ENHANCING DURABILITY OF BRIDGE DECKS USING UHPC

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ABSTRACT

Penetration of chlorides from the deicing materials contributed to concrete bridge deck deterioration, leading to structurally deficient or functionally obsolete rating of bridges in the United States (U.S). In order to overcome this challenge and to improve longevity of bridge decks, this project explores the possibility of using a thin layer of Ultra High Performance Concrete (UHPC) overlaying Normal Strength Concrete (NC) deck. Shear friction behavior at the interface between UHPC and NC was characterized by evaluating the influence of roughness, concrete strength and curing condition on the interface shear friction behavior using slant shear tests. A total of sixty test units with five different surface textures and three different concrete strengths were loaded to failure. Then, three 200-mm thick, 0.6-m wide and 2.75-m long deck specimens with 38-mm thick UHPC overlay were tested to failure. With the interface texture being the main variable, the composite deck sections were subjected a combined monotonically increasing flexure and shear loading. The slant shear test results demonstrated that the bond strength for all five different textures is adequate for overlay applications, which was later confirmed by the composite deck sections tests. The paper will present the summary of the completed experimental work and conclusions.

Keywords: Ultra-high performance concrete (UHPC), Deck overlays, Bridge deck repair and rehabilitation, Slant shear tests, and Composite deck.

INTRODUCTION

The combination of aging infrastructure, growing number of structurally deficient or obsolete bridges, and continuous increase in traffic volume in the United States demands rapid improvements to the nation's bridge infrastructure with an emphasis on increasing bridge longevity. Currently, bridge deck deterioration is known to be a leading cause for poor rating of bridges in the U.S. According to the Federal Highway Administration (FHWA), nearly $200-$300 billion dollars is needed to rehabilitate or replace all structurally deficient bridges in the nation[1]. Hence, Federal, State and municipal bridge engineers are seeking alternative ways to build better bridges, reduce travel disruptions, and improve repair techniques, thereby reducing maintenance costs and increase bridge longevity. Additionally, owners are challenged with replacing critical bridge components, particularly bridge decks, during limited or overnight road closure periods. Consequently, there is an impending need to develop technologies, which are not only economical and durable, but can also be safely and rapidly implemented in practice.

Ultra High Performance Concrete (UHPC) is a self-leveling high strength concrete material with excellent durability[2] and tensile strength[3] properties when compared to normal strength concrete (NC) used in today's bridge construction. This unique combination makes UHPC as an ideal material for minimizing deck cracking and associated bridge deterioration. Consequently, UHPC has gained significant momentum in terms of its utilization in bridge applications among several Department of Transportations (DOTs) and the Federal Highway Administration (FHWA). A recent project entitled "*Full depth UHPC precast waffle deck panels for bridge applications*, confirmed the significant benefits of UHPC deck systems in terms of excellent structural performance and ease of construction [4]. However, initial capital cost is comparatively higher than the traditional normal strength concrete decks, which may hinder the wider usage of UHPC waffle decks in bridges.

To minimize the cost of the UHPC deck system and realizing that the deck deterioration occurs due to formation of crack as well as penetration of deicing chemicals placed on the top surface, a composite bridge deck concept was motivated by overlaying a thin UHPC layer over a NC slab. This system not only provides a cost-effective solution by reducing the amount of UHPC by up to 50% in comparison to the waffle deck system, but also yields a highly durable alternative to the traditional concrete deck system which has high maintenance costs. However, a performance characterization of the composite deck system is essential to make this concept a reality for field applications. As illustrated in previous successful rehabilitation projects[5], the behavior of the interface connection plays a significant role on the overall structural and durability performance of the UHPC-NC composite deck system. Consequently, an integrated experimental and analytical study was conducted at Iowa State University to understand the influence of several parameters such as normal concrete strength, interface roughness and curing condition on the interface shear-friction or bond behavior. The results and observations from this study are presented below.

EXPERIMENTAL PROGRAM

An experimental program consisting of two phases of testing was completed. The goal of phase-1 testing was to identify the most suitable interface for the UHPC-NC composite deck with due consideration given to constructability, strength and along with estimating the bond strength between UHPC and NC for different interface textures under variable curing conditions. The ASTM C 882 slant shear test[6] (Figure 1a) was used for this purpose. In Phase-2 testing, three point flexural tests were conducted on small segments of bridge decks to evaluate the performance of the composite section under combined flexural and shear loading. In both phases, the tests were intended to examine the performance of the connection interfaces under the maximum stresses expected for bridge decks using different load combinations.

