Behavior of Ultra-High Performance Concrete Bridge Deck Panels Compared to Conventional Stay-in-Place Deck Panels

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Abstract: The remarkable features of Ultra-High Performance Concrete (UHPC) have been reported. Its application in bridge construction has been an active research area in recent years, attributed to its higher compressive strength, higher ductility and reduced permeability when compared with conventional concrete and even high-strength concrete. With that in mind, this study investigated the performance of UHPC stay-in-place (SIP) bridge deck panels subjected to high loads in both flexure and shear. The test matrix consisted of twelve (12) half-scale panels 4 feet long and 2 feet wide. The variable parameters that were studied included thickness (i.e., 2-in. and 3-in.) as well as non-discrete reinforcement type. The non-discrete reinforcement included conventional mild reinforcement, welded wire fabric (WWF), and no reinforcement (UHPC only). UHPC panels in the latter case were cast without minimum reinforcement, as the fibers alone are expected to bridge and restrict crack development. A control deck panel with conventional concrete was fabricated and tested to serve as a baseline for comparison.

Keywords: Ultra High Performance Concrete, Stay-in-place form, Partial depth concrete deck, Bridge deck, UHPC flexure behavior, UHPC shear behavior.

1. Introduction

The maintenance of bridges in the US, especially for high demand durability structures such as bridge decks, utilizes an important portion of this nation’s available maintenance funds. One of the main reasons for high maintenance in a bridge deck is the corrosion of deck steel caused by applied deicing salts where chlorides penetrate into the concrete and attack reinforcing steel.

One way to help improve the overall durability of deck systems may be the use of UHPC panels as either stay-in-place forms for partial-depth concrete decks or even perhaps as a full depth precast deck system. The panel would span between girders, serving as form for the bridge deck concrete and bearing the positive reinforcement. The low permeability and crack-free nature of UHPC would protect the reinforcing bars from corrosion.

The objective of this research was to study the behavior of those panels in high flexure and shear load configurations when compared to conventional SIP concrete panels. To evaluate the role of the tensile strength of UHPC, thickness and reinforcement type were varied.

2. Background

The application of UHPC in bridge construction has already been investigated in Canada, Europe and Japan. In the US, the Federal Highway Administration (FHWA) began the evaluation of UHPC for highway infrastructure in 2001. Most of the applications were in joints, full-depth deck panels and girders (Russell & Greybeal, 2013).

A stay-in-place formwork (also known as partial-depth concrete deck panel) consists in a concrete panel that spans between girders and simultaneously acts as form and as positive reinforcement for the cast-in-place deck. Shear studs, when structural steel girders are used, are placed on girders to support the panels, as shown in Figure 1 (Chavel, 2012). SIP forms are also used in concrete deck and girder systems. Because of this isostatic setup, it is important to protect the negative and positive deck reinforcement from corrosion. Using UHPC in this kind of element would reduce corrosion because of the crack-free, low permeability nature of the concrete, along with improving its performance in flexure and shear. As previously mentioned, UHPC may also have application in full deck usage if extended service life performance and limited maintenance costs are found to be economically feasible. Limited work to date has carefully examined the upfront initial costs to extended service life performance.

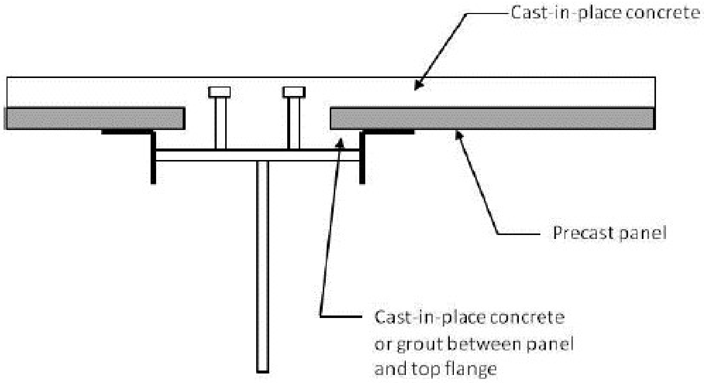

Figure 1. Stay-in-place formwork layout (Chavel, 2012)

3. Experimental Program

3.1. Test Matrix

The research herein aimed to better understand how the UHPC panels would behave in high flexure and shear loads compared to conventional concrete SIP panels. To investigate this, panels of several types were fabricated varying in concrete type, thickness, and reinforcement type.

The panels were 3-in. (76.2 mm) or 2-in. (50.8 mm) in thickness. Although AASHTO LRFD (2012) specifies that the minimum thickness of a SIP concrete form be a minimum 3.5-in. (88.9 mm), it was chosen lower to scale the panels down due to the limited capacity of the mixer that the research team had access to.

