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**PRECAST CONCRETE DECK-TO-CONCRETE GIRDER CONNECTION USING UHPC**

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**Abstract:** Precast concrete deck panels have been widely used in accelerated bridge construction (ABC) in various forms and sizes. Typically, deck panels are connected to the girders by clustered shear connectors and formed openings in panels (i.e., shear pocket) to achieve a composite action between girders and precast concrete deck panels on a bridge. One of the disadvantages of the current systems is that shear connectors are required to have minimum embedment in the shear pockets to develop the design capacity, which necessitates higher level of QA/QC in girder and panel production. In order to address this issue, a new connection is developed by eliminating the need for clustered shear connectors and replacing them with typical girder shear reinforcement or shear studs. The shear reinforcement/studs are stopped below the bottom mat of deck reinforcement, which eliminates any changes to the girder design and possible conflicts during panel installation. Ultra-High performance concrete (UHPC) is then placed through grouting holes to fill the deck openings and haunch areas. UHPC has the advantages of high workability, high early compressive strength that can reach 90 MPa (13 ksi) within 3 days, and high durability. In this study, the literature review of existing UHPC deck-to-girder connections is presented along with the interface shear resistance of monolithic UHPC connections. The new proposed connection is discussed along with the experimental investigations planned to evaluate the constructability and structural performance of the new connection.

1. **INTRODUCTION**

In 1980s, Ultra High-Performance Concrete (UHPC) was developed in Europe as an advanced cementitious composite material for specialized applications that demand superior strength and corrosion resistance like marine anchors, piers, and seismic structures. The exceptional properties of UHPC are achieved with: (1) low water-to-cement ratio, (2) high particle-packing density, (3) high quality aggregate and cement, (4) supplemental cementitious materials, (5) high particle dispersion during mixing, and (6) in most cases the incorporation of fiber reinforcement. According to Federal Highway Administration (FHWA), UHPC is a cementitious composite material composed of an optimized gradation of granular constituents, water-to-cementitious materials ratio less than 0.25, and high percentage of discontinuous internal fiber reinforcement. The mechanical properties of UHPC include compressive strength greater than 150 MPa (21.7 ksi) and sustained post-cracking tensile strength greater than 5 MPa (0.72 ksi). UHPC has a discontinuous pore structure that reduces liquid ingress, significantly enhancing durability compared to conventional concrete (Graybeal 2010).

UHPC became commercially available in the U.S. through several proprietary sources in early 2000s. Since its introduction to the commercial market, the use of UHPC in various applications has been the focus of multiple research endeavors. Specifically, UHPC has been used in field-cast connections of prefabricated bridge components (Graybeal 2010), precast/prestressed girders (Rouse et al. 2011), precast piles (Wipf 2011; Ng et. al 2015), and waffle-type bridge decks (Aaleti and Sritharan 2014; Aaleti et al. 2011; Honarvar et al. 2016). Additionally, the seismic performance of UHPC elements/connections has been the subject of several research efforts (Lee et al. 2014; Zohrevand and Mirmiran 2013). Recently, the use of UHPC in transportation applications has been actively researched/promoted by the FHWA (Graybeal 2013). In this paper, the focus is on the use of UHPC for connecting precast concrete deck panels to concrete or steel bridge girders. Replacing conventional concrete/grout by UHPC in bridge field-cast connections significantly improves connection performance, reduces construction time, and enhances bridge durability.

1. **DECK-TO-GIRDER BRIDGE CONNECTION USING UHPC**

This section summarizes the literature review conducted on UHPC used for deck-to-girder connections. Typically, this connection is made of shear connectors, such as bent rebars or threaded rods in concrete girders, and shear studs in steel girders, that are embedded into discrete shear pockets or continuous troughs in the precast concrete deck panels. Then, a flowable concrete or grout is used to fill these pockets or troughs to establish the connection. One of the disadvantages of these systems is that shear connectors are required to have minimum embedment into the shear pockets/troughs to develop the design capacity, which necessitates high level of QA/QC and complicates girder and panel production.

A new UHPC connection concept was developed to eliminate this problem and simplify production and erection procedure, which consequently improve construction speed and economy. A series of interstate highway bridges near Syracuse, NY were constructed using this UHPC deck-to-girder connections developed by NYSDOT (Graybeal 2014). The connection consists of panel-to-panel longitudinal shear key with lap spliced transverse reinforcing rebars over the girder lines. Conventional shear connectors (19 mm (¾ in.) x 83 mm (3 ¼ in.)) are welded to the top flange of the steel I-girder as shown in Figure 1. The V-shaped shear keys have roughened/exposed aggregate finish to properly bond with the field-cast UHPC that connects the adjacent panels to each other and to the supporting girders. Dimensions of the longitudinal joint is typically 178 mm (7 in.) at the top and bottom of the deck slab and 254 mm (10 in.) at the middle of deck slab. Length and spacing of lap splices depends on bar size and type.



