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Design, Installation, and Condition Assessment of a Concrete Bridge Deck Constructed With ASTM A1035 CS No. 4 Bars

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Abstract:

Recently developed corrosion-resistant reinforcing structural design guidelines were used to design, construct, and assess a reinforced concrete bridge deck with high-strength ASTM A1035 CS steel bars. The bridge replacement is located along the North Scenic Highway over the Wolf Creek in Bland County, Virginia. The bridge deck design used the higher yield stress available from ASTM A1035 CS steel to replace No. 5 bars with No. 4 bars that saved 23% by weight of steel in the deck and reduced reinforcement bar congestion, especially near the traffic barrier-bridge deck splice. The material cost savings was also 23% compared to a standard Virginia Department of Transportation bridge deck since the bars were bid as a cost per unit weight.

The Wolf Creek Bridge deck surface (i.e., cracks, slope, and surface profile) was documented using an automated computer vision system assembled with off-the-shelf cameras that accurately surveyed the bridge deck in less than 10 minutes, providing a high resolution 3D digital state model before and after the bridge was opened to traffic. The bridge deck is in excellent condition after 2 months in service, with only one crack of 0.004 in observed near a construction joint.

The study concluded that concrete bridge decks can be designed with No. 4 bars and constructed considering the structural benefits of gradually yielding, high-strength ASTM A1035 CS reinforcement bars with satisfactory in-service performance and some cost savings.

FINAL REPORT

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ABSTRACT

Recently developed corrosion-resistant reinforcing structural design guidelines were used to design, construct, and assess a reinforced concrete bridge deck with high-strength ASTM A1035 CS steel bars. The bridge replacement is located along the North Scenic Highway over the Wolf Creek in Bland County, Virginia. The bridge deck design used the higher yield stress available from ASTM A1035 CS steel to replace No. 5 bars with No. 4 bars that saved 23% by weight of steel in the deck and reduced reinforcement bar congestion, especially near the traffic barrier-bridge deck splice. The material cost savings was also 23% compared to a standard Virginia Department of Transportation bridge deck since the bars were bid as a cost per unit weight.

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The study concluded that concrete bridge decks can be designed with No. 4 bars and constructed considering the structural benefits of gradually yielding, high-strength ASTM A1035 CS reinforcement bars with satisfactory in-service performance (based on evaluations after several months in service) and some cost savings. Another evaluation in the spring of 2019 is recommended.

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INTRODUCTION

The goal of this study was to demonstrate the application of high strength corrosion-resistance reinforcing steel (CRR), and specifically ASTM A1035 CS (A1035 CS) steel No. 4 reinforcement bar (ASTM, 2016b), in a Virginia bridge deck. The design and proportioning of CRR for the Wolf Creek Bridge replacement in Bland County (see Figure 1) was guided by CRR structural design guidelines developed during a multi-year laboratory study at Virginia Tech (Lama Salomon and Moen, 2015).

Figure 1. US52 Bridge Deck Constructed With ASTM A1035 CS Steel Bars

The beneficial corrosion resistance of CRR bars is well documented. Sharp and Moruza (2009) evaluated the performance and costs of placement of epoxy-coated and A1035 CS steel deck reinforcement on the Route 123 Bridge over the Occoquan River in Northern Virginia, demonstrating and recommending the use of A1035 CS reinforcement bars for concrete bridge decks because of their reduced costs in comparison to epoxy-coated reinforcement bar (ECR) when considering the indirect labor costs and road user costs to the public concerning crack sealing operations that may be needed with ECR. The Utah Department of Transportation replaced the ECR in the US-6/White River Bridge with A1035 CS reinforcement bars observing that the placement of A1035 CS bars required no additional labor costs in comparison with ECR and that it provides up to 60% reduction in corrosion rate when compared to mild reinforcement

(Barr and Wixom, 2009). A1035 CS bars have been used for bridge deck reinforcement in Connecticut, Delaware, Iowa, Kentucky, Pennsylvania, Texas, Vermont, and Virginia (Barr and Wixom, 2009). Ozyildirim and Moruza (2014) found that concrete bridge decks using lightweight high-performance concrete (LWHPC) and stainless steel reinforcement bars meeting the requirements of ASTM A955/A955M (ASTM, 2016a) can be constructed with no visible cracks after 2 years in service. Other non-metallic CRR bars (e.g., glass-fiber-reinforced polymer), after multiple field studies (Berman and Brown, 2009; El-Salakawy et al., 2005; Frosch et al., 2006; Thippeswamy et al., 2000), have been found to perform well as reinforcement for concrete bridge decks, but their use has been limited by their high initial cost. The cost premium for A1035 CS CRR was overcome in this construction project by using its higher yield strength to justify using No. 4 rather than the standard No. 5 bars while maintaining structural integrity.

PURPOSE AND SCOPE

The purpose of this study was to employ recently developed CRR structural design guidelines, tools, and details to design, construct, and assess a reinforced concrete bridge deck constructed with high strength, corrosion resistant A1035 CS steel No. 4 bars (ASTM, 2016b) rather than the typically specified No. 5 bars. The demonstration effort replaces an existing bridge (VA Structure No. 1008; Federal ID No. 2962; Bristol District) in Bland County, Virginia.

