Ultra-High-Performance Concrete: The Keystone for Adjacent Prestressed Concrete Box-Beam Bridges

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The keystone is an engineering marvel whose origin dates back thousands of years. When this innovation was developed, its use in combination with traditional materials and construction methods revolutionized the performance and value of the arch. Ultra-high-performance concrete (UHPC) may be considered a comparable "keystone" development for recent bridge design. When this revolutionary construction material is combined with appropriate application and construction methods, UHPC can significantly improve the strength, performance, durability, and resiliency of structures such as those constructed from prestressed concrete box beams.

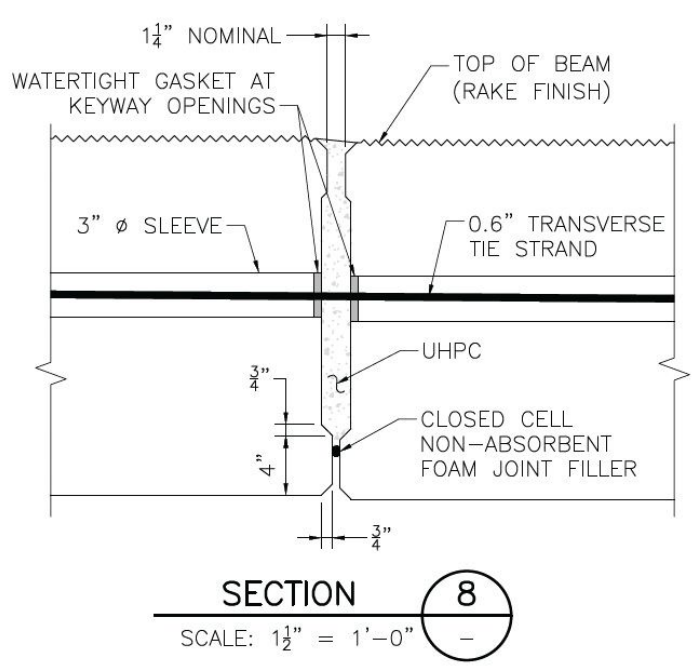
As shown in the preliminary design charts in Chapter 6 of the *PCI Bridge Design Manual*,[1] adjacent prestressed concrete box beams can be a very economical and efficient shape for short- to medium-span bridges. These adjacent box beams were quite popular for some time before owners began reporting challenges such as leaking joints, reflective cracking in asphalt or overlay surfaces, loss of continuity between beams, and other negative behaviors that were generally associated with the lack of performance of the grouted keyways between the box beams. The unreinforced grout frequently cracks due to a combination of forces and water-ingress-related deterioration such as damage from freezing and thawing cycles.

In recent years, some owners and engineers have begun leveraging the advanced mechanical properties of field-cast UHPC to revitalize these bridges. For this application, UHPC-class materials are strain-hardening materials reinforced with steel fibers at common volume fractions of 2% in joints or 3% in overlays. UHPC materials can be applied in the following three specific ways to improve the structural performance and durability of adjacent prestressed concrete box-beam structures:

- A simple keyway, which is filled with UHPC with no reinforcing bars present (**Fig. 1**)
- A UHPC field-cast joint between two beams with reinforcement in the joint at the top of the box beam only (**Fig. 2**)
- A UHPC overlay (typically 1.5 to 2 in. thick) on top of the box beams (**Fig. 3**)

Each of these construction details has a distinctive effect on the behavior of the superstructure, but all three leverage the same unique material properties of UHPC to impart structural benefits that can extend service life. To date, these details have mostly been used to structurally rehabilitate prematurely failing bridges in service. However, information gathered through these necessary repairs can also be applied to improve new construction, and some new bridges have been constructed with UHPC joints. By improving the weakest link of the system, a portion of the existing infrastructure can be revitalized, and prestressed concrete box beams can once again be a durable and cost-effective option for designers in the short- to medium-span bridge market. In new bridge design, the use of UHPC for improvements to this type of bridge system could increase initial costs. However, the cost analysis should extend beyond just initial cost and consider the service life of the bridge and the reduction in maintenance costs, which would be captured in a life-cycle cost analysis. A similar cost analysis process should be followed for rehabilitation efforts.

Figure 1. Detail for ultra-high-performance concrete in an unreinforced keyway. Figure: Massachusetts Department of Transportation.