PHASE-1 TESTING: SLANT SHEAR TESTS

Based on a previous experimental study on the bond behavior of composite specimens incorporating UHPC[7] and the slant shear test concept[8], all interface tests in Phase-1 were completed using prismatic members as shown in Figure 1a. A test matrix consisting of five different textures and three concrete strengths was used to examine the feasibility and effects of different interface textures, concrete strength, casting sequence, and curing condition (fully cured vs. partially cured vs. wet conditions) on the shear friction behavior of the composite deck interface. To ensure easy constructability, mechanical connections such as shear studs across the UHPC and NC interface were not considered for experimental evaluation. The details of the test matrix are summarized in Table 1**Error! Reference source not found.**.

Table 1: Summary of completed UHPC-NC interface tests

Test type	Texture (# of specimens)	Casting sequence	Target NC Strength	Measured NC Strength
UHPCw-NC5	5 textures (TR 1 to TR 5) (3 per texture)	Wet UHPC over cured NC	34 MPa	36.4 MPa
UHPCw-NC7	5 textures (3 per texture)	Wet UHPC over cured NC	52 MPa	52.2 MPa
UHPCw-NC10	5 textures (3 per texture)	Wet UHPC over cured NC	69 MPa	44.8 MPa
UHPCh-NC5	5 textures (3 per texture)	Wet NC on heat treated UHPC	34 MPa	33 MPa

w –wet UHPC; h-heat treated UHPC

Each UHPC-NC composite specimen was 114 mm by 150 mm in cross-section, 600 mm long, and consisted of an inclined joint with different interface textures at the mid-height of the specimen. Based on the preliminary calculations and previous research, an inclination angle of 53.1 degrees to the horizontal axis was chosen to ensure sliding along the interface[9]. The joint interface surface was prepared using five different form-liners with varying roughness as shown in Figure 1b to achieve a consistent texture/roughness along the joint and among the specimens. These form-liners are regularly used in the precast industry in producing precast architectural products. The roughness of different form-liner patterns was chosen to replicate the different surface conditions expected during field applications. The degree of roughness in each case was established based on the macro texture depth, which varied from 2 mm to 6.5 mm for textures used in this study. In addition, the study investigated the influence of concrete strengths using 34 MPa, 52 MPa and 69 MPa mix designs.