US52 Bridge in Bland County, Virginia

The project site is located along the North Scenic Highway over Wolf Creek (latitude, 37.175050; longitude, -81.145814) in Bastian, Virginia. The new Wolf Creek Bridge is a 74 ft long steel girder simple span (Figure 2a) with two traffic lanes (one eastbound, one westbound). The bridge cross-section is shown in Figure 2b with five hot-rolled steel girders (W30x211) spaced at 6 ft 11 in supporting an 8.5 in concrete deck slab. The bridge deck is reinforced with No. 4 A1035 CS bars in the top and bottom mats, spaced at 7.5 in transversely along the bridge. The bridge deck was constructed in two phases (i.e., Phase I and II) to keep the existing bridge open during the replacement. Phase I consisted of a 12 ft 10 in section supported by two steel girders that provided a traffic lane width of 10 ft 0 in during the Phase II construction (UPC number 90177).

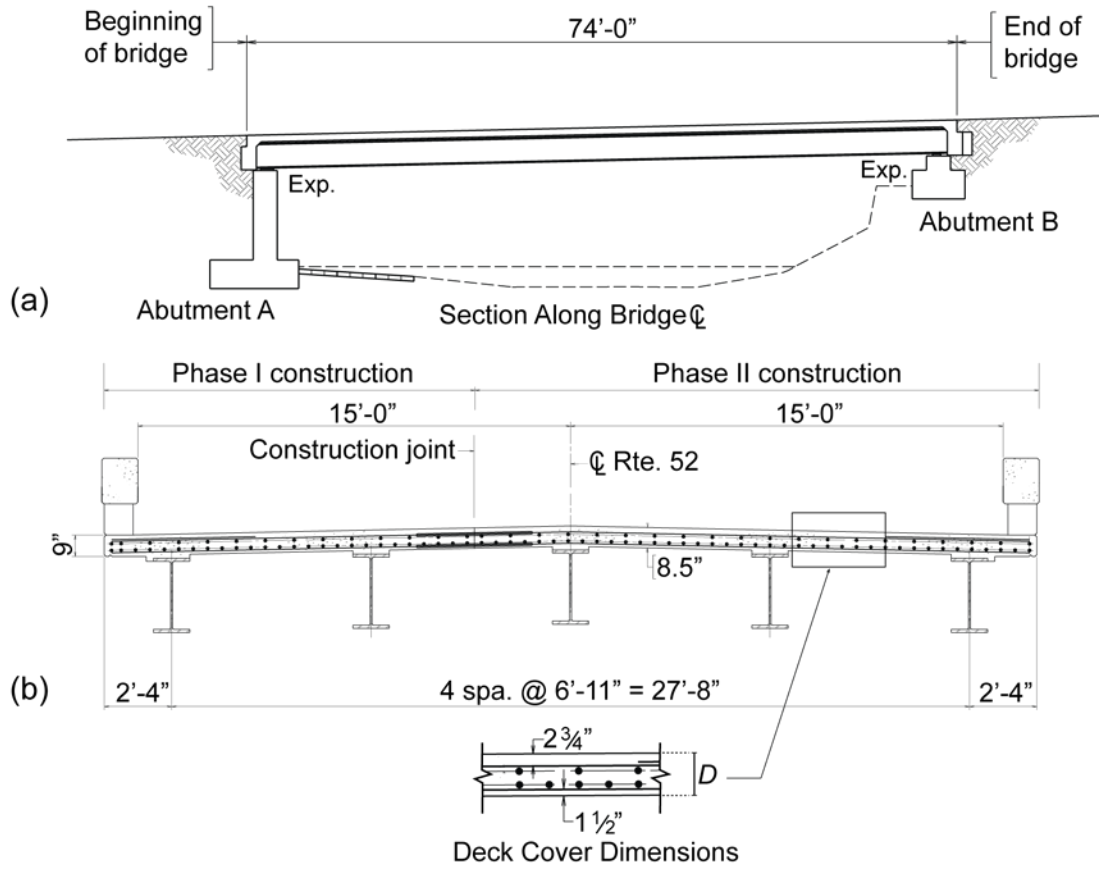

Figure 2. US52 Bridge Across Wolf Creek: (a) Elevation; and (b) Section

METHODS

Bridge Deck Design

The bridge deck was designed in accordance with the American Association of State Highway and Transportation Officials (AASHTO) LRFD Bridge Design Specifications (AASHTO 2010), VDOT modifications (VDOT, 2010), and the VDOT's Road and Bridge Standards (2008). The construction specifications included the VDOT's Road and Bridge Specifications (2007). During the design process, a Virginia Tech team worked in conjunction with the bridge engineers at VDOT's Bristol District, in coordination with the Virginia Transportation Research Council (VTRC), to convey their experimental results and conclusions on the use of A1035 CS reinforcement bars for concrete bridge decks. Serviceability calculations were conducted to confirm that predicted crack widths were within AASHTO limits when reducing the bridge deck transverse bars from A1035 CS No. 5 bars to A1035 CS No. 4 bars. The concrete cover and bar spacing remained consistent with VDOT standard details.

Field Inspections

Site visits were made during and soon after the construction of the bridge to document the placement and tying of the A1035 CS reinforcement bars, the concrete placement, and the condition of the bridge deck.

Deck Casting

The bridge deck was cast with a Low Shrinkage Class A4 Modified (LSA4M) concrete mix design. This mix design provides a minimum 28-day compressive strength of 4000 psi. The concrete was consolidated with electric spud vibrators and bridge deck finishers. The bridge deck was covered with polyethylene plastic and heater blankets for 7 days to cure the concrete in place. Figure 3 illustrates the bridge deck finishers and the workers consolidating the concrete during the concrete placement. Measurements were made using a calibrated metal probe to ensure a bridge deck depth within 0.5 in of the original 8.5 in design.

Figure 3. Concrete Placement for Phase I Construction

Reinforcement Bar Placement

During construction, the vertical top and bottom reinforcement mat distances were documented during the bars placement. Thirty measurements were made to characterize the mat depth variance in the bridge deck. The depth measurements were made from the top flute of the galvanized deck pan to the bottom of each reinforcement mat.