All the reinforcement types were located on the bottom half of the panels, with a clear cover of 0.75-in (19.1 mm).

Different load configurations were used to achieve higher bending moments or shear values within the panels. Panels were identified in this study as *"flexure panels"* if the load was located at mid span, and *"shear panel"* if the load was located at a quarter of the span.

The specimen test matrix is summarized in Table 1.

Table 1. Test Matrix

Test Type	**Concrete Type**	**Reinf. Type**	**Reinf. Detail**	**Reinf. Steel Grade (ksi)**	**Panel Thickness (in)**	**Panel Designation**
Flexure	Conventional	Conventional	#3 (#10) @ 3-in.	60	3	F – C – C – 3
	Conventional	Wire fabric	4x4 – W5.5xW5.5	65	3	F – C – W – 3
	UHPC	Conventional	#3 (#10) @ 3-in.	60	3	F – U – C – 3
	UHPC	Wire fabric	4x4 – W5.5xW5.5	65	3	F – U – W – 3
	UHPC	Wire fabric	4x4 – W5.5xW5.5	65	2	F – U – W – 2
	UHPC	None	-	-	3	F – U – N – 3
	UHPC	None	-	-	2	F – U – N – 2
Shear	Conventional	Conventional	#3 (#10) @ 2-in.	60	3	S – C – C – 3
	UHPC	Conventional	#3 (#10) @ 2-in.	60	3	S – U – C – 3
	UHPC	Conventional	#3 (#10) @ 2-in.	60	2	S – U – C – 2
	UHPC	None	-	-	3	S – U – N – 3
	UHPC	None	-	-	2	S – U – N – 2

Conversion: 1-in. = 25.4 mm, 1 ksi = 6.9 MPa

3.2. Mixture Proportions

The UHPC and conventional concrete (CC) mix designs used is this research were a modified version of the UHPC one used by Willey and Myers (2013) and a standard DOT conventional mix design. They are described in Tables 2 and 3, respectively. The compressive strength of the UHPC mix was 16 ksi (110 MPa) at testing, while the compressive strength of the CC mix was 5 ksi (34.5 MPa) at testing.

Table 2. UHPC Mixture Proportions

Material	**Amount: lb./yd^3 (kg/m^3)**
Type III cement	923.9 (548.1)
Silica fume	70.0 (41.5)
Ground-granulated Blast-furnace Slag	902.1 (535.2)
River sand	1193.7 (708.2)
Masonry sand	522.7 (310.1)
Superplaticizer	117.2 (69.5)
Steel fibers	263.0 (156.0)
Water	246.2 (146.1)

Table 3. Conventional Concrete (CC) SIP Panel Mixture Proportion

Material	**Amount (lb/yd^3 (kg/m^3))**
Type I cement	517.0 (306.7)
Pea gravel	1558.0 (924.3)
River sand	1588.0 (924.3)
Water	284.4 (168.7)

3.3. Test Setup

The panels were tested under a 3-point load configuration. A hydraulic jack was used to input load. A 10-in. x 5-in. x 1.75-in. (254 mm x 127 mm x 44.45 mm) steel plate followed by a 10-in. x 5-in. x 1-in. (254 mm x 127 mm x 25.4 mm) neoprene pad was used to transfer the load between the hydraulic jack and the concrete surface.