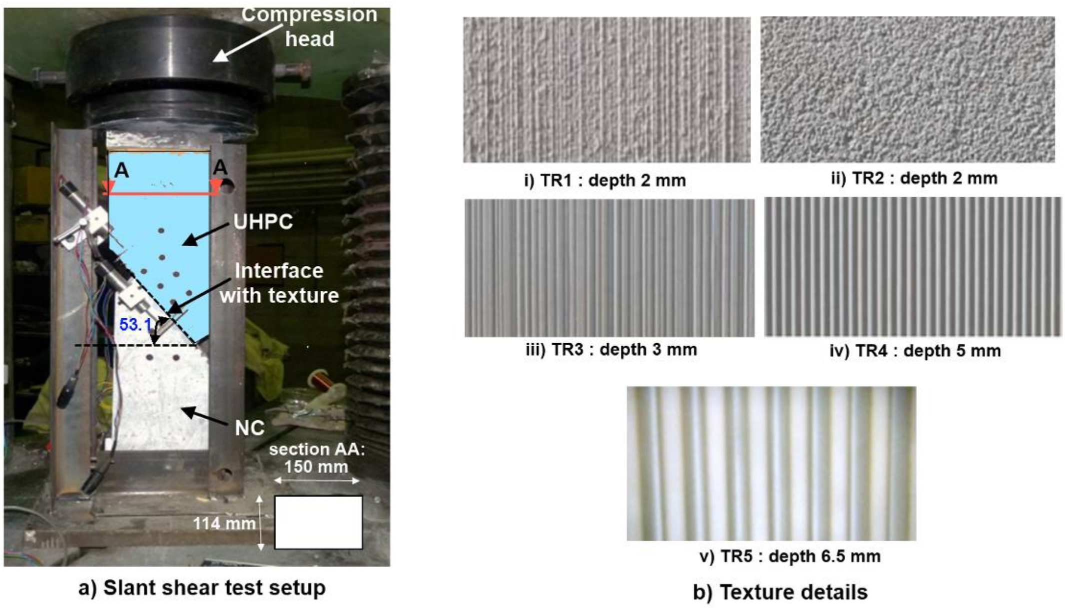
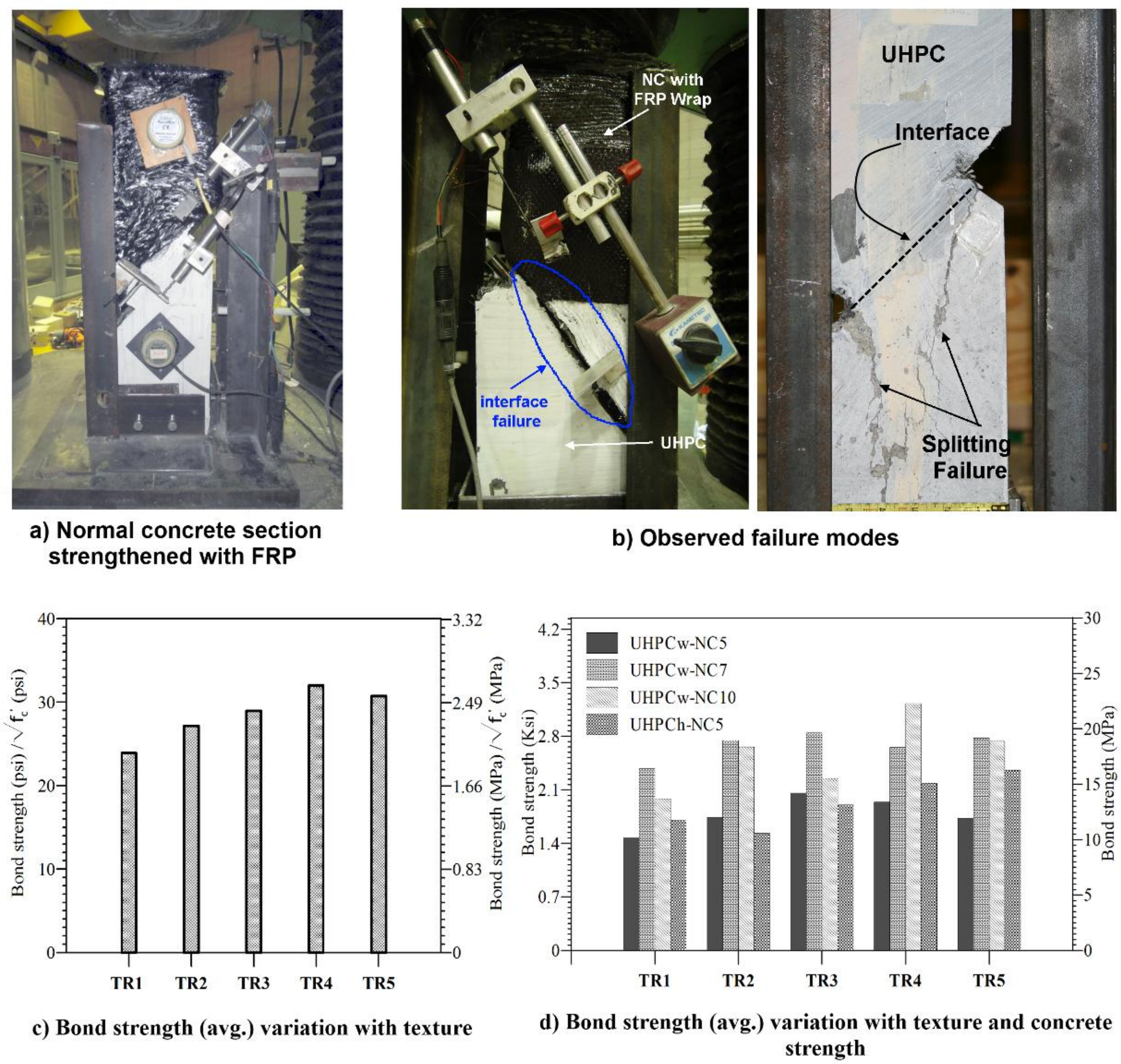


Figure 1 Test setup and textures used for slant shear tests

The composite specimens were cast using standard flexural beam molds with appropriate texture and concrete mix. Depending upon the casting sequence and curing conditions, the interface texture was first created on either UHPC or normal concrete half-sections. For specimens with wet UHPC, the normal concrete with specified concrete strength was poured in the mold with the form-liner and the half-section was then cured for 28 days under ambient conditions. After the curing process, the normal concrete half sections were placed back into molds with the slant side up and were filled with UHPC. The final composite sections were cured under ambient conditions until the day of testing.

