Ultra-high-performance concrete connections for precast concrete bridge decks

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- Prefabricated concrete bridge decking systems present challenges of constructability and serviceability related to their field-cast connections.
- Ultra-high-performance concrete (UHPC) has been demonstrated to address these challenges through simplified connection details whose performance exceeds that of traditional connections details.
- Bridge-deck-level connection details employing UHPC with lap splices of no. 5 (16M) reinforcing bars within less than 6 in. (150 mm) were successfully tested under a range of loadings.
- UHPC composite connection details that facilitate simplified construction by eliminating the need for interlacing the girder shear connectors into pockets in the deck panels were also tested under cyclic and static loadings.

There is a growing need for durable and resilient highway bridge construction/reconstruction strategies that facilitate rapid completion of on-site activities to minimize effects on the traveling public. Prefabricated bridge elements can provide high-quality, accelerated, and safe construction; however, prefabrication of modular components necessitates an increased reliance on the long-term performance of field-installed connections.[1] These connections have sometimes proved lacking in terms of constructability, durability, and/or structural response, resulting in decreased overall bridge performance.

Prefabricated bridge girders, which are common and reliable structural components, have been deployed countless times in the highway infrastructure over the past century. In their most common form, these superstructure elements are connected to a cast-in-place concrete deck through the use of discrete steel connectors to develop composite action. Construction of such a slab-on-stringer bridge structure is straightforward, but it can be slow due to the need for field activities related to the casting of the concrete deck. As a result, there is an interest in using precast concrete deck elements or decked girders to accelerate on-site construction while simultaneously improving the quality of the bridge deck concrete.[2]

Evidence of the importance of this topic includes the large number of related National Cooperative Highway Research Program (NCHRP) projects and the Federal Highway Administration's Every Day Counts Initiative on Prefabricated Bridge Elements and Systems. NCHRP report 407, "Rapid Replacement of Bridge Decks"; NCHRP report 584, "Full-Depth Precast Concrete Bridge Deck Panel Systems"; and NCHRP web-only document 173, "Cast-in-Place Concrete Connections for Precast Deck Systems," all address precast concrete bridge decks.[3–5] Ongoing NCHRP projects 12-95, 12-96, and 12-98 address deck-level connections between box beams, deck panel–to–girder connections, and prefabricated system tolerances, respectively. FHWA has been encouraging owners to increase their use of prefabricated bridge systems to accelerate construction, increase jobsite safety, and improve long-term performance of bridges.

One concern with the use of this type of prefabricated bridge technology is the connections that tie the elements to one another and, in the case of deck panels, to the supporting girders.[6–9] These connections commonly require the interlacement of discrete connecting elements emanating from the prefabricated girders and decks, with the potential for problems with tolerance and fit-up in the field. Also, the field-cast grouts that are used to fill the connection voids have sometimes displayed inadequate durability.[10] Finally, the number and size of the panel-to-panel and panel-to-girder connections frequently specified for these types of prefabricated bridge technologies can lead to aesthetic, ridability, and durability problems in the finished bridge deck.

To address these challenges, a set of novel connection details was developed, tested, and brought to initial deployment. These details make use of ultra-high-performance concrete (UHPC) to provide simple connections that address field fit-up concerns and offer aesthetic and deck ridability features along with enhanced durability. The unique rheological, mechanical, and durability properties of UHPC are particularly well suited to facilitating this type of innovation in bridge construction.

Ultra-high-performance concrete

Advances in concrete materials technology have led to the development of a new generation of cementitious materials. As a class, these concretes generally have high cementitious material contents, low water–to–cementitious materials ratios, compressive strengths above 22 ksi (150 MPa), and sustained tensile strength resulting from internal steel fiber reinforcement.[11–14] Of particular interest, UHPC can significantly shorten the development length of embedded reinforcement, exhibit exceptional bond strength when cast against previously cast concrete, and display both high and sustained tensile resistance. These properties have facilitated the redesign of the component connections for prefabricated bridge elements, opening the door to simplified construction and enhanced long-term bridge performance.[15]

The UHPC employed in this research program and in United States bridge deployments completed to date is a commercially available product from a major construction materials supplier. It commonly contains 2% steel fiber reinforcement, has a water–cementitious material ratio less than 0.20, contains no coarse aggregate, and has a self-leveling consistency. Similar proprietary and nonproprietary products that fall within the same class of materials are widely available in Europe and are becoming available in the United States.

The concept of using the advanced properties of UHPC to significantly modify the design of connections between precast concrete elements is not new. In fact, research and deployments in this area date back to at least 1995.[16] At that time, a commercially available UHPC was used for closure pours in the connection of slab elements in a building at Aalborg University in Denmark. A few years later, a second project at the same university resulted in the use of field-cast UHPC connections between slab elements and between slabs and columns.

Based on the research team's experience with UHPC, along with past deployment experiences in Europe and Canada, FHWA initiated a research program to develop and demonstrate appropriate field-cast UHPC connection details that could immediately be deployed by bridge owners across the United States. Subsequent research efforts have resulted in other advancements in this topic area as well.[17–19]

Deck-level UHPC connections

The full development of reinforcing bars within a fraction of the normally required length can allow a designer to eliminate long lap splices, hooked bars, and other details that add cost and complexity to fabrication and construction activities. Limited static pullout testing conducted by the New York State Department of Transportation on UHPC-class materials demonstrated that development lengths can be shorter than 2.9, 3.9, and 4.9 in. (74, 99, and 124 mm) for straight lengths of black and epoxy-coated no. 4, 5, and 6 (13M, 6M, and 19M) steel reinforcing bars, respectively.[20] Similar results have been obtained by Fehling at al.[21] and by Swenty and Graybeal[22] in research on the embedment length of reinforcing bars in UHPC. A large study with hundreds of specimens investigating reinforcing bar size, type, embedment, and cover is also being completed by the author and is confirming these short embedment lengths. By potentially allowing 6 in. (150 mm) or shorter lap lengths for the sizes of reinforcing bars commonly used in bridge decks, UHPC allows closure pours between deck panels and other bridge deck elements to be redesigned as relatively narrow shear keys.