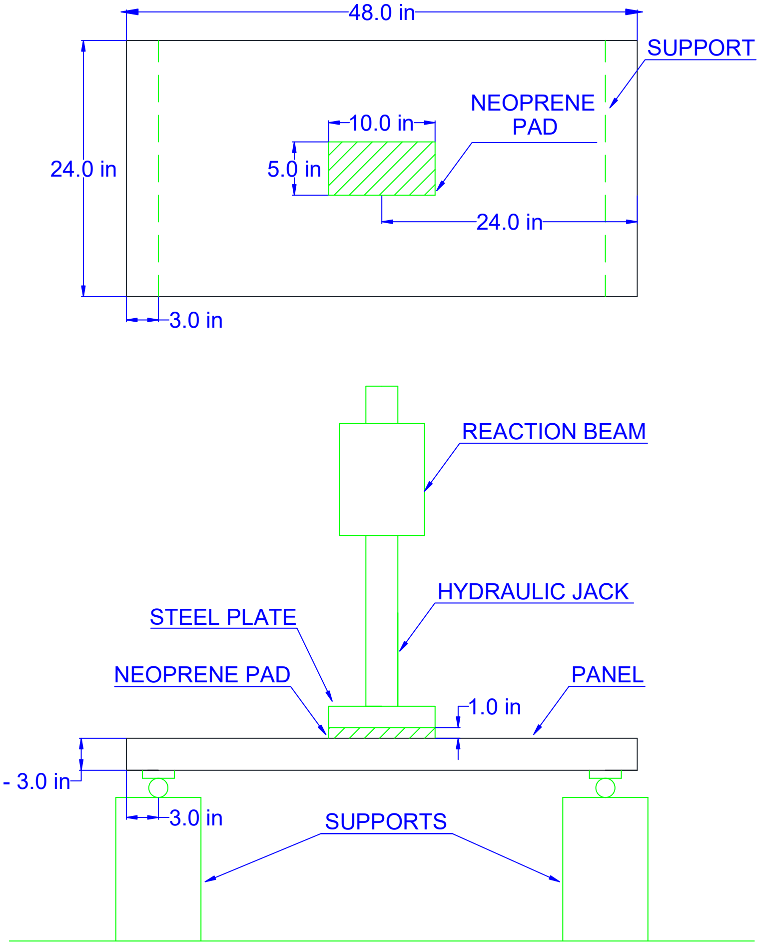

Figure 2. Test setup for flexure panels

The dimensions of the steel plate and the neoprene were chosen to simulate an AASHTO HS20 half scale truck tire. The jack reacted in a beam that was supported on two steel rod supports fixed in the laboratory floor. Figures 2 and 3 illustrate the respective test setups and loading locations.

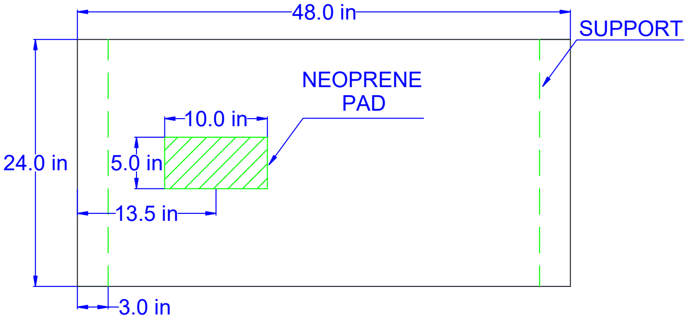

Figure 3. Test setup for shear panels

A load cell was placed between the steel plate and the jack to monitor the evolution of the load applied on the panel. Linear variable differential transformers (LVDT's) were placed mid-span in the direction of the load, 2-in. (50.8 mm) away from the edge of the panel to monitor displacement. Strain gauges were applied at the reinforcement and at the concrete surface. The test was considered complete when the panel dropped at least 10% below its peak applied load.

4. Results and Discussion

4.1 Flexure testing results

The UHPC "flexure panels" performed better compared to conventional concrete panels of the same thickness, as illustrated in Figure 4. A problem occurred during testing panel F-C-C-3, therefore testing could not proceed further after its peak value was attained.

Comparing panels that had equal reinforcement, F-U-C-3 had 120% more capacity than F-C-C-3 and F-U-W-3 had 74% more capacity than F-C-W-3. Also, even when having 33% less thickness, F-U-W-2 had 14% more capacity than F-C-W-3.

It is important to note that the low difference in the flexural capacity between F-U-N-3 and F-C-C-3 (9% less), F-U-W-3 and F-C-C-3 (4% more), and F-U-W-3 and F-U-N-3 (14% more), shows that the tensile strength of UHPC plays a major role in low depth-span ratio elements.

