge construction considerably closer to a streamlined manufacturing process. The UK government and highway authorities, such as Highways England, should learn from the FHWA's success and invest in parallel research to develop better precast concrete joining techniques to facilitate quicker bridge construction in the UK.

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