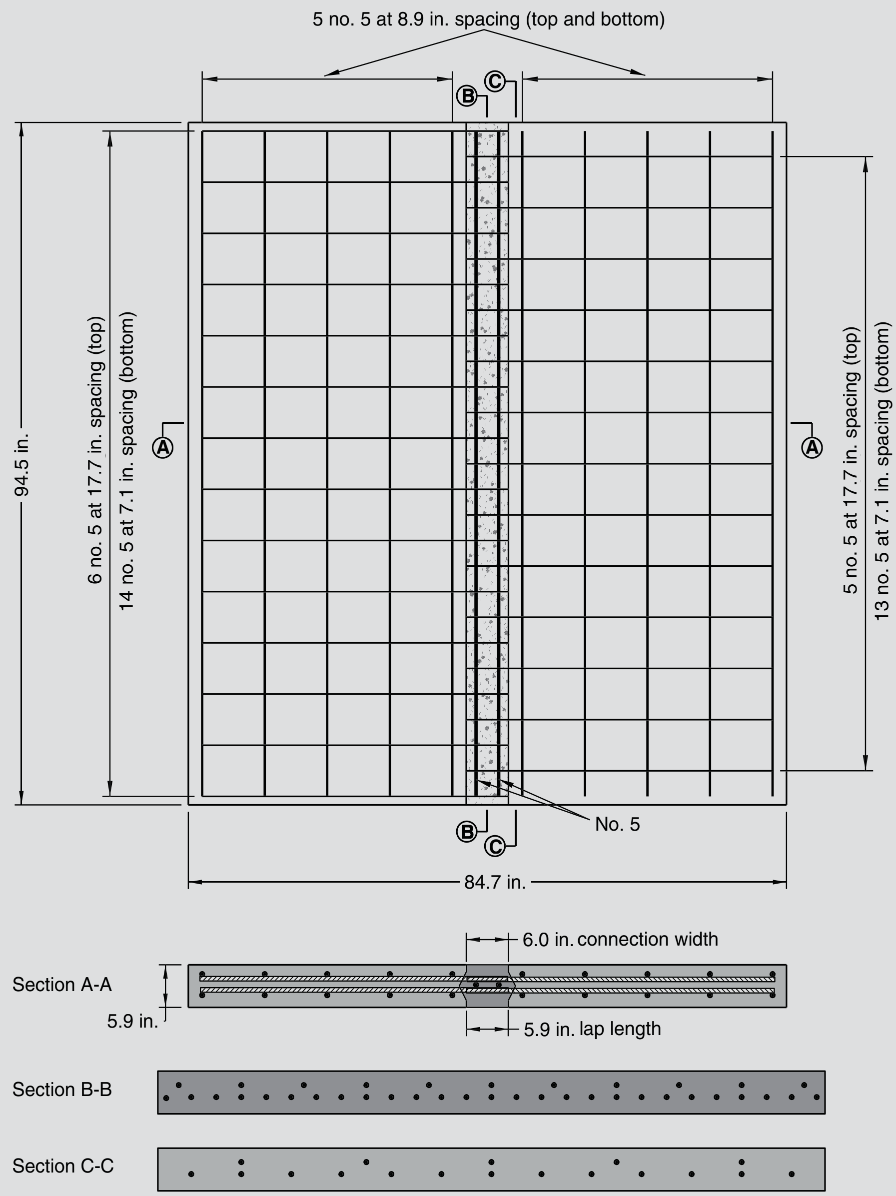

Figure 1. Ultra-high-performance concrete longitudinal connection specimen with noncontact lap splice detail. Note: no. 5 = 16M; 1 in. = 25.4 mm.

Full-scale structural testing of field-cast UHPC deck-level connections was conducted as part of a series of research projects. These projects investigated the performance of field-cast UHPC connections between precast concrete deck panels subjected to large cyclic and static flexure and shear forces. Results of this research have been extensively reported elsewhere and thus will only be summarized here.[20,23,24] Additional studies on this topic are also ongoing and continue to show promising results for this type of connection.

In the published research, bridge deck components simulating both longitudinal and transverse connections were fabricated and tested. Four transversely connected specimens simulated the connections between precast concrete deck panels. These specimens were identical aside from the different discrete reinforcing details, which included straight lapped bars, headed bars, and intersecting hoop bars. Two longitudinally connected specimens simulated the connections between the top flanges of decked girders. These two specimens were identical aside from the inclusion of two different discrete reinforcing details, namely straight lapped bars and lapped headed bars. **Figure 1** provides details on the longitudinally connected specimen with a straight bar noncontact lap splice connection. This specimen represents a simple and cost-effective connection detail in that it only requires the lapping of straight lengths of reinforcing bar.

All specimens were loaded on a simple span, with the load applied through a simulated wheel patch placed adjacent to the connection near midspan. Cyclic loads were applied first, with the test program including at least 2 million cycles to a load just below the cracking strength of the specimen followed by at least 5 million cycles to a load greater than the cracking strength. After completion of the cyclic testing, each test specimen was statically loaded to failure.

The loading program was designed to allow for the assessment of three critical behaviors. First, the cyclic loading below the cracking load allowed for the assessment of the cracking of the field-cast UHPC and the bonding of the UHPC–to–precast concrete interface. Second, the cyclic loading that generated stresses above the static cracking strength of the specimen allowed for the assessment of the cracking performance of the system, including whether there was any uncontrolled progressive cracking or interface debonding. Finally, the static loading program allowed for the assessment of the static overload performance of the system, thus providing an indication of whether the system effectively emulated the performance anticipated from a monolithic concrete deck.

Due to the support and loading conditions applied during testing, the cyclic loads generated stresses more severe than those that would be observed in a traditional concrete bridge deck under routine loading conditions prescribed by current AASHTO LRFD specifications for HL-93 loading. For transversely connected specimens, a simple analytical approximation suggests that the first phase of the cyclic testing, with loads peaking at 16 kip (71 kN), generated stresses similar to those that would be observed in a conventional concrete deck spanning 10 ft (3 m) between adjacent girders and loaded to a peak wheel patch load of 28 kip (125 kN). Subsequent cyclic testing, with loads peaking at 21.3 kip (95 kN), generated even higher stresses and structural cracking of the decks.

In terms of transverse deck connections, the structural behavior of the field-cast UHPC connections equalled or surpassed the performance that would be anticipated from a monolithically cast concrete bridge deck. The cyclic responses demonstrated favorable cracking behavior with no interface debonding. The static loading to failure resulted in global flexural failure of the simply supported panels, with behaviors progressing through cracking, reinforcing bar yielding, and eventual crushing of the conventional concrete in the precast concrete panels.

