EXPERIMENTAL TESTING OF UHPC OPTIMIZED BRIDGE GIRDERS: EARLY RESULTS

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ABSTRACT

The Federal Highway Administration's Ultra-High Performance Concrete (UHPC) research program is investigating the optimal use of this concrete in highway bridge superstructures. Structural optimization has been completed, resulting in a 33-inch deep bulb-double-tee girder that spans 70 feet. This prestressed girder has an 8-foot wide integral deck and weighs 23 tons. The cross-section contains no mild steel, thus requiring the UHPC matrix and the steel fiber reinforcement to carry all secondary tensile forces. Four of these girders have been constructed using a 28 ksi compressive strength, steel-fiber reinforced UHPC.

Two girders were used in a demonstration highway bridge. The remaining two girders are undergoing structural testing. The flexural and shear capacities of this girder cross-section have been determined through full-scale experimental testing. The elastic lateral load distribution across an individual girder and between adjacent girders has also been determined.

Keywords: Ultra-High Performance Concrete, UHPC, Optimized Cross-Section, Bulb-Double-Tee Girder, Pi Girder, Prestressed Girder, Steel Fiber

INTRODUCTION

The Federal Highway Administration's research program investigating the use of Ultra-High Performance Concrete (UHPC) in highway bridges is now focusing on the optimal structural use of UHPC in bridge girders. The advanced properties exhibited by UHPC are well suited to use in prestressed concrete bridge girders, particularly decked girders. Optimization of a prestressed girder cross-section for use with UHPC has been completed and four full-scale optimized girders have been fabricated. Two of these girders were used as the superstructure for a demonstration highway bridge. The remaining two girders are currently undergoing structural testing.

ULTRA-HIGH PERFORMANCE CONCRETE

UHPC is a new class of concrete that exhibits significantly enhanced strength and durability properties as compared to normal and high-performance concretes. In general, UHPC is a steel fiber reinforced concrete consisting of an optimized gradation of fine powders and a very low water to cementitious materials ratio. Two of the primary sources for the enhanced material behaviors are the finely graded and tightly packed nature of the concrete constituent materials and the steel fibers which knit the material together after cracking has occurred.[1-4]

There is currently one UHPC widely available in the United States. It is being marketed by Lafarge, Inc. under the name Ductal®. This proprietary material contains a very high proportion of cementitious materials, fine sand as the largest aggregate, and steel fiber reinforcement. The steel fibers are 0.5-inch long, 0.008-inch diameter undeformed steel wires included in the mix in the proportion of 2 percent by volume. The water to cementitious materials ratio is less than 0.20.

In association with the research that is the topic of this paper, the Federal Highway Administration (FHWA) at its Turner-Fairbank Highway Research Center (TFHRC) has been conducting an extensive research program aimed at characterizing the material properties exhibited by UHPC.[5-7] A summary of some of the results is presented in Table 1. The table provides results for the manufacturer recommended steam treated condition (90°C and 95%RH for 48 hours), to which the optimized girders were subjected after casting.

OPTIMIZED GIRDER DESIGN

Consideration of the material characteristics of UHPC guided the work that was undertaken to determine the optimum cross-section for a UHPC highway bridge superstructure. A group of researchers at the Massachusetts Institute of Technology, in conjunction with the FHWA, developed an innovative bulb-double-tee shaped girder.[8-9] This cross-section is scalable depending on the span desired and is well suited to rapid construction as the deck is integral to the girder.

Table 1. UHPC Material Characterization.

Property Investigated	Result
Compressive Strength	28.0 ksi
Modulus of Elasticity	7700 ksi
Cracking Tensile Strength (ASTM C496 setup)	1.6 ksi
Weight	155 lb/ft^3
Rapid Chloride Ion Penetrability (ASTM C1202)	18 Coulombs
28-day Shrinkage	850 microstrain
Post-treatment Shrinkage	Negligible
Creep Coefficient	0.3

Figure 1 shows the optimized cross-section for a 70-foot span. This 8 foot wide girder contains twenty-two 270-ksi low-relaxation prestressing strands in its bulbs, is 33 inches deep, and weighs 23 tons. There is no mild steel reinforcement in the girder, with all secondary tensile forces being carried by the UHPC matrix and fiber reinforcement.

This girder is designed based on the AASHTO LRFD Bridge Design specifications.[10] The dead load includes the girder self weight and a 25 lb/ft^2 wearing surface, and the live loads are consistent with the HL-93 configuration. The girder is designed for both a service limit state where no cracking is permitted and an ultimate strength limit state.