The slant shear specimens were subjected to uniaxial compression at the ends using a universal testing machine (see Figure 1a), subjecting the interface to shear stresses along the inclined joint interface. Several instruments, including displacement transducers and rotation meters, were used in the interface region to adequately characterize the performance, and closely monitor the movement along the inclined shear interface. Based on the observations from the initial tests, in specimens with deeper texture and lower concrete strength, the normal concrete section was strengthened using FRP wrap (see Figure 2a) to prevent compression splitting failure. All samples were tested to failure until sliding at the interface or splitting of the NC is observed (see Figure 2b).



a) Normal concrete section strengthened with FRP

b) Observed failure modes

c) Bond strength (avg.) variation with texture

d) Bond strength (avg.) variation with texture and concrete strength

Figure 2 Observed damage to composite specimens and experimental bond strength variation

A total of 60 slant UHPC and NC interface specimens were tested to failure. The specimens were predominantly failed with sliding occurring along the interface. However, in a few specimens with deeper textures, even after the FRP retrofit, the splitting of the NC took place prior to sliding interface failure. The interface shear strength was calculated for all the specimens by dividing the maximum load along the inclined plane at failure by the contact area. This method gives a minimum value for the interface shear strength for the specimens failed in splitting of normal concrete and an exact value for those specimens failed along the interface. A comparison of the average interface shear capacity for each surface roughness and concrete strengths is presented in Figure 2c and Figure 2d, respectively. The bond strength generally increased with the increase of texture roughness and concrete strength. The casting sequence, however, did not significantly influence the bond strength. It was found that the bond strength developed for all textures would be adequate for applications in bridge decks as long the effects of differential shrinkage can be tolerated.

PHASE-2 TESTING: TESTING OF UHPC-NC COMPOSITE DECKS

Following the investigation of bond behavior using the slant shear tests on the composite test units, a total of five specimen including four UHPC-NC composite deck specimens with a texture depth varying from 2 mm to 6 mm and a specimen with standard concrete overlay were tested under combined flexural and shear loading. The textures along the interface in the test specimens were created using TR1, TR3 and TR4 form-liners as well as a hand broom finish on top of a NC surface. For the specimen with normal concrete overlay, the interface was prepared by sandblasting. The standard concrete overlay specimen was constructed according to the standard Iowa DOT practice and is used as the reference specimen to evaluate the performance of the UHPC-NC composite deck specimens. In each specimen, the dimensions of the NC portion were 2.74 m (length) x 0.81 m (width) x 203 mm (thickness), which represented a portion of the standard Iowa DOT bridge deck[10]. All the specimens were constructed using concrete with a specified strength of 28 MPa. The measured compressive strengths of NC and UHPC at 28 days after casting were found to be 32 MPa and 107 MPa, respectively. The reinforcement in the NC portion was designed (conventional method) according to the AASHTO standards[11] and represented the reinforcement as included in current Iowa DOT bridge decks. The details and layout of the reinforcement is shown in Figure 3a. Consistent with the Iowa DOT standards, a 38-mm thickness was chosen for the overlay, which was either wet UHPC or normal concrete. The overlay was placed on the rough surface of NC after 28 day curing.

A three-point bending configuration as shown in Figure 3a was used to perform the all of the load tests. The specimens were simply supported on rollers at a distance of 1.83 m apart. This span was chosen to maximize the shear demand on the interface and represents the minimum girder spacing used in typical Iowa bridges. The load was applied at the center of the specimen with a hydraulic actuator, causing maximum moment and shear at the center of the specimen. A 25 cm by 50 cm steel plate was used to distribute the load, which is in accordance with the AASHTO design specifications to represent a standard truck wheel contact area. The measured force-displacement responses of the three composite specimens along with the standard overlay specimen are shown in Figure 3b and the eventual damaged states at the ultimate load are shown in Figure 3c. At the service-level loading of 95 kN, a few hairline cracks formed directly under the load. All specimens ultimately failed with the initiation of shear failure in the normal concrete portion of the composite deck at a load in the range of 320 to 347 kN, which is nearly 4.5 - 4.9 times the design service-level wheel load.

The ultimate moment capacity of the composite specimen is nearly 3 times the design moment demand.