The study also demonstrated that the discrete reinforcement in the transverse and longitudinal UHPC-filled connections is not susceptible to debonding from the UHPC under severe loading conditions such as applied in this test program. In the most severe test, the longitudinally connected specimen shown in Fig. 1 was subjected to a large static overload and then 11.5 million subsequent cycles of structural loading at increasing loads. The overload and subsequent cycling were not observed to cause any debonding of the straight lengths of reinforcing bar that were lapped across the connection. At test cessation, more than 40% of the bottom mat of reinforcing bars had fractured due to metal fatigue of the bars coincident with the large number of cycles applied and the stress ranges imparted.

Composite connection between precast concrete deck panels and girders

The composite connection between a set of precast concrete deck panels and supporting girders must be capable of carrying significant shear and tensile forces. Traditionally, this has been accomplished by engaging discrete steel elements (reinforcing bars or studs) that extend from the girder and pass through the haunch into the deck. The field-cast grout would then provide geometric integrity to the connection but would not resist applied loads by itself. The discrete connector elements are commonly clustered to limit the number of pockets in the deck panels. The American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*[25] limit the distance between groups of clustered connectors to no more than 24 in. (610 mm) in most cases. Separate studies investigating the potential relaxation of this spacing provision to facilitate the use of precast concrete deck panels are under way.

To eliminate the fabrication, congestion, and assembly problems associated with interlacing these girder connectors into the numerous deck panel pockets, a novel concept was developed wherein the sustained tensile capacity of UHPC is engaged as a key structural element within the composite connection system.[26] The field-cast UHPC engages discrete connectors both in the deck and on the girder and, through its high sustained tensile capacity, transfers applied forces between the prefabricated components.

Figure 2 provides schematic illustrations of example UHPC connection details for precast concrete deck panels supported by steel and concrete girders. The connection at the girder resembles the traditional connection, with steel studs or reinforcing bar passing into the haunch. The primary difference is that the extension height of the connectors can be reduced so as to not interfere with the precast concrete deck. The connection at the deck is composed of a continuous channel or void cast into the underside of the deck panel through which the bottom mat of transverse deck reinforcement passes. The gaps between the girder and deck discrete connectors allow for simple assembly of components in the field. The channel void under the precast concrete panel eliminates the need for full-depth pockets and the need to cluster the girder connectors. The lower two illustrations in Fig. 2 represent the more severe cases with a vertical gap between the discrete connec-

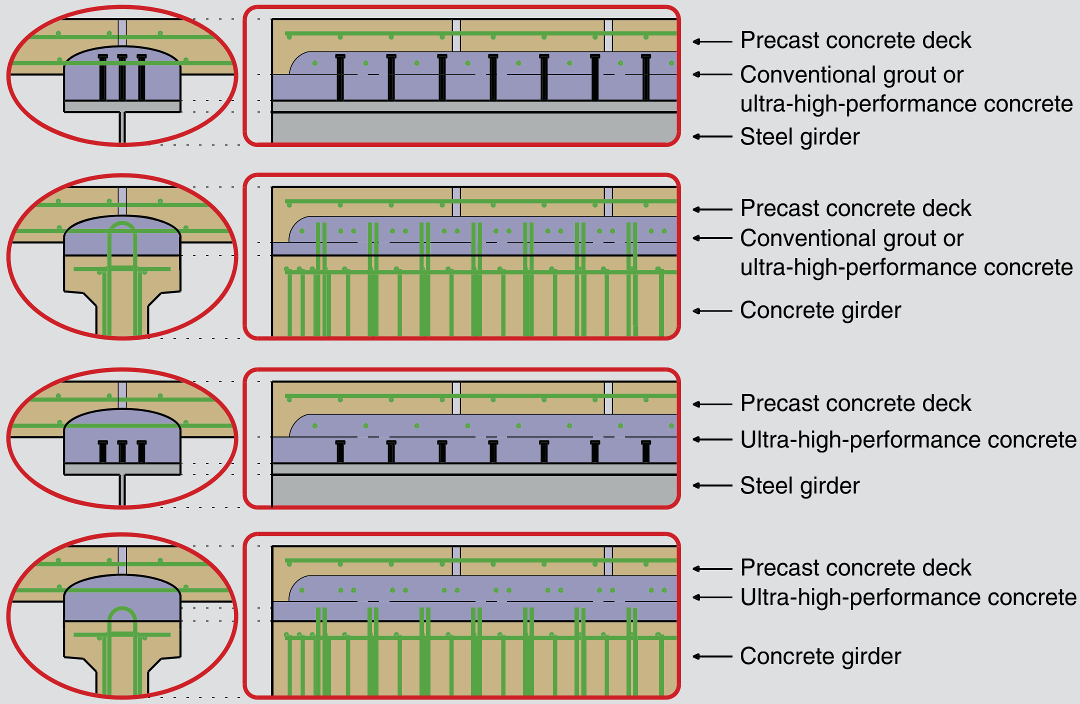

Figure 2. Ultra-high-performance concrete composite connection details.

tors. The upper two illustrations in Fig. 2 are conservative alternatives that afford connector overlap while still reducing potential geometric interferences. Connection details similar to each of those shown in Fig. 2 were tested in this study, with a summary provided here and with dimensions and extensive results provided in the associated report.[26]

After the prefabricated components are assembled in the appropriate configuration and the haunch is formed, the UHPC is cast into the void to completely fill the haunch connection. The self-leveling rheology of the UHPC allows it to flow into the hidden connection and engage all discrete connectors. Vent holes in the deck ensure that the UHPC has completely filled the void. For simplicity of field operations, it is advisable to combine this composite connection concept with the UHPC panel-to-panel noncontact lap splice connection discussed earlier.[20]

Test program

The steel girder composite connections (Fig. 2 and **Fig. 3**) and the concrete girder composite connections (Fig. 2 and **Fig. 4**, were constructed and subjected to physical testing.

Two full-scale test specimens were designed to mimic the type of slab-on-stringer construction commonly used throughout the United States for highway bridge construction. Although composed of precast concrete deck panels on prestressed concrete girders, the specimens were designed to emulate the composite connections between precast concrete deck elements and both steel and concrete girders. The design of the test specimens mimicked the line-girder design concept commonly implemented in U.S. highway bridge superstructure design. In this test program, individual superstructure elements (that is, girder-deck systems) were simply supported and subjected to a symmetric four-point bending load. This test setup allowed for the generation of realistic flexure and shear stresses within the test specimen. The test specimens were subjected to loads simulating the types of truck and lane structural loadings that are the primary basis for the structural design of bridge superstructures.