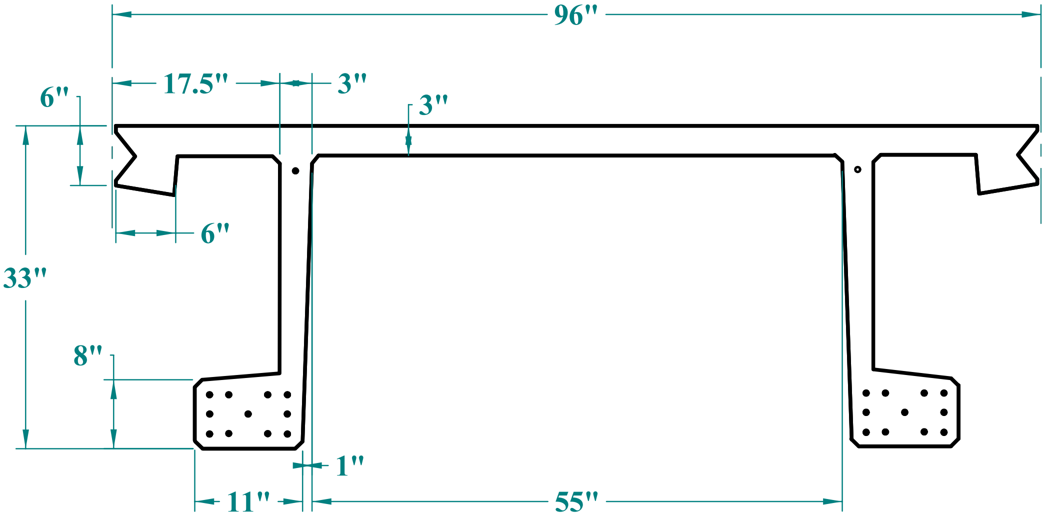

Figure 1. Optimized UHPC Girder for a 70-Foot Span.

STRUCTURAL BEHAVIOR OF THE UHPC OPTIMIZED GIRDER

Four full-scale UHPC bridge girders were fabricated at Prestress Services of Kentucky, Inc. in late 2003 and early 2004. These girders were then delivered to TFHRC for further testing. Two of these girders were erected and comprise the main structural elements of a demonstration highway bridge. The remaining two girders are undergoing structural testing. The results from structural tests performed on the demonstration bridge and the initial tests on the individual girders are presented below.

ELASTIC LATERAL LOAD DISTRIBUTION IN A UHPC BRIDGE

A series of tests were completed to determine the elastic lateral load distribution in the UHPC demonstration bridge. Further detail on these tests can be obtained from Reference 11. Preliminary analysis of the behavior of the bridge indicated that the flexural cracking of the bulbs could occur under a total load of 200 kips, assuming that the load was applied at two locations 3 feet either side of midspan. As such, the loading of the bridge was limited to 120 kips evenly distributed over this load pattern. Unsymmetric loads applied to the bridge were limited to proportionally similar load levels.

The testing of this bridge included four specific loading configurations. Figure 2 shows cross-section of the bridge and the five load application locations relative to the cross-section. Table 2 shows the four loading configurations and the load application locations used for each configuration. Of note, the load patches for Configuration 2D simulated a rubber wheel patch (10 in. wide by 20 in. long) as defined in the AASHTO LRFD Bridge Design Specification. The load patches for the other configurations consisted of 9 in. diameter steel plates, as these load points were directly above girder webs and no local distortions were anticipated.

The primary purpose of these tests was to determine the stiffness of the optimized UHPC girders, specifically as related to lateral load distribution across a bridge. Although technically a two girder bridge, the spans between girder webs and the thin deck result in a bridge that behaves as if it were a four girder bridge, with each of the four webs behaving largely independent of the others. The four loading configurations along with the instrumentation applied to the midspan cross-section produced a clear indication of the portion of the applied loads that is carried by each of these four webs.

Table 2. Loading Configurations.

Load Configuration	Description	Locations Loaded (Figure 2)	Peak Load on Bridge
1	Both Girders	A,B,C,D	118 kips
2W	South Girder Webs	A,B	61 kips
2D	South Girder Deck	E	27 kips
3	South Leg of South Girder	A	27 kips

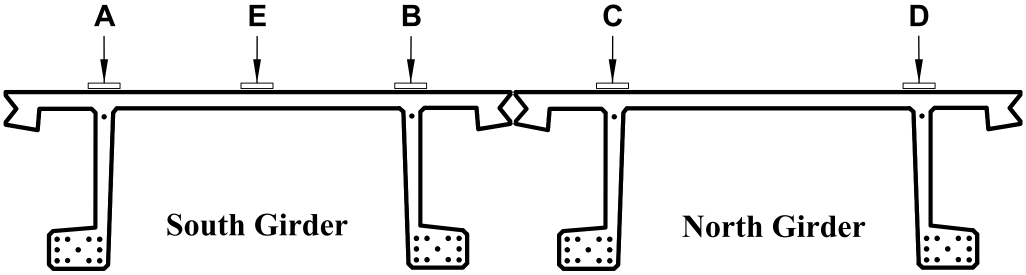

Figure 2. Loading Configurations.