Material Properties

Reinforcement Bar Properties

Tensile tests of reinforcement bar specimens placed in the bridge deck were conducted in accordance with ASTM A370 (ASTM, 2005). Yield strength and ultimate strength of the reinforcement bar specimens, as well as the general stress-strain diagrams, were obtained for two specimens per production batch. Since the stress-strain curve of A1035 CS reinforcement bars lacks a sharp yield plateau, the yield strength was determined by the 0.2% offset method.

Concrete Properties

Freshly Mixed State

Prior to concrete placement, a series of tests was performed to check that the freshly mixed properties were consistent with the LSA4M concrete specification ranges. The mix design should produce concrete with 2 in to 4 in slump and 5% to 8.0% air content. A cubic yard of the bridge deck concrete was on average composed of 1,761 lb of No. 57 coarse aggregate, 1,146 lb of fine sand aggregate, 504 lb of cement, 265 lb of water, 126 lb of fly ash, and a combination of retarder, air entraining and other admixtures. Slump, air content and concrete temperatures were measured in accordance with ASTM C143 (ASTM, 2010a), ASTM C231 (ASTM, 2010b), and ASTM C1064 (ASTM, 2008), respectively.

Hardened State

Laboratory tests were conducted to characterize the concrete properties in the bridge deck. A group of six concrete cylinders (4 in x 8 in) and one rectangular specimen (3 in x 3 in x 11.2 in) were prepared for each concrete truck at the time of concrete placement in accordance with ASTM C31 (ASTM, 2012). The specimens were cured on site under conditions consistent with the bridge deck until tested (ASTM C 31). The modulus of elasticity, cylinder compressive strength, and splitting tensile strength were determined after 56 days from the placement date in accordance with ASTM C469 (ASTM, 2014a), ASTM C39 (ASTM, 2015a), and ASTM C496 (ASTM, 2004), respectively. The cylinder compressive strength and splitting tensile strength were computed as the average of three tests. The modulus of elasticity was determined as the average of two tests. The drying shrinkage strain was computed in accordance with ASTM C157 (ASTM, 2014b) using the rectangular concrete specimens.

As-Built Bridge Deck Condition Assessment

The initial bridge deck condition was documented with a mobile computer vision-based infrastructure condition assessment platform developed at Virginia Tech called OJOS. OJOS employs off-the-shelf digital single lens reflex (DSLR) cameras and image processing software that employs Structure for Motion (Koenderink and Doorn, 1991) to create high fidelity 3D

bridge deck geometry, feature, and crack maps (Lama Salomon et al., 2016). The mobile platform is composed of four DSLR cameras installed on a truck that records still image frames as it drives across the bridge deck surface. The images were used to compute a 3D digital state model (dSM) and document the condition of the bridge deck, including crack patterns, deck geometry, and surface roughness (Lama Salomon, 2017). Figure 4 shows an example of a 3D dSM of the Wolf Creek Bridge deck reconstructed during construction.

Figure 4. Example of a 3D Digital State Model of the Wolf Creek Bridge Deck During Construction: (a) Walking View Along the Bridge; and (b) Transverse-Looking View. This model is available online for viewing and downloading (Lama Salomon, 2016, 2017).

The cameras (Nikon D7100) were equipped with a Nikon AF NIKKOR 20 mm f/2.8 lens and a Marrex MX-G20M MKII Geotagger GPS. The global positioning system (GPS) information was used to split the set of pictures into 18 different sections with 900 images per section to reconstruct the 3D dSMs, as described by Lama Salomon et al. (2016, 2017). This step was necessary because the required pixel to point cloud density for the bridge deck digital state model was too large for the computers to generate a model in one single processing batch. The images were compiled to create multiple 3D digital state models of the bridge deck, which were used to document its condition at multiple time steps.

The bridge deck scans and visual inspections were carried out at 01:30 PM on May 24, 2016 (before opening traffic and concrete deck grooving [Scan 1]), at 12:30 PM on June 9, 2016 (before opening traffic and after concrete deck grooving [Scan 2]) and at 11:30 AM on July 27, 2016 (after opening to traffic [Scan 3]). The bridge was opened to traffic on June 10, 2016. The ambient temperature was 70 °F, 67 °F, and 82 °F for Scan 1, Scan 2, and Scan 3, respectively. The sky was clear during Scans 1 and 2 and cloudy during Scan 3. A scan took less than 10 minutes to perform.

The US52 Wolf Creek Bridge deck dSMs (see Figure 7), represented as point clouds, were created with 15,000 24-megapixel images each, and they are available online for viewing and download at (Lama Salomon, 2016, 2017). The image processing was performed using one computing workstation with 32 GB of RAM memory, dual graphics processing units (GPUs), and six core processors. Digital state models, as textured meshes and point clouds, were also computed and saved as OBJ and PLY files which are the standard format for 3D mesh models and point clouds (Pears, 2012). A fine scaling was performed using the field measured distance of 887 in (22.5 m) between the ends of the bridge deck.