The design of the test specimens was based on preliminary structural designs by the New York State Department of Transportation (NYSDOT) as part of the Prospect Mountain Interchange Project. This project is rehabilitating 11 bridges in the Binghamton, N.Y., area, including six bridges in the Interstate 81/Interstate 86/U.S. Route 17 interchange over the Chenango River. NYSDOT identified six bridges in this project as potential candidates for the use of this particular accelerated bridge construction technology and as appropriate structures on which to base the experimental program. NYSDOT identified a likely structural configuration for each bridge and completed the design according to the fourth edition of the AASHTO LRFD specifications.[27] Further details on the bridges and their designs can

Figure 3. Ultra-high-performance concrete composite connection detail for steel girders.

be found elsewhere.[26] The maximum horizontal shear fatigue range was a critical factor in the design, with the maximum value on any girder line in any of the six bridges determined to be 0.937 kip/in. (0.164 kN/mm). This load pertains to a two-span continuous bridge with 209 ft (63.6 m) spans and 79 in. (2000 mm) deep steel plate girders that is hereafter referred to as the design bridge for this portion of the research effort. Although the Prospect Mountain Interchange Project has proceeded without the use of this novel UHPC composite connection concept, NYSDOT began deploying it in 2013 with the redecking of a set of interstate highway bridges in the Syracuse area.

The two test specimens had the same basic precast concrete panel and girder designs, but one was built as a conventional specimen with conventional composite connection details, and the other was built as a UHPC specimen with novel connection details. Each specimen included one end that emulated a steel girder connection to precast concrete deck panels and one end that emulated a concrete girder connection to precast concrete deck panels. The emulated steel girder connection was created by embedding a 0.75 in. (19 mm) thick steel plate with studs attached into the top of the top flange of a prestressed concrete girder. In total, the two test specimens provided results related to two conventional connection designs and two novel UHPC connection designs.

The conventional connection detail test specimen comprised a 40 ft (12 m) long, 39 in. (1000 mm) deep prestressed concrete girder; a 3 in. (75 mm) tall haunch; and 8.5 in. (220 mm) thick precast concrete deck panels. The emulated steel girder composite connection included sets of four transversely positioned studs with a diameter of 0.75 in. (19 mm) and a height of 6 in. (150 mm) welded to the steel top flange at a longitudinal spacing of 12.6 in. (320 mm). The concrete girder connection included sets of four transversely positioned headed dowel-in reinforcing bars with a diameter of 0.75 in. that were longitudinally spaced at 11.8 in. (300 mm). In both cases, the connectors were designed to pass through the haunch into the full-depth pockets in the precast concrete deck elements. The connections were completed through the use of a conventional nonshrink grout.

The novel UHPC connection detail specimen also comprised a 40 ft (12 m) long, 39 in. (1000 mm) deep prestressed concrete girder with 8.5 in. (220 mm) thick precast concrete deck panels. On this test specimen, the haunch height was increased to 4 in. (100 mm) to create a more severe loading condition. This height is the maximum allowed by NYSDOT in conventional composite connections without supplemental mild steel reinforcement. The emulated steel girder composite connection included sets of two transversely positioned studs with a diameter of 0.75 in. (19 mm) and a height of 3 in. (75 mm), which were welded to the steel top flange at a longitudinal spacing of 6.4 in. (162 mm). The concrete girder composite

Figure 4. Ultra-high-performance concrete composite connection detail for concrete girders.

connection included pairs of no. 4 (13M) hairpin reinforcing bars longitudinally spaced 5.1 in. (130 mm) apart. In these connections, the maximum extension height of the connectors was 3 in. (75 mm), meaning that the connectors stopped short of the bottom of the deck. For both the steel and concrete girder connections, the connection at the deck was created by exposing the bottom mat of no. 4 transverse reinforcing bars in the area above the girder top flange. These transverse bars were spaced 7.9 in. (200 mm) apart along the length of the test specimen. The connections were completed using field-cast UHPC.

The test program for each specimen included two phases. First, each test specimen was subjected to cyclic loads to simulate fatigue loadings commonly applied to highway bridge structures in service. **Figure 5** shows a photograph of this test setup. Each test specimen was supported on a 39 ft (12 m) span by roller supports. Vertical loads were applied symmetrically 13.5 ft (4.11 m) from each roller. Loads were applied by servo-hydraulic controlled actuators operated under load control. The pair of 100 kip (445 kN) capacity actuators applied loads to the top of the deck along the centerline of the girder through 12 × 12 in. (300 × 300 mm) elastomeric pads backed by steel plates.

The cyclic loading program was designed to generate large horizontal shear force ranges within the composite connection between the girder and the deck. A four-stage loading program was used (**Fig. 6**). The first three stages subjected each test specimen to more than 2 million cycles of structural loading. The final stage subjected each test specimen to more than 5 million additional cycles of structural loading. The vertical shear force range was increased by approximately one-third at each stage, resulting in the final stage applying twice the vertical shear force range as the initial stage. In this final stage, the vertical shear force range was 94 kip (418 kN).

The design of the composite connection in a slab-on-stringer bridge is frequently driven by service-level fatigue load considerations. Section 6.10.10 of the AASHTO LRFD specifications provides guidance on the design of a shear stud composite connection. These provisions were used to determine the amount of steel crossing all of the girder-to-haunch composite connection interfaces. The goal was to simulate the resistance of the design bridge while imparting loads exceeding those that the bridge may experience. **Figure 7** shows that the horizontal shear fatigue load range per unit length generated in the first

Figure 5. Test setup for cyclic loading of composite connection specimens.