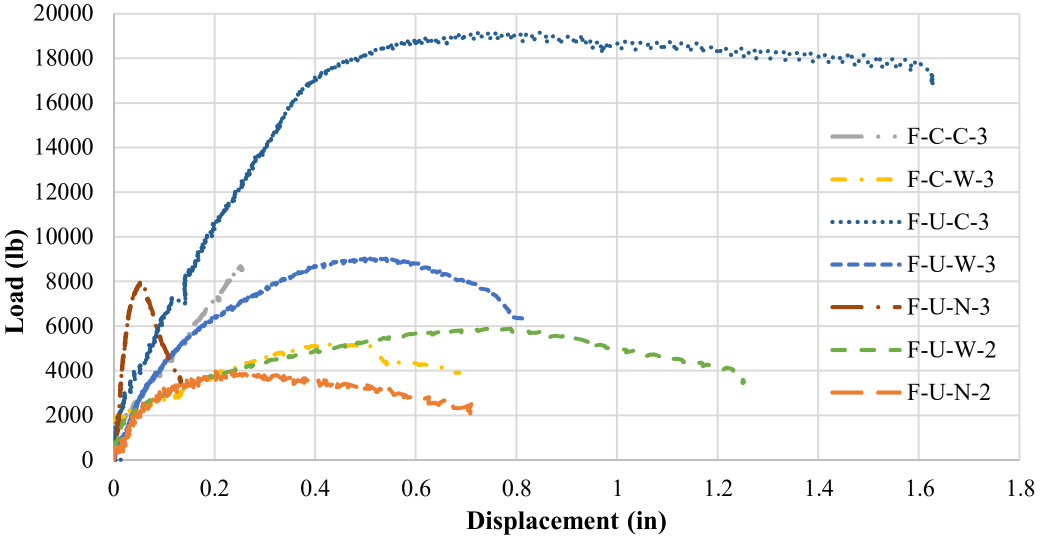

Figure 4. Load versus Displacement for the "Flexure Panels" Series

4.2 Shear testing results

The conventional concrete panel S-C-C-3 resulted in a diagonal tension failure mode, which was characterized by shear failure as expected. All of the others UHPC "shear panels" unexpectedly did not exhibit a shear type failure, but rather failed in flexure, even with the high shear loading configuration from the load located close to the support. This was a very important observation because it suggests that the shear capacity of UHPC in panels is much greater than what ACI 318-14 would predict for conventional concrete (V_c). The test results are shown in Figure 5. Figure 6 compares the crack pattern between S-C-C-3 and S-U-C-3.

The flexural type failure of the "shear panels" shows the high shear capacity that UHPC can provide, compared to conventional concrete. This characteristic can be seen as flexure failure occurred on both reinforced and unreinforced UHPC panels, and on both 3-in. (76.2 mm) and 2-in. (50.8 mm) panels. This is perhaps the most significant finding from this research study to date.

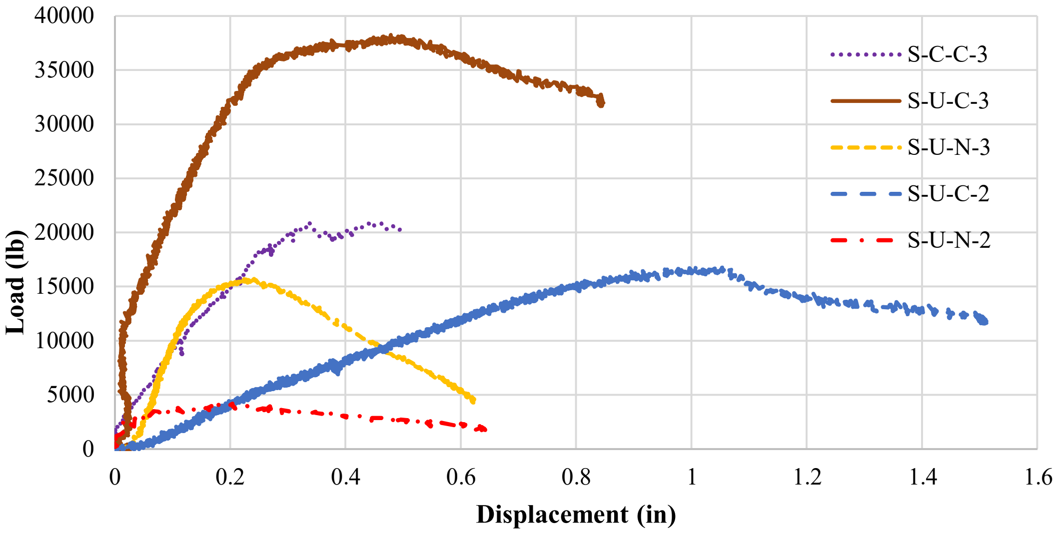

Figure 5. Load versus Displacement for "Shear Panel" Series

(a) Diagonal Tension Crack in a CC Control "Shear Panel" Test

(b) Flexural crack development in a UHPC "Shear Panel" Test

Figure 6. Failure Mode in Control and UHPC Panel Tests under High Shear Loading

5. Conclusions

A total of nine UHPC and three conventional concrete panels were developed and tested. When comparing panels with the same thickness and reinforcement, all UHPC panels performed better than the control panels. Comparing panels with same thickness but with different reinforcement showed the importance of the tensile strength of the UHPC in low depth-span ratio elements.

On panels tested under high shear loading, only the conventional concrete panels resulted in a diagonal tension failure mode (i.e. traditional shear type failure). All of the UHPC panels tested under this loading condition failed in flexure, which suggests that a higher shear capacity was provided by the UHPC concrete since all of the panels in the shear phase of testing were designed to fail in a shear type failure mode.

Although the proposed panel system had a promising performance, further investigations are needed:

- A cost study that compares panels made of both concretes and includes not only material, but maintenance over its service life and a life cycle estimate;
- A study that evaluates the behavior of prestressed UHPC stay-in-place forms for bridge deck panels and full depth precast deck panels.

6. Acknowledgements

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