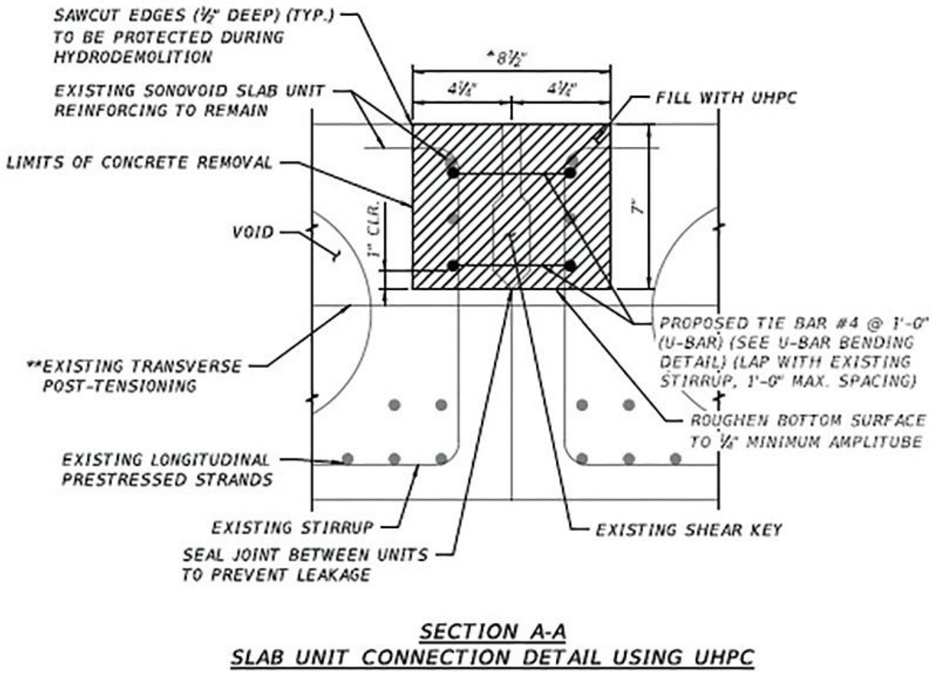


Figure 2. Detail for ultra-high-performance concrete in a reinforced joint between beams. Figure: Florida Department of Transportation.

The UHPC applications detailed in this article use the strain-hardening behavior to continue load transfer and maintain watertightness after cracking occurs in the joints. The stiffening response after cracking allows the keyway, joint, or overlay to continue to provide efficient load transfer between beam units. This load transfer can reduce the forces on an individual beam by enhancing load distribution, leading to potential benefits such as improved load ratings, reduced deflection through improved stiffness, improved fatigue performance through reduced stress ratios, enhanced resiliency, increased redundancy in the event of deterioration or sudden loss of capacity in a beam, and preservation of wearing surfaces through reduction of independent girder movements. The use of UHPC in critical locations in box-beam bridges is analogous to the behavior of a keystone; the relative volume of UHPC in the structure is low, but the effect on the performance of the overall system is substantial because selective application of UHPC optimizes the benefits of UHPC's mechanical properties.

These applications also benefit from other enhanced properties inherent to UHPC-class materials such as the enhanced capability of UHPC materials to bond with the concrete substrate and reinforcement. This capability allows the UHPC to transfer loads, achieve composite behavior, develop reinforcement, and maintain watertightness at the vertical interface.[2] The bond can be accomplished in existing or new structures, aiding in the development of strength properties and prevention of substructure damage caused by leaking joints. The combination of increased compressive strength and tensile and flexural toughness allows the material to absorb more energy, enhancing strength and resiliency relative to traditional materials. The durability characteristics of UHPC-class materials are typically an order of magnitude higher than those of high-performance concrete and another order of magnitude greater than those of conventional concrete (**Table 1**).[3] These properties extend the useful life of the system, further enhancing the value for the owner.

On an interstate highway in New York that is subject to significant truck traffic, a prestressed concrete box-beam bridge was rehabilitated using a UHPC overlay (Fig. 3). The UHPC overlay reestablished a safe and smooth riding surface and improved the structural response of the