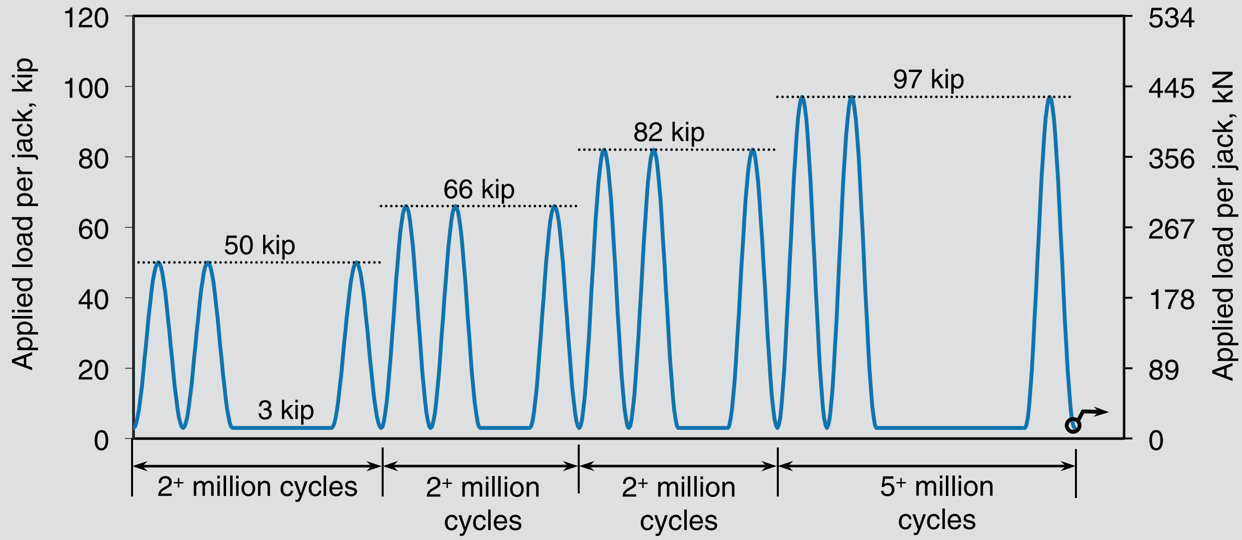

Figure 6. Composite connection test cyclic loading program. Note: 1 kip = 4.448 kN.

phase of the cyclic testing exceeded the anticipated load range for the design bridge as well as the design resistances at the girder-haunch and haunch-deck interfaces. Each successive loading step surpassed the design capacities by a larger margin. In the figure, ΔV_f indicates the range of vertical shear force on the beam, which is equal to half the live load applied through the actuators onto the beam. The circle-arrow marker indicates that the specimen capacity was sufficient to resist the applied loads throughout each loading phase, constituting a fatigue runout at that load.

After the cyclic loading program, each specimen was subjected to static loading in the second phase of the testing. The basic loading setup was the same as that used for the cyclic loading, with additional static hydraulic actuators added to achieve the necessary higher loads. The test specimens were loaded in a stepwise fashion until failure.

Test results

The novel UHPC connections succeeded in resisting all cyclic structural loads to which they were subjected

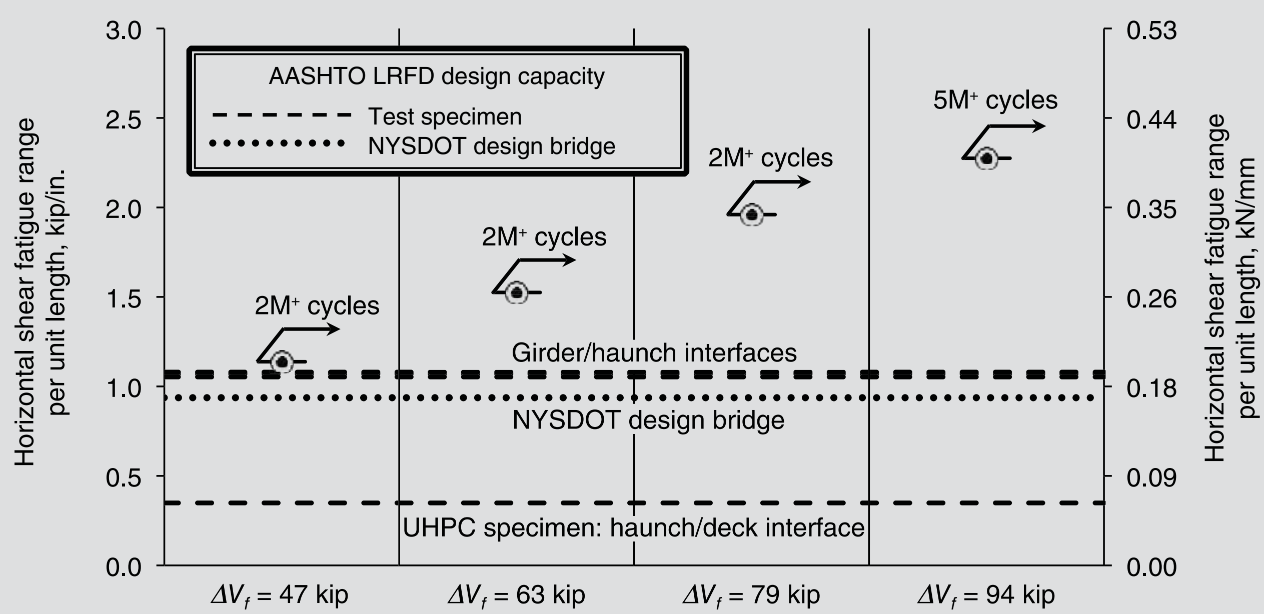

Figure 7. Horizontal shear fatigue ranges during composite connection cyclic testing. Note: ΔV_f = range of vertical shear force on the beam element. 1 kip = 4.448 kN.

throughout the testing program. No damage was observed within the UHPC composite connection or in the adjoining steel connectors throughout the duration of this testing. During the final phase of cyclic testing, the cyclic horizontal shear stress in the field-cast UHPC haunch was 168 psi (1.16 MPa), indicating that a minimum shear plane within the composite connection can carry this stress.

During the static testing to failure, the UHPC test specimen carried a peak applied shear load of 498 kip (2215 kN), which corresponds to a horizontal shear per unit length of 12.0 kip/in. (2.10 kN/mm). At this load, the prestressed concrete girder began to fail in a combination of horizontal and vertical shear in the web and top flange of the girder. Horizontal shear distress was also observed in the precast concrete deck elements adjacent to the haunch. No damage was observed within the UHPC connection or in the discrete steel elements (that is, reinforcing bar or studs). The peak horizontal shear stress on the otherwise unreinforced field-cast UHPC haunch was 789 psi (5.44 MPa) along the minimum shear plane.

The conventional connection specimen also survived the full set of cyclic load applications. However, as cyclic testing progressed, it was apparent that the connection between the emulated steel girder top flange and the haunch was degrading. The conventional specimen began to show increasing horizontal movement along the haunch interface per applied load compared with the UHPC specimen. This increasing movement can be attributed to progressive deterioration of the composite connection along the interface. The deterioration continued to increase as the cycling progressed. Regardless, the overall performance of the conventional specimen met the design requirements.