Figure 1: Panel-to-Panel Connection over Steel Girder (Graybeal 2014)

Another precast concrete deck-to-steel girder connection was recently developed and tested using UHPC (Graybeal 2014). In this connection, 19 mm (¾ in.) x 83 mm (3 ¼ in.) shear studs are installed on the girder top flange similar to cast-in-place (CIP) deck construction (i.e. similar spacing requirements). A 267 mm (10.5 in.) wide and 114 mm (4.5 in.) deep trough with exposed aggregate finish is formed in precast concrete deck slab with 51 mm (2 in.) grouting holes every 610 mm (24 in.) over each girder line as shown in Figure 2a. Shear studs are kept below the bottom mat of deck reinforcement without embedment in the deck panels to simplify panel and girder production and eliminate any conflicts during panel installation. An interstate highway bridge near Syracuse, NY was constructed using this connection concept with single field casting of UHPC through grouting holes for each girder line to hide the connection and eliminate the need for deck overlay. The same concept can be used with concrete girders by replacing the shear studs with conventional shear reinforcement (i.e. U bars) that are extended above the top flange and below the bottom mat of deck reinforcement (Graybeal 2014) as shown in Figure 2b. This connection has been tested but not implemented yet.



Figure 2: Hidden UHPC Deck-to-Girder Connection in Steel Girder (a) and Concrete Girder (b) (Graybeal 2014)

Recently, a study was conducted on implementing UHPC as a grout for deck-to-steel girder composite connection using two new concepts (Haber et al. 2017): a) using shear lugs through deck slab with different areas, and b) using vertical rebar dowels from the deck slab to connection without lugs as shown in Figure 3. The second concept was investigated for different haunch thicknesses (127 mm (5 in.) and 89 mm (3.5 in.)) and different distributions of shear studs. Push-off specimens were fabricated by having a symmetric layout with W10x60 steel beam at the middle connected to two 508 mm (20 in.) x 610 mm (24 in.) precast slabs through a grouted UHPC connection. The push-off test was performed by applying the shear force on the steel stub and evaluate the connection performance at the shear interface surface. The UHPC shear lugs have shown to be effective in transferring shear forces and the location and number of shear studs have an effect of the capacity of the connection. Adding rebar dowels to the connection increases the shear resistance, develops better anchorage, and achieve ductile failure behavior due to rebar dowel action.



Figure 3: New Haunch-to-Deck Connection Using UHPC Through Shear Lug (a) and Rebar Dowels (b) (Haber et al. 2017)

1. **INTERFACE SHEAR RESISTANCE OF MONOLITHIC ULTRA-HIGH PERFORMANCE CONCRETE (UHPC)**

This section summarizes the literature on the interface shear resistance of monolithic UHPC as it controls the design of the connections presented above. In addition, all design codes do not provide provisions that can accurately predict the interface shear resistance of UHPC due to its unique characteristics, such as high compressive strength, presence of steel fibers, and absence of coarse aggregate

Crane (2010) performed vertical interface shear push-off tests of monolithic UHPC specimens to determine whether ACI 318 (2008) and AASHTO LRFD (2007) equations of interface shear are applicable to monolithic UHPC. UHPC specimens with un-cracked and pre-cracked interfaces, and with reinforcement ratios of 0 and 0.5% were tested. Three identical push-off specimens were tested for each combination of interface type and reinforcement ratio. Test results indicated that the ultimate interface shear strength was significantly higher than that predicted for monolithic concrete in all cases. Regression analysis was performed to estimate UHPC cohesion and friction coefficients (c and μ). For un-cracked UHPC, μ = 4.5, and c = 13.8 MPa (2 ksi) were proposed, and for cracked monolithic UHPC, μ = 4.0, and c = 4.48 MPa (0.65 ksi) were proposed. These high values were attributed to the contribution of the steel fibers distributed across pre-existing cracks even when no mild shear reinforcement is used. Also as expected, the specimens with reinforced UHPC exhibited more ductile behavior than those with unreinforced UHPC. Average interface shear strength was found to be 13.1, 17.9, 18.6, and 27.6 MPa (1.9, 2.6, 2.7 and 4.0 ksi) for pre-cracked monolithic with 0% reinforcement ratio, pre-cracked monolithic with 0.5% reinforcement ratio, un-cracked monolithic with 0% reinforcement ratio, and un-cracked monolithic with 0.5% reinforcement ratio specimens respectively.