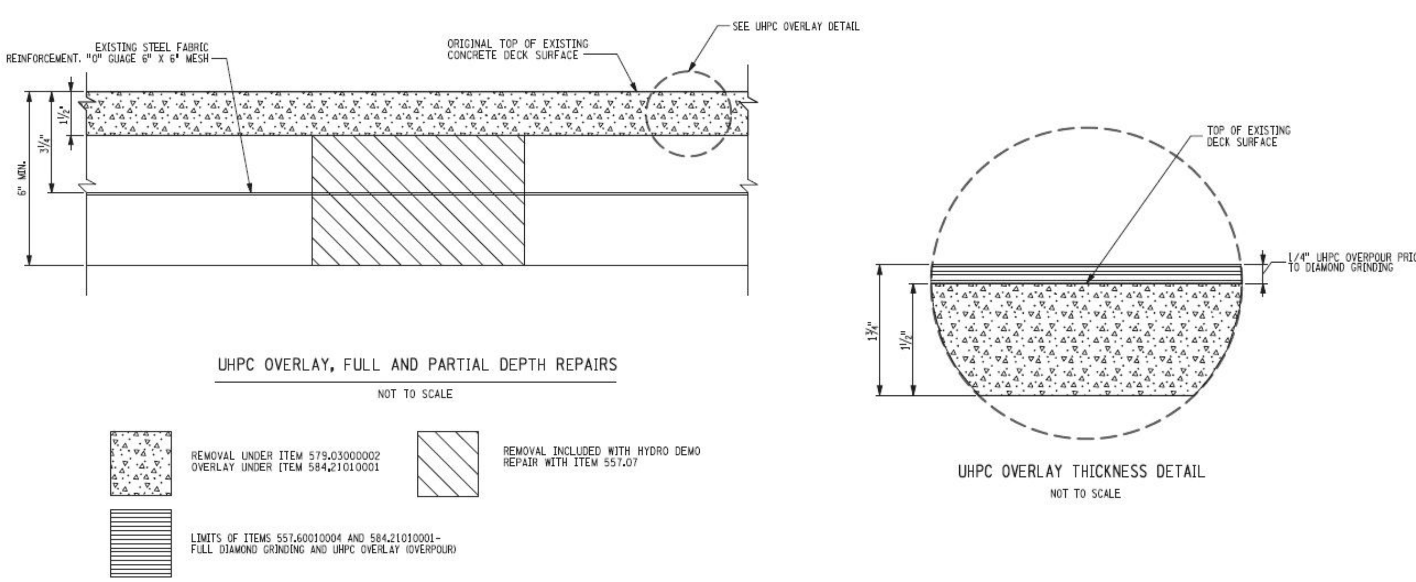


Figure 3. Detail for ultra-high-performance concrete overlay on a topping slab for a side-by-side box-beam bridge. Figure: New York State Department of Transportation.

Table 1. Comparison of the durability properties of ultra-high-performance concrete (UHPC), high-performance concrete, and conventional concrete materials

Parameter	UHPC	High-performance concrete		Normal concrete	
		Value	Ratio to UHPC	Value	Ratio to UHPC
Salt scaling mass lost (28 cycles)	0.010 lb/ft^2	0.031 lb/ft^2	3.0	0.31 lb/ft^2	30
Chloride ion diffusion coefficient	2.2×10^{-13} ft^2/s	6.5×10^{-12} ft^2/s	30	1.2×10^{-11} ft^2/s	55
Chloride ion penetration depth	0.04 in.	0.32 in.	8	0.91 in.	23
Chloride ion permeability total charge passed	10 – 25 coulombs	200 – 1000 coulombs	34	1800 – 6000 coulombs	220
Carbonation depth (3 years)	0.059 in.	0.16 in.	2.7	0.28 in.	4.7
Reinforcement corrosion rate	4×10^{-7} in./yr	9.8×10^{-6} in./yr	25	4.7×10^{-5} in./yr	120
Abrasion resistance relative volume loss index	1.1 – 1.7	2.8	2.0	4.0	2.9
Resistivity	53.9 kΩ-in.	37.8 kΩ-in.	0.70	6.3 kΩ-in.	0.12

bridge. After hydrodemolition and before placement of the overlay, significant cracking was observed in the joints between the box-beam units, indicating loss of load transfer between units. The UHPC overlay was placed continuously over the skewed abutment to the end of the approach slabs, which were more than 25 ft long. Upon observation after one year in service, the UHPC overlay exhibited no signs of distress and no cracking between units. There was one hairline crack directly over the skewed abutment at both ends of the bridge; it was due to the negative moment created in the overlay by extending beyond the expansion joint between the bridge and approach slabs. The strain-hardening behavior of the UHPC overlay keeps the crack tight, and the material protects the expansion joint, preventing moisture ingress to the bearings or beam ends.

Similar to the keystone, the use of UHPC materials increases the strength and durability of the overall system. The benefits of UHPC extend beyond the isolated joint placements to improve the overall structural system performance. The details used on a given bridge should reflect the challenges that must be addressed, and they should also be uniquely tailored to the bridge design to maximize the enhanced properties of UHPC materials. The significant systematic improvements that can be accomplished with relatively small amounts of UHPC can help owners improve bridges in their existing inventory, salvage bridges that might otherwise be demolished, or facilitate further use of the economically efficient adjacent prestressed concrete box-beam bridge type.

References

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