The conventional test specimen carried a peak applied shear load of 445 kip (1980 kN), which corresponds to a horizontal shear per unit length of 10.45 kip/in. (1.829 kN/mm). At this load, the composite connection at the emulated steel girder–to–haunch interface failed, with nearly all of the studs in the shear span detaching from the steel plate at their bases. By the end of the test, 10 of the studs had completely detached and 23 had partially detached during cyclic loading, leaving fewer studs to carry the horizontal shear during the static loading.

Both specimens exceeded the AASHTO LRFD specifications ultimate design capacities for the critical horizontal shear interfaces. In the UHPC specimen, the applied horizontal shear at failure exceeded the design capacity of the steel crossing the emulated steel girder/haunch interface by 66% and of the steel crossing the haunch and deck interface by 240%. In the conventional specimen, the applied horizontal shear at failure exceeded the design capacity of the steel crossing the emulated steel girder and haunch interface by 45%.

Conclusion

The results demonstrate that the novel field-cast UHPC connection details are capable of meeting critical design, construction, and response requirements. The connections withstood loads greater than those required by AASHTO LRFD specifications while equalling or surpassing the performance of conventional connection details.

Compared with conventional construction, connections designed with these details are simple to fabricate and assemble using technologies and materials already available in the United States bridge market. Deck panels and other bridge deck elements can be fabricated without resorting to the complex forming techniques that can be necessitated by conventional connection details. No clustering of girder and deck connectors is necessary, and the aesthetic and durability problems commonly cited with regard to full-depth composite connector blockouts are eliminated.

Recommendations

Based on the findings of this study, a set of limited recommendations can be provided to practitioners and researchers interested in engaging the field-cast UHPC connection details. These recommendations are conceptual guidance, not formal design specifications.

Deck-level connections

Extensive testing and dozens of field deployments have demonstrated that field-cast UHPC deck-level connections can be successfully deployed in bridge construction and rehabilitation. Details similar to those in Fig. 1 are appropriate for splicing precast concrete bridge deck panels in either the transverse or longitudinal direction. Common deck reinforcement can be spliced over distances shorter than that specified for conventional concrete without resorting to hooked, hooped, or headed bars. As such, the connections can become simpler to fabricate and construct while affording the long-term performance benefits of precast concrete deck panels with robust connections.

Innovation in design details is under way around North America as this connection concept is deployed more broadly. Additional research into appropriate design details for a wider range of reinforcing bar types and sizes is being conducted. Owners and designers interested in this connection concept are advised to remain abreast of the latest advancements in this field.

Composite connections between deck panels and girders

The composite connection details investigated and discussed here have been demonstrated to equal or surpass the performances expected from this type of connection.

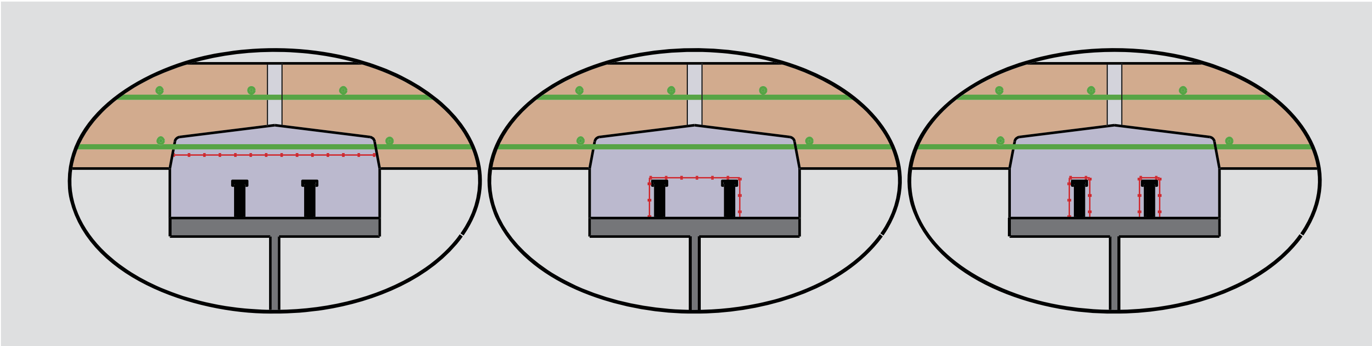

Figure 8. Minimum shear planes for horizontal shear transfer in the ultra-high-performance concrete composite connection.

Figure 2 provides conceptual composite connection details that can be used as a basis for the design of specific structural details. Reliance on the tensile and shear performance of the field-cast UHPC is a prerequisite for engaging the concepts shown in the lower half of the figure. The illustrations in the upper half of Fig. 2 show details that can be constructed using either UHPC or conventional grout. These details do not completely eliminate problems with connector interference but mitigate them by providing large spaces for the interlacing of the connectors. Compared with some conventional grouts, the rheological properties of UHPC can be advantageous when filling this type of connection detail.

Existing provisions of the AASHTO LRFD specifications should be retained and engaged as appropriate in the design of this detail. Relevant provisions include those in section 6.10.10 pertaining to the design of shear stud connectors on a steel girder and those in section 5.8.4 pertaining to the design of the connection to precast concrete girders. Requirements for extension of girder composite connectors into the deck will not be met if all aspects of this composite connection concept are engaged.

The horizontal shear resistance of the UHPC must be considered when designing this type of connection. In this study, the monolithic UHPC in the connection was capable of carrying at least 168 psi (1.16 MPa) of cyclic horizontal shear stress and at least 789 psi (5.44 MPa) of static horizontal shear stress. To calculate the horizontal shear capacity of any detail, the analysis must consider the minimum shear plane engaged within the detail, which is heavily dependent on the geometry of the connection and the arrangement of the composite connection connectors emanating from the adjoining prefabricated elements. It may be possible to increase the minimum shear plane through careful arrangement of these connectors. The red lines in the three illustrations in **Fig. 8** depict some potential horizontal shear planes for a steel girder–to–precast concrete deck panel composite connection.

Although not parametrically investigated in this study, using smaller bars for the bottom mat reinforcement of the deck is likely beneficial. Larger bars create larger local stresses in the conventional deck concrete, potentially resulting in local failure of that concrete. Similarly, providing longitudinal reinforcement adjacent to the blockout and immediately above the bottom mat of reinforcement is also likely beneficial to the performance of the overall connection.

Connection interfaces

As a general rule, roughened precast concrete surfaces are desirable at locations where the field-cast grout or UHPC is cast against the precast concrete. Roughening the top flange of a precast concrete girder is common practice. Extending this concept to interfaces in deck-level connections and deck-to-girder connections is beneficial. Roughened surfaces will enhance both the tensile and shear resistances at the interface. An emerging roughening solution that has shown promise in the laboratory and is already being deployed by bridge owners is the use of an exposed aggregate surface created by applying paste-like retarders to the precast concrete formwork before casting and then washing it off after stripping. This creates an open surface on the precast concrete component to which the field-cast grouting material can easily bond.