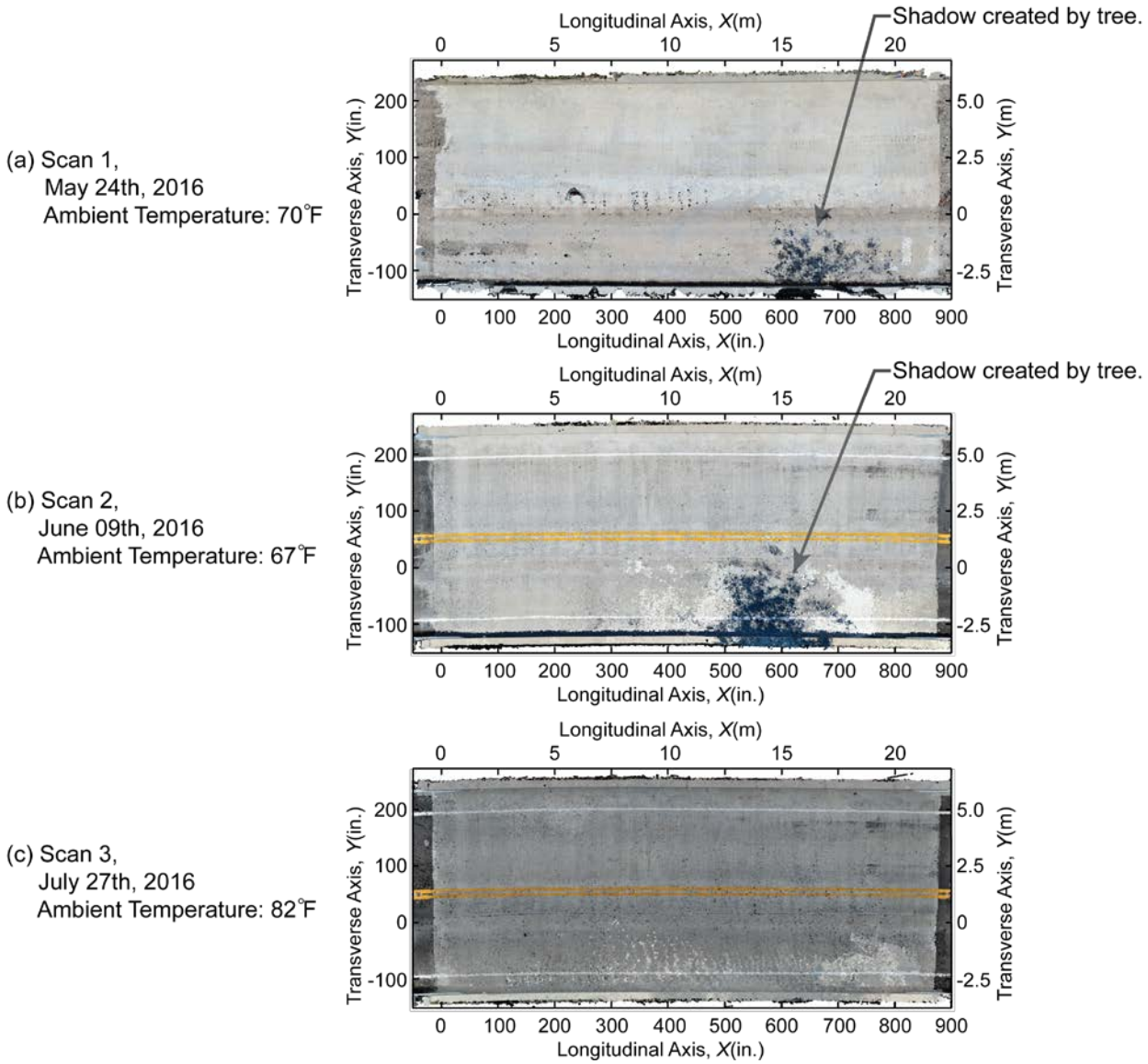

Figure 5. Plan View of Wolf Creek Bridge Deck dSMs: (a) Scan 1, Before Opening to Traffic and Concrete Deck Grooving; (b) Scan 2, Before Opening to Traffic and After Concrete Deck Grooving; (c) Scan 3, After Opening to Traffic. These digital state models are available online (Lama Salomon, 2016, 2017).

RESULTS AND DISCUSSION

Field Inspections

Deck Casting

Figure 6 shows a histogram of the as-built bridge deck depth for Phase I (Figure 6a) and Phase II (Figure 6b), measured from the top flute of the galvanized deck pans. The average bridge deck depth was 8.79 in and 8.98 in for Phase I and Phase II, respectively. The depth

measurements were within the 0.5 in allowable deviation from the 8.5 in targeted depth with a coefficient of variation (CV) of 0.03.