Maroliya (2012) investigated the behavior of reactive powder concrete (which is another term for UHPC) in direct interface shear. A series of direct shear specimens having inverted “L” shape in shear failure plane were tested using monolithic UHPC with different percentages of steel fibers. Test results showed that plain UHPC samples failed in a brittle manner at the first-crack load, which happens to be the maximum load taken by the specimen. On the other hand, samples having 2.5% fibers indicated multiple visible cracks, while samples having 2% fibers resulted in a maximum load much higher than the first-crack load, which clearly reflects failure after the strain hardening of the material. These results helped concluding that UHPC exhibits a ductile failure mode depending on the percentage of fibers. Results also indicated an average value of direct shear strength for normal cured monolithic UHPC with 2% fiber volume fraction of about 13.8 MPa (2 ksi).

Haber et al. (2017) evaluated direct shear strength of UHPC using two test configurations: Small-scale prismatic beam specimens with 51 mm (2 in.) square section in double shear; and Large-scale push-off test with different interface dimensions. Results of testing small-scale and large-scale specimens indicated that the direct shear strength of UHPC could be between 27.6 and 55.2 MPa (4 and 8 ksi), which is significantly higher that indicated in previous researchers. Jang et al. (2017) performed vertical push off tests to investigate the shear performance of construction joints using UHPC and reinforcement. A case of monolithic 179 MPa (26.0 ksi) UHPC without any construction joint was studied and considered as a reference for other types of roughened or grooved interfaces. Results for the monolithic placement specimen indicated that the interface shear strength could reach 18.6 MPa (2.7 ksi).

1. **EXPERIMENTAL INVESTIGATION PLAN**

A new UHPC connection between precast concrete deck panels and precast/prestressed concrete girders is developed to eliminate any changes to girder design/production and any possible conflict between deck and girder reinforcement. Typical girder shear reinforcement will be used and positioned below the bottom mat of deck reinforcement, then, UHPC is placed through grouting holes to fill the trough and haunch areas (i.e., a hidden composite connection). Several options of haunch configuration and panel trough will be analyzed and designed to evaluate their structural performance, constructability, and economy. Figure 4 and Figure 5 show two alternatives for forming the haunch: option I requires continuous deck support system and large quantity of UHPC, and option II requires discrete deck support system, compressible material, and smaller quantity of UHPC. Figure 6 shows a preliminary design of the panel trough proposed for this application. Figure 7 shows two alternatives for panel reinforcement and pre-tensioning strands: Option I with solid concrete zones at the panel ends and middle to provide two layers of pre-tensioning stands at these locations; and Option II with three equal troughs and two layer of pre-tensioning strands at the solid concrete zones. The main advantage of these options over the continuous trough concept presented in the literature is the use of pre-tensioning strands to transversely prestress the precast concrete panels, which minimizes panel cracking during handling and transportation.



Figure 4: Proposed Connection (Option I) (1in. = 25.4 mm)



Figure 5: Proposed Connection (Option II) (1in. = 25.4 mm)

 

Figure 6: Proposed Panel Trough (1in. = 25.4 mm)



Figure 7: Alternatives for Panel Reinforcement and Pre-Tensioning (1in. = 25.4 mm and 1 ft. = 0.305 m)

In addition, the interface shear resisting area between UHPC to UHPC increases as the wide trough covers most of the deck-to-girder connections shown in Figure 8. This area, as shown in Figure 9, will improve the shear resistance of the connections compared to existing connections.



Figure 8: Interface Shear Planes in The Proposed Connection (1in. = 25.4 mm)



Figure 9: Proposed Interface Shear Resisting Area (1 in. = 25.4 mm and 1 ft. = 0.3048 m)

According to panel design shown above, at least six push-off specimens will be fabricated and tested: three connections for each of the two alternatives presented in Figure 7. Specimens will be tested using the setup shown in Figure 10. Additional specimens might be tested to evaluate the effect of other parameters, such as stirrup hook type and height, trough depth and width, and surface roughening.



Figure 10: Proposed Push-off Test Setup

The outcome of this study will be an economical concrete deck-to-concrete girder connection that simplifies girder design and production as well as panel erection. The new connection will provide full composite action while maintaining deck durability and speed of construction

1. **CONCLUSION**

Using UHPC provides an efficient solution for deck-to girder connections and recently used in constructions of several bridges. However, the existing connections using small interface shear area between UHPC and UHPC surfaces to resist the horizontal shear forces, the main aim of the proposed connection is developing the maximum interface shear area of resistance by changing the connection from pocket concept to wide trough. The proposed connection presents new simple UHPC connection with regular horizontal shear reinforcement without any changes to the girder design and possible conflicts during panel installation.

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