Field-cast UHPC

Quality control is necessary, particularly to ensure that the prefabricated components are staged properly and that the field-cast UHPC is mixed and cast properly. Compared with conventional concrete, greater reliance on the inherent structural performance of UHPC requires that it be mixed and cast according to the design. Field modifications of predefined mixture proportions or casting procedures are not advised. UHPC rheological indicators are frequently used to ensure appropriate mixing and can predict likely success in filling the hidden composite connection voids that are inherent to this connection detail. As with any construction material, care must be taken to ensure that owners, designers, and contractors are aware of the best practices related to its use.

Deployment of UHPC connections

Over the past few years dozens of highway bridge projects that engage field-cast UHPC connections between prefab-

Table 1. Deployments of field-cast ultra-high-performance concrete connections in the U.S. highway infrastructure

Route	Crossing feature	Location	Year	Owner	UHPC connection type(s)
SR 31	Canandaigua Outlet	Lyons, N.Y.	2009	NYSDOT	DBT
SR 23	Otego Creek	Oneonta, N.Y.	2009	NYSDOT	DP
Dahlonega Road	Little Cedar Creek	Ottumwa, Iowa	2011	Iowa DOT	DP, CC
Fingerboard Road	Staten Island Expressway	Staten Island, N.Y.	2011–12	NYSDOT	DBT
SR 248	Bennett Creek	Greenwood, N.Y.	2011	NYSDOT	DBT
US Route 30	Burnt River and UPRR	Huntington, Ore.	2011	Oregon DOT	DP, CC
US Route 6	Keg Creek	Council Bluffs, Iowa	2011	Iowa DOT	DG
Seven Lakes Drive	Ramapo River	Sloatsburg, N.Y.	2011	NYSDOT	DP
SR 42 (two bridges)	Westkill River	Lexington, N.Y.	2012	NYSDOT	DP, CC
SR 31	Putnam Brook	Weedsport, N.Y.	2012	NYSDOT	DP
I-690 (two bridges)	Peat Street	Syracuse, N.Y.	2012	NYSDOT	DP
I-690 (two bridges)	Crouse Avenue	Syracuse, N.Y.	2012	NYSDOT	DP
US Route 87	BNSF Railroad	Moccasin, Mont.	2012	Montana DOT	DP, CC
I-481	Kirkville Road	Syracuse, N.Y.	2012	NYSDOT	DP
SR 12	Spring Brook	Greene, N.Y.	2013	NYSDOT	DP
SR 10	Webster Brook	Dehli, N.Y.	2013	NYSDOT	DP
SR 38	Wilson Creek	Newark, N.Y.	2013	NYSDOT	DP
SR 962G	US Route 17	Owego, N.Y.	2013	NYSDOT	DP
SR 907W	US Route 1	Pelham, N.Y.	2013	NYSDOT	DP
SR 2 (two bridges)	SR 9	Colonie, N.Y.	2013	NYSDOT	DG
I-81 (two bridges)	E. Castle St.	Syracuse, N.Y.	2013	NYSDOT	DP, CC
I-81 (two bridges)	E. Calthrop Ave.	Syracuse, N.Y.	2013	NYSDOT	DP, CC
I-84 (two bridges)	Dingle Road	Southeast, N.Y.	2013	NYSDOT	NB
I-690 westbound	Onondaga Creek	Syracuse, N.Y.	2013	NYSDOT	DP, CC
I-690	N. Salina St.	Syracuse, N.Y.	2013	NYSDOT	DP, CC

Note: CC = composite connections between full-depth deck panels and supporting girders; DBT = deck-level connections between the top flanges of deck-bulb-tee girders; DG = deck-level connections between predecked modular steel superstructure units; DOT = Department of Transportation; DP = deck-level connections between full-depth precast concrete deck panels; NB = deck-level connections between northeast extreme tee (NEXT) beams; NYSDOT = New York State Department of Transportation; UHPC = ultra-high-performance concrete; UPRR = Union Pacific Railroad..

ricated elements have been completed in the United States. **Table 1** lists the projects that have been completed through December 2013. Dozens of additional projects have been completed in Canada, and many additional projects are under way during the 2014 construction season in both countries.

Deployed examples of the connection details discussed here are provided in **Fig. 9** and **Fig. 10**. Figure 9 shows a deck-level connection between precast concrete deck panels. This drawing is based specifically on the CR47 bridge over Trout Brook in Stockholm, N.Y., but is similar to the deck-level connection details in most of the bridges listed in Table 1. Note that the lap length of the reinforcing bars is dependent on bar size and that construction tolerances must be considered when designing the lap length. Figure 10 shows the composite connection detail between a steel girder and a precast concrete deck panel on the same CR47 bridge.