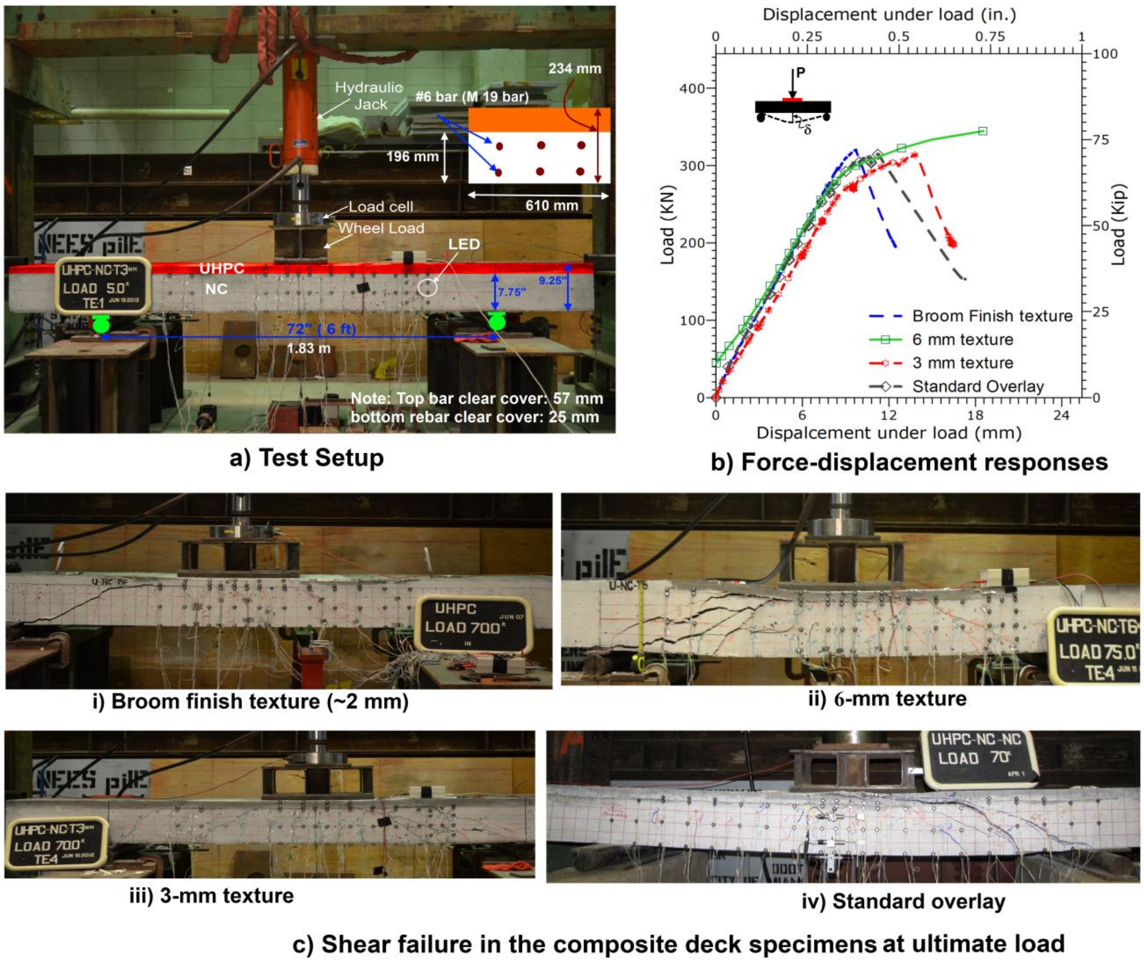
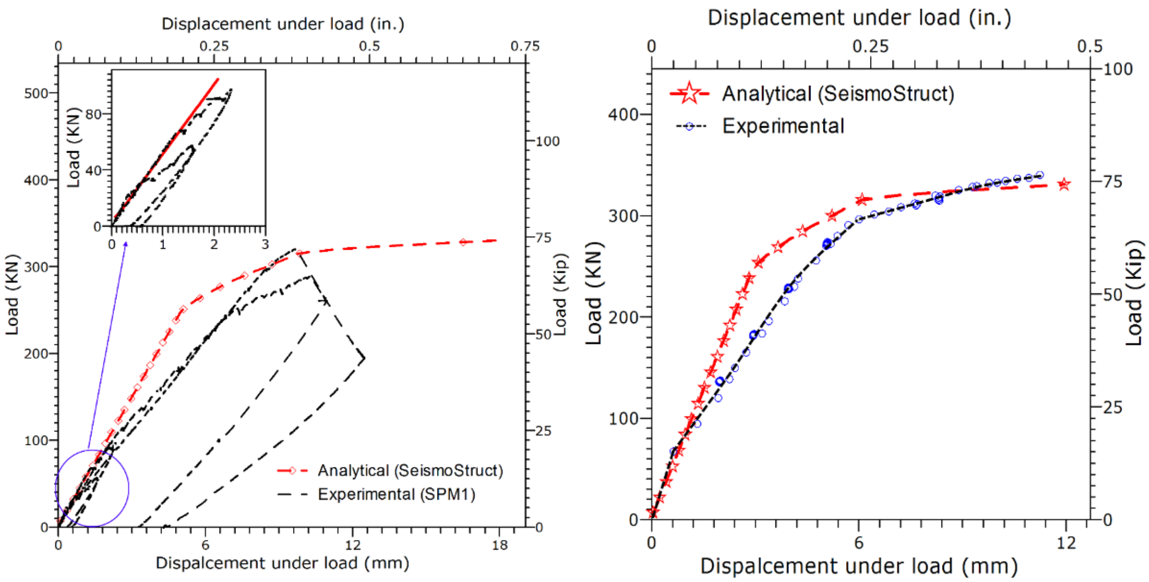