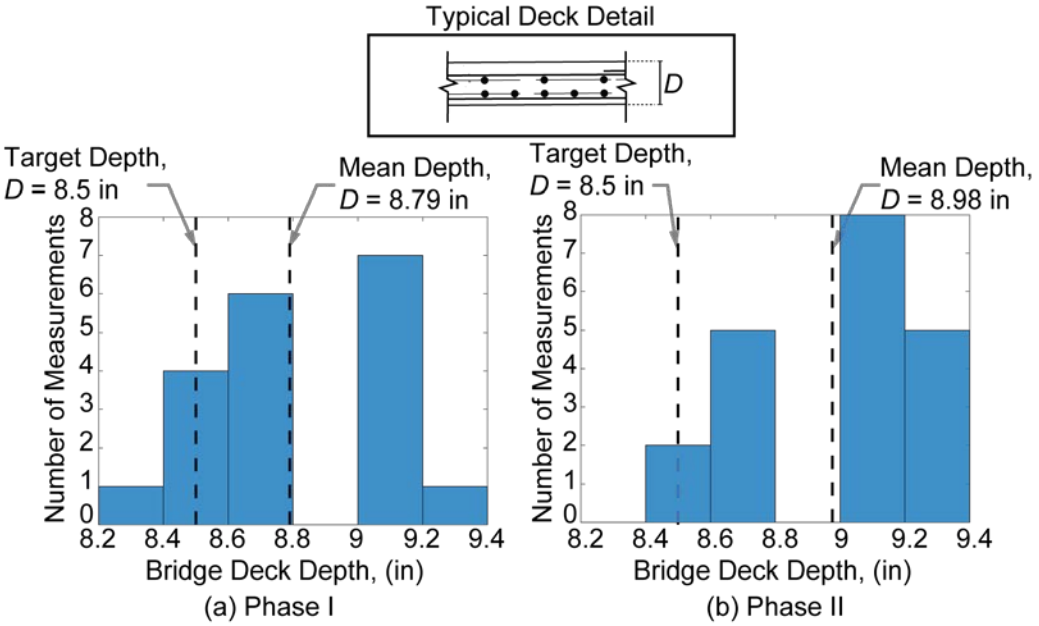

Figure 6. Histograms for the As-Built Bridge Deck Depths for (a) Phase I, and (b) Phase II

Reinforcement Bar Placement

The depth of the bottom and top mat reinforcement were measured at 15 different locations along the bridge deck Phase 1 construction to characterize its variability. Figure 7 shows a histogram of the as-built reinforcement steel depths. The bottom and top mat reinforcement were on average 1.85 in and 4.0 in from the top flute of the deck pan and COV of 0.02 and 0.01 for the bottom and top mat, respectively. The VDOT specified bottom and top bar mat locations on the shop drawings are 1.25 in for the bottom mat and 5.0 in for the top mat. This means that the top mat is as much as 1 in lower than what was assumed in design, which reduces the bridge deck transverse structural efficiency and the longitudinal flexural capacity.

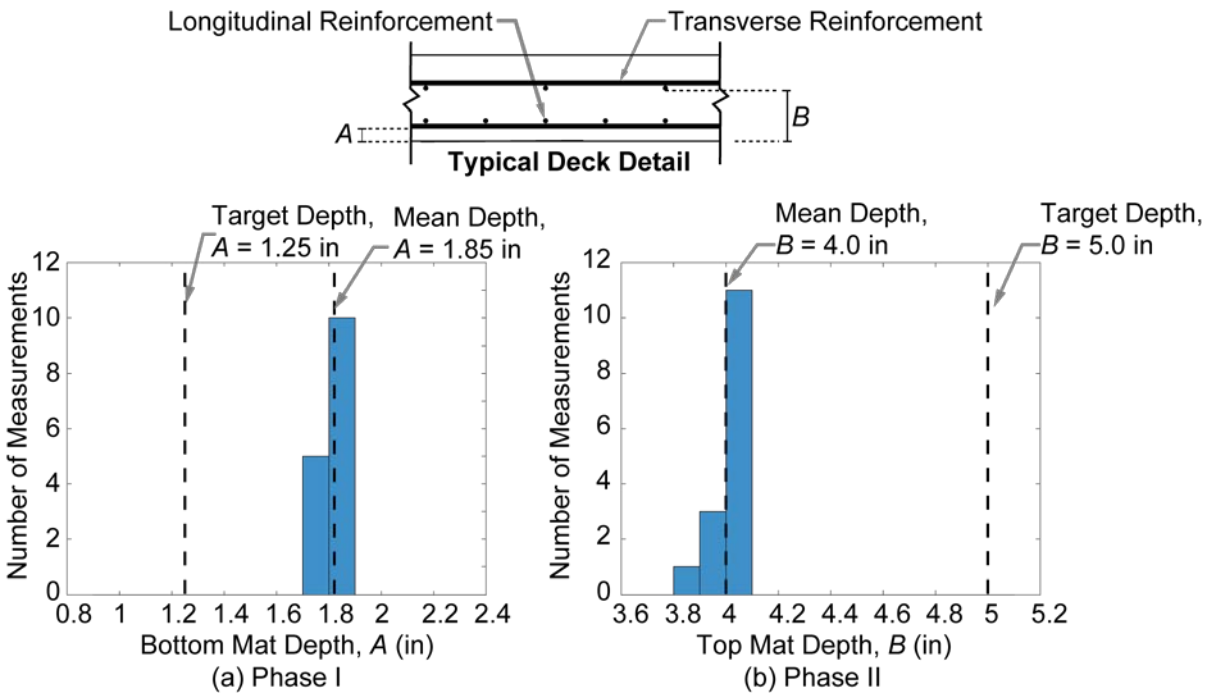

Figure 7. As-Built Reinforcement Depths for (a) Bottom Mat, and (b) Top Mat

Material Properties

Reinforcement Bar Properties

Bridge deck A1035 CS reinforcement bars were from two different production lots (i.e., lot numbers 371914 and 508314). Both production lots were used in the bottom and top mats. The bottom mat, located from Abutment A to midspan, was mainly composed of bars from production lot 508314, while the bottom mat located from midspan to Abutment B was mainly composed of bars from production lot 371914, and vice versa for the top mat.

Figure 8 provides the engineering stress-strain diagrams for each of the four A1035 CS bars tested (i.e., two specimens per production lot). Specimens belonging to the same production lot had a similar stress-strain curve and mechanical properties. Table 1 shows the yield strength, ultimate strength and percent of elongation for each specimen tested. The average yield strength and ultimate strengths were 140 ksi (183 ksi) and 131 ksi (168 ksi), for production lots 371914 and 508314, respectively. Specimens from production lot 371914 had on average a 6.9% higher yield strength than bars from production lot 508314.