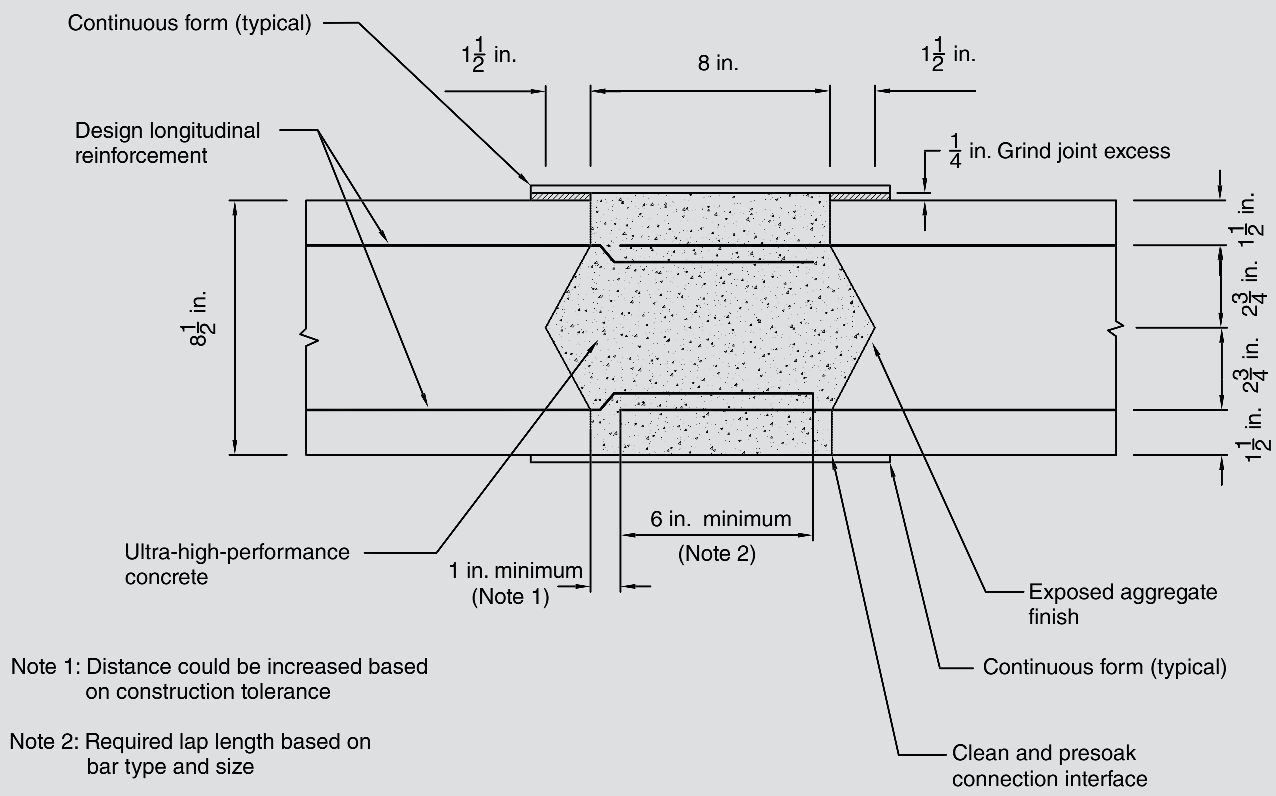

Figure 9. Ultra-high-performance concrete connection between full-depth precast concrete deck panels. Note: 1 in. = 25.4 mm.

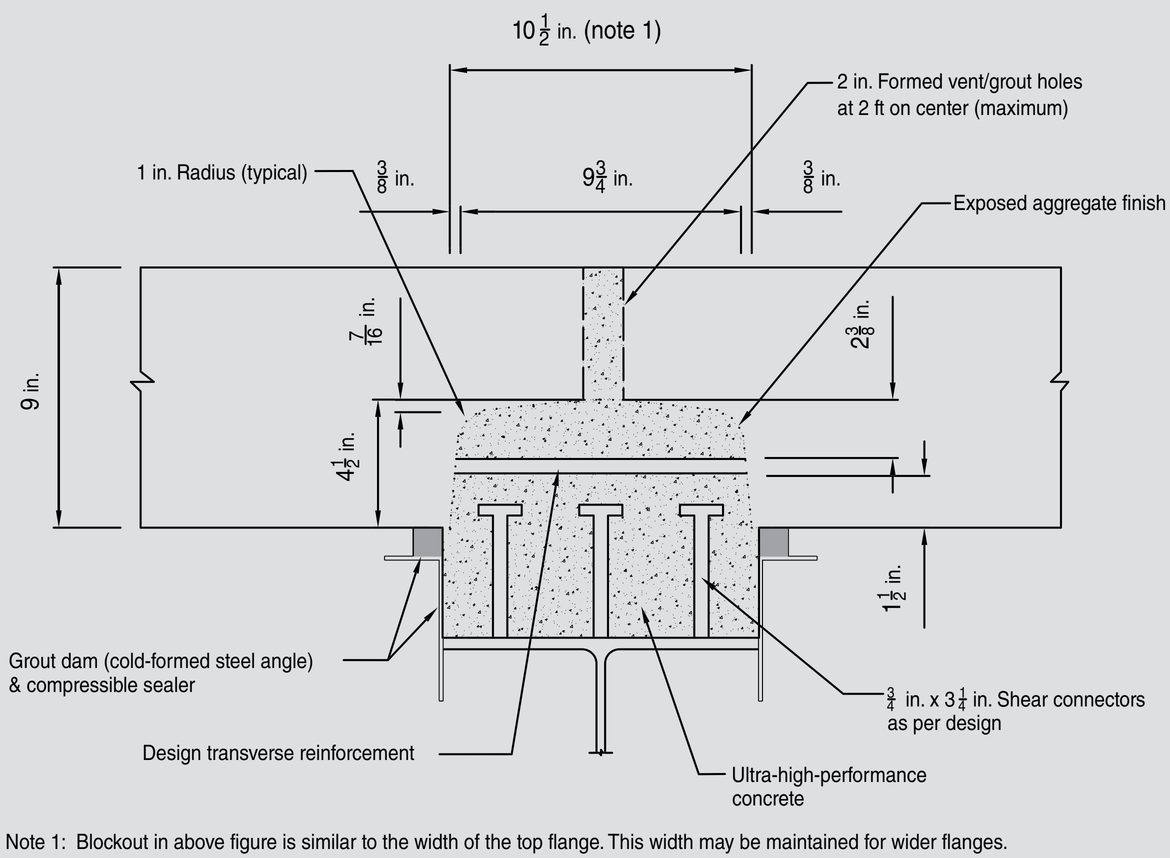

Figure 10. Ultra-high-performance concrete composite connection between full-depth precast concrete deck panel and supporting girder. Note: 1 in. = 25.4 mm.

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Notation

ΔV_f = range of vertical shear force on the beam element

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Abstract

Deployment of prefabricated concrete bridge decking systems continues to face constructability and serviceability challenges related to the field-cast connections between the components. A set of connection details was developed, tested, and brought to initial deployment. These details engage the performance of ultra-high-performance concrete (UHPC) to afford simple connections with minimal field fit-up concerns, reduced aesthetic and ridability concerns, and an expectation of enhanced durability. Bridge deck–level connection details that allow for the noncontact lap splicing of no. 5 (16M) reinforcing bars within less than 6 in. (150 mm) were successfully tested under a range of structural loadings. Composite connection details that facilitate simplified construction by eliminating the need for interlacing the discrete connectors and pockets in adjacent girders and deck elements were also tested under cyclic and static loadings. The UHPC connections were found to display performances that equalled or superseded that of conventional systems.

Keywords

Bridge, composite flexural behavior, interface shear, precast concrete deck panels, prefabricated element connections, reinforcing bar development length, UHPC, ultra-high-performance concrete.

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This paper was reviewed in accordance with the Precast/Prestressed Concrete Institute's peer-review process.

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