Figure 3 Testing of UHPC-NC composite deck specimens

The slip along the UHPC-NC interface was monitored using a 3D state-of-the-art Optotrak system and no slip was observed at the interface until the initiation of the shear failure in the specimens. From Figure 3b, it is clear that all three interfaces would be adequate for composite action. The broom finish specimen did not experience any significant ductility compared to other two specimens. Once the shear capacity of the composite deck was reached, delamination of the UHPC overlay was observed, which appeared to be triggered by the shear cracking in the normal concrete. The shear crack in the normal concrete didn't penetrate through the UHPC overlay. Instead, the crack propagated horizontally along the interface, causing delamination. In the other two specimens, due to higher interface capacity resulted from deeper texture, the delamination due to shear cracking in normal concrete was triggered at larger deformation compared to the broom finish specimen. This resulted in wider shear cracks (see Figure 3c), larger shear deformations and yielding of the reinforcement leading higher displacement capacity at failure. In case of the reference standard overlay specimen, there was also no delamination observed at the interface. Similar to the UHPC-NC specimen, the failure of the standard overlay specimen was initiated with formation of shear crack in the normal concrete, which propagated across the interface into the overlay material. This lead to a sudden failure of the specimen at the peak load unlike in the composite specimens.

ANALYTICAL MODELING

The moment-curvature response of the composite slab section was calculated by modeling the section using a zero length fiber-based beam-column element in SeismoStruct software[12]. The beam cross-section is discretized into a series of fibers in both directions. The stress-strain behavior of fibers was represented using appropriate uniaxial material models available in the analysis software. The longitudinal steel, normal concrete and UHPC were modeled respectively using stl_bl, con_ma and con_tl material models[12]. Tension behavior of the normal concrete is modeled using softening model with a peak tensile capacity of 2.1 MPa. The comparison of experimental and analytical force-displacement response for two specimens is shown in Figure 4. From Figure 4, it is clear that the analytical model captured the observed force-displacement response and initial stiffness of the composite system accurately. The predicted ultimate moment capacity of the composite system was within 2% of the measured value.



a) Broom finish texture **b) 6 mm texture**

Figure 4 Comparison of experimental and analytical force-displacement responses for two composite specimens

CONCLUSIONS

An economical and durable solution for rehabilitation and replacement of deteriorating bridge decks is proposed using a composite UHPC-NC deck system. Two phases of experimental testing, focusing on the interface behavior under combined shear-compression, shear-flexure loading was completed. The influence of design parameters such as interface texture, concrete strength and casting sequence on the composite action was evaluated. Based on the observations from the experimental testing and analytical modeling, the following conclusions are drawn:

1) Based on the slant-shear tests, a minimum roughness of 2 mm was sufficient to develop adequate bond strength between UHPC and NC interface under combined shear and compression loading.
2) The bond strength between UHPC and NC increases with the increase in interface roughness and concrete strength. The casting sequence did not have any significant influence on the bond strength.
3) Based on the flexural tests on composite slabs, it is clear that UHPC can be used as a durable overlay in bridge decks with a 2 mm minimum roughness for the UHPC and NC interface.
4) The composite section behavior can be accurately calculated using analytical models with fiber-based beam elements.

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