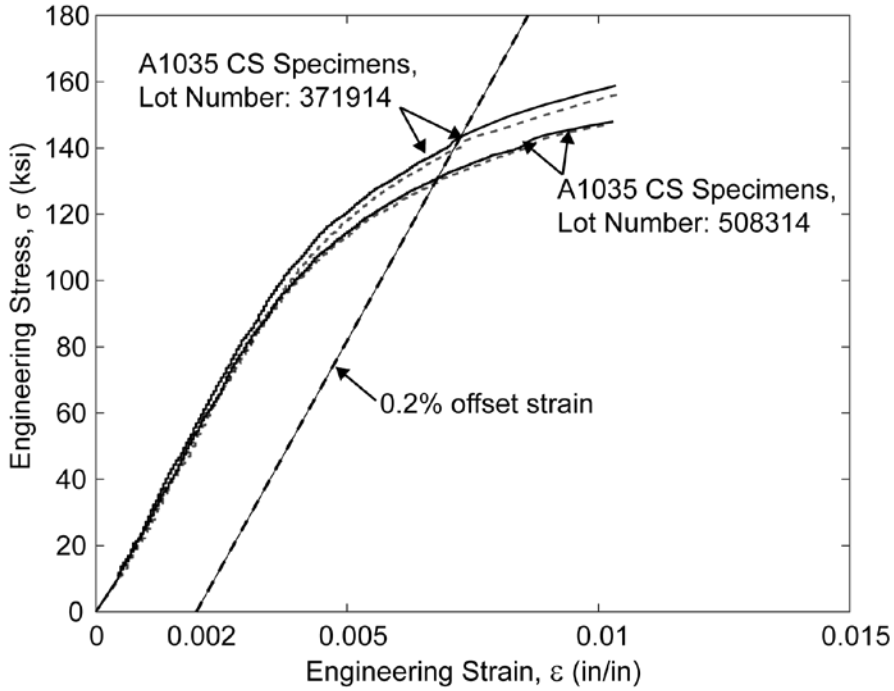

Figure 8. Stress-Strain Diagrams for Each A1035 CS Specimen Tested

Table 1. A1035 CS Reinforcement Bar Properties for Each Specimen Tested (Two per Production Lot)

Lot Number	Specimen ID	Measured Yield Strength, f_y (ksi)	Measured Tensile Strength, f_u (ksi)	Total Elongation, (%)	Average Yield Strength, f_y (ksi)	Average Tensile Strength, f_u (ksi)
371914	01	139	182	10.0	140	181
	02	140	183	9.8		
508314	03	131	167	8.0	131	168
	04	130	168	8.0		

Concrete Properties

Figure 9 illustrates a plan view of the Wolf Creek Bridge deck showing the locations where concrete from each truck (T) was placed. The properties in the freshly mixed state and hardened state were computed for each concrete truck and they are detailed in the following subsections.

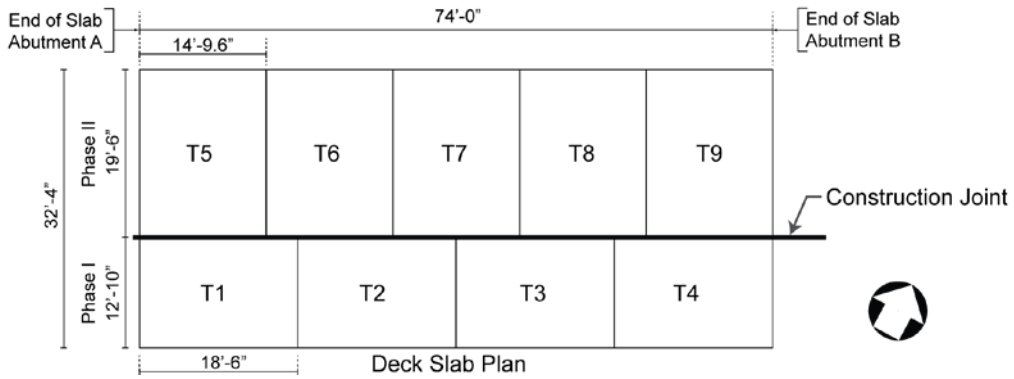

Figure 9. Wolf Creek Bridge Deck Plan Showing the Approximate Material Property Locations for Tables 2 and 3

Freshly Mixed State

Table 2 provides the measured concrete properties in the freshly mixed state by truck. The slump was measured to be between 2.5 in to 3.25 in. Six gallons of water was added on site to the concrete in T3 to increase the slump to a minimum value of 2.0 in. The air content was measured to be between 5.0% to 6.1%. The concrete temperature for T1 to T4 is around 16 °F colder than the concrete temperature for T5 to T9. This difference was caused by the weather temperature. Concrete fromT1 to T4 was cast on February 16, 2016 (winter), T5 to T9 was cast on May 16, 2016 (end of spring).

Table 2. Concrete Properties in the Freshly Mixed State by Truck

Truck ID	Slump (in)	Air Content (%)	Concrete Temperature (°F)	Water Added on Project (Gal.)
T1	3.0	5.0	51	0
T2	3.0	6.1	53	0
T3	2.5	5.0	53	6
T4	3.0	5.6	54	0
T5	3.0	5.0	63	0
T6	3.0	5.0	70	0
T7	3.0	5.1	78	0
T8	3.0	5.0	69	0
T9	3.25	5.3	65	0

Hardened State

Table 3 shows the measured concrete properties in the hardened state by truck. The concrete compressive strength ranged from 4.85 ksi (T1) to 6.40 ksi (T6). The splitting tensile strength remained consistent around 0.55 ksi. The elastic modulus was measured to be between 2750 ksi (T2) to 3450 ksi (T8). The drying shrinkage strain was consistent for all trucks placed on May 16, 2016, (Phase II construction) at $\varepsilon_s \approx 0.0006$. The concrete trucks from Phase I construction presented a drying shrinkage strain ranging from 0.00062 in/in (T2) to 0.00085 in/in (T1).

Table 3. Concrete Properties in the Hardened State after 56 Days by Truck

Truck ID	Compressive Strength, f'_c (ksi)	Splitting Tensile Strength (ksi)	Elastic Modulus, E (ksi)	Drying Shrinkage, ε (in/in)
T1	4.85	0.590	2900	0.00085
T2	4.95	0.550	2750	0.00062
T3	5.15	0.530	3100	0.00069
T4	5.60	0.530	3100	0.00084
T5	5.70	0.590	3400	0.00056
T6	6.40	0.550	3150	0.00059
T7	5.75	0.530	3400	0.00060
T8	5.50	0.530	3450	0.00060
T9	5.50	0.530	3300	0.00053
Mean	**5.50**	**0.550**	**3170**	**0.00065**
Coefficient of Variation	**0.09**	**0.04**	**0.08**	**0.18**

As-Built Bridge Deck Condition Assessment

During the field inspections and after analyzing the digital state models reconstructed from the US52 Wolf Creek Bridge deck, only one (1) crack was found in the bridge deck during the third field inspection on July 27, 2016. This crack is located near the construction joint of Phase II (Figure 10b). Figure 10 illustrates the location and image of the crack found 182 in from the west end of the bridge deck. The crack had a random pattern (i.e., spread in all directions) and had a mean width of 0.004 in measured using a crack microscope and the digital state models.

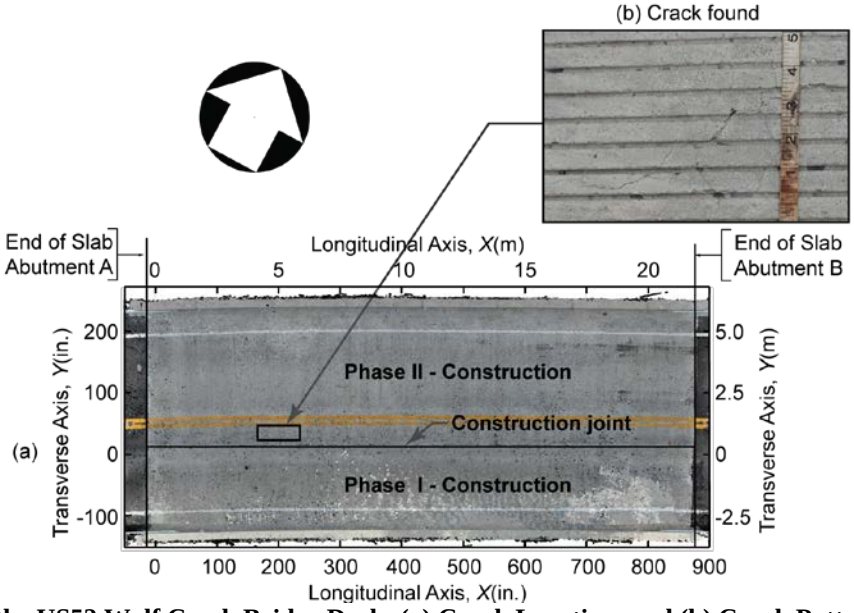

Figure 10. Scan 3 of the US52 Wolf Creek Bridge Deck: (a) Crack Location, and (b) Crack Pattern Cost Savings

Contractors found the change from No. 5 to No. 4 to be beneficial for reducing bar congestion and improving concrete consolidation, especially near the traffic barriers. The use of 1035 CS No. 4 bars instead of No. 5 bars reduced the weight of deck reinforcement by 23%, reducing the bridge deck cost by $7,513, or 23% when compared to the standard deck design for this bridge.

CONCLUSIONS

- *Concrete bridge decks can be successfully built using ASTM A1035 CS reinforcement bars with a decrease in bar size (No. 4 instead of No. 5) without presenting significant serviceability defects within 2 months of construction.*

- *Off-the-shelf cameras and software can be used to survey bridge decks accurately.*

RECOMMENDATIONS

1. *VDOT's Structure and Bridge Division and VTRC should continue the inspection on the Wolf Creek Bridge over a period of 3 years* (through June 30, 2019) *to evaluate its performance.* Condition assessments were conducted only within 2 months of finishing the construction; therefore, continued inspections are critical to study the long-term performance of the bridge deck.

BENEFITS and IMPLEMENTATION

Benefits

The benefits of implementing Recommendation 1 would be to identify early age cracking or other defects that can be attributed to the use of No. 4 bars in the deck or seeing no cracking or defects that can be attributed to the use of No. 4 bars providing less or more confidence in using No. 4 bars in other decks.

Implementation

The VDOT Bridge Office will arrange for the evaluation of the condition of the Wolf Creek Bridge in the spring of 2019.

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REFERENCES

American Association of State Highway and Transportation Officials. *Standard Specifications for Highway Bridges, 16th Edition.* Washington, DC, 1996.

American Association of State Highway and Transportation Officials. *AASHTO LRFD Bridge Design Specifications, 5th Edition*. American Association of State Highway and Transportation Officials, Washington, DC, 2010.

ASTM International. ASTM C496: Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens. In *Annual Book of ASTM Standards, Vol. 04.02: Concrete and Aggregates*. West Conshohocken, PA, 2004.

ASTM International. ASTM A370: Standard Test Methods and Definitions for Mechanical Testing of Steel Product. In *Annual Book of ASTM Standards, Vol. 01.03: Steel Plate, Sheet, Strip, Wire; Stainless Steel Bar.* West Conshohocken, PA, 2005.

ASTM International. ASTM C1064: Standard Test Method for Temperature of Freshly Mixed Hydraulic-Cement Concrete. In *Annual Book of ASTM Standards, Vol. 04.02: Concrete and Aggregates.* West Conshohocken, PA, 2008.

ASTM International. ASTM C143: Standard Test Method for Slump of Hydraulic-Cement Concrete. In *Annual Book of ASTM Standards, Vol. 04.02: Concrete and Aggregates.* West Conshohocken, PA, 2010a.

ASTM International. ASTM C231: Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method. In *Annual Book of ASTM Standards, Vol. 04.02: Concrete and Aggregates*. West Conshohocken, PA, 2010b.

ASTM International. ASTM C31: Standard Practice for Making and Curing Concrete Test Specimens in the Field. In *Annual Book of ASTM Standards, Vol. 04.02: Concrete and Aggregates.* West Conshohocken, PA, 2012.

ASTM International. ASTM C469: Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression. In *Annual Book of ASTM Standards, Vol. 04.02: Concrete and Aggregates.* West Conshohocken, PA, 2014a.

ASTM International. ASTM C157: Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete. In *Annual Book of ASTM Standards, Vol. 04.02: Concrete and Aggregates.* West Conshohocken, PA, 2014b.

ASTM International. ASTM C39: Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. *In Annual Book of ASTM Standards, Vol. 04.02: Concrete and Aggregates*. West Conshohocken, PA, 2015.

ASTM International. ASTM A955: Standard Specification for Deformed and Plain Stainless-Steel Bars for Concrete Reinforcement. In *Annual Book of ASTM Standards, Vol. 01.04: Steel Structural, Reinforcing, Pressure Vessel, Railway.* West Conshohocken, PA, 2016a.

ASTM International. ASTM A1035/A1035M: Standard Specification for Deformed and Plain, Low-carbon, Chromium, Steel Bars for Concrete Reinforcement. In *Annual Book of ASTM Standards, Vol. 01.04: Steel Structural, Reinforcing, Pressure Vessel, Railway.* West Conshohocken, PA, 2016b.

Barr, P., and Wixom, K. *Feasibility of Using High-Strength Steel and MMFX Rebar in Bridge Design.* UT-09.09. Utah Department of Transportation Research Division, Taylorsville, 2009.

Berman, J., and Brown, D. Field Monitoring and Repair of a Glass Fiber-Reinforced Polymer Bridge Deck. *Journal of Performance of Constructed Facilities,* 2009, pp. 215-22.

El-Salakawy, E., Benmokrane, B., El-Ragaby, A., and Nadeau, D. Field Investigation on the First Bridge Deck Slab Reinforced with Glass FRP Bars Constructed in Canada. *Journal of Composites for Construction,* Vol. 9, No. 6, 2005, pp. 470-79.

Frosch, R., and Pay, A. Implementation of a Non-Metallic Reinforced Bridge Deck, Volume 1: Bond Behavior. *JTRP Technical Reports,* January 1, 2006.

Khal, S. *Corrosion Resistant Alloy Steel (MMFX) Reinforcing Bar in Bridge Decks.* R-1499. Michigan Department of Transportation, Lansing, 2007.

Koenderink, J. J., and van Doorn, A.J. Affine Structure From Motion. *Journal of the Optical Society of America A,* Vol. 8, No. 2, 1991, pp. 377-385.

Lama Salomon, A. *US52 Wolf Creek Bridge Deck - Scan 1,* 2016. https://skfb.ly/PoK9. Accessed December 10, 2016.

Lama Salomon, A. *Digital State Models for Infrastructure Condition Assessment and Structural Testing*. Ph.D. Thesis, Virginia Tech, Blacksburg, 2017.

Lama Salomon, A., and Moen, C.D. *Structural Design Guidelines for Concrete Bridge Decks Reinforced with Corrosion-Resistant Reinforcing Bars.* VCTIR 15-R10. Virginia Center for Transportation Innovation and Research, Charlottesville, 2015.

Lama Salomon, A., Sprinkel, M., and Moen, C.D. Bridge Deck Cracking Structural Investigation With Computer Vision-Informed Infrastructure Condition Assessment. In *Proceedings of the Transportation Research Board Annual Conference*, Washington, D.C., 2016.

Ozyildirim, H.C., and Moruza, G.M. Redefining High-Performance Concrete. *Concrete International*, Vol. 36, No. 10, 2014, pp. 37-42.

Russell, H.G. *Concrete Bridge Deck Performance.* Transportation Research Board, Washington, DC, 2004.

Sharp, S.R., and Moruza, A.K. *Field Comparison of the Installation and Cost of Placement of Epoxy-Coated and MMFX 2 Steel Deck Reinforcement: Establishing a Baseline for Future Deck Monitoring.* VTRC 09-R9. Virginia Transportation Research Council, Charlottesville, 2009.

Thippeswamy, H.K., Craigo, C., and GangaRao, H.V.S. Review of Bridge Decks Utilizing FRP Composites in the United States. In *Condition Monitoring of Materials and Structures.* American Society of Civil Engineers, 2000, pp. 110-119.

Triandafilou, L. Implementation of High-Performance Materials: When Will They Become Standard? *Transportation Research Record: Journal of the Transportation Research Board*, Washington, DC, 2005, pp. 33-48.

Virginia Department of Transportation. *Road and Bridge Specifications*. Richmond, 2007.

Virginia Department of Transportation. *Road and Bridge Standards*. Richmond, 2008.

Virginia Department of Transportation. *Modifications to the AASHTO LRFD Bridge Design Specification*s, 5th Edition. Richmond, 2010.