The internal moment resulting from each load configuration as distributed throughout the four girder legs is shown in Figure 3. The results for Load Configuration 1 show that the loads were relatively well distributed between the four girder legs. Configurations 2W and 2D both show that the south girder carried approximately 85 percent of the load that was applied to it and only transferred 15 percent to the north girder. Finally, Configuration 3 shows that 95 percent of the load that was applied to the exterior web of the south girder was carried by the south girder. Also note that this load configuration induced a small negative moment into the north leg of the north girder.

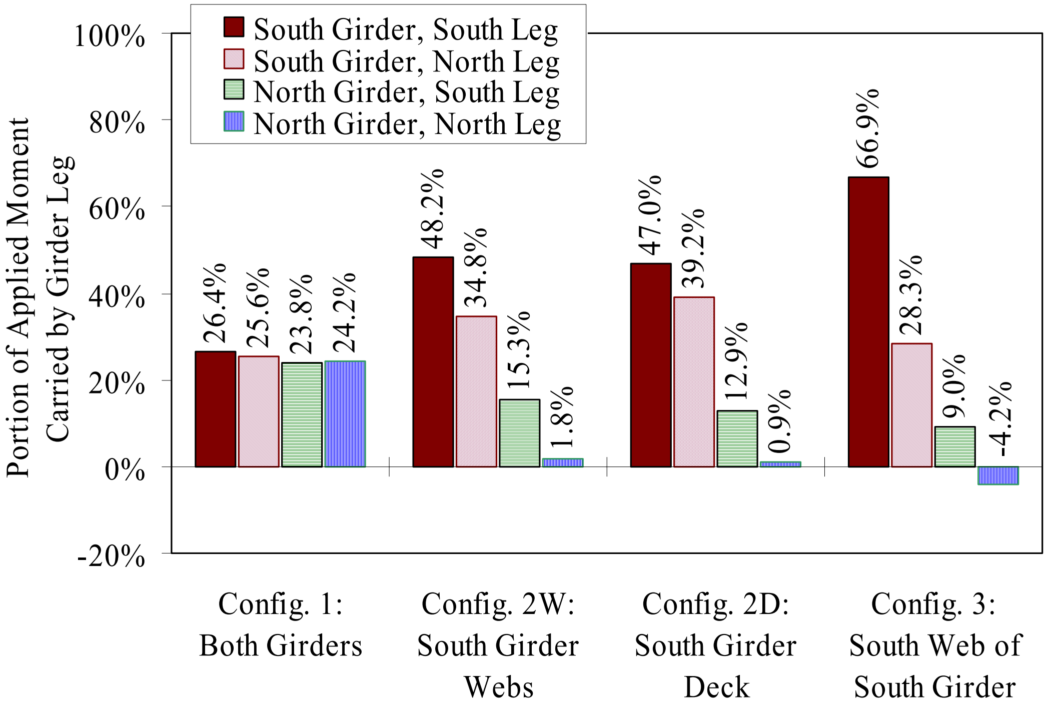

Figure 3. Elastic Lateral Flexural Load Distribution Between Two UHPC Girders.

FLEXURAL CAPACITY

The flexural behavior of this girder cross-section was determined through full-scale structural testing of an individual girder. The girder was loaded symmetrically by four point loads, each located above a web at 3 feet from midspan. The overall span of the girder was 69 feet.

The load-deflection response of the girder is shown in Figure 4. The design of this girder required an LRFD Service III flexural capacity of 1400 k-ft and an LRFD Strength I ultimate flexural capacity of 2600 k-ft. The actual applied loads that would cause these moments are 66 kips and 143 kips, respectively, as shown in Figure 4. During testing, first cracking of the girder was observed at an applied load of 75 kips, thus the service requirement for primary flexure was met. The peak load applied to the girder was 165 kips. When combined with the dead load flexural forces, this results in an ultimate flexural capacity of 3070 k-ft for this cross-section.

The tensile cracking of the bottom flange of this prestressed UHPC girder is quite instructive in terms of the tensile behavior of UHPC. After the application of 3 inches of midspan deflection into the girder, approximately 300 cracks had occurred in the bottom of each bulb with the crack spacing near midspan being less than 0.5 inches. The width of each of these cracks was approximately 0.001 inches, making them invisible to the naked eye. After the application of 7.5 inches of midspan deflection into the girder, approximately 1100 cracks were present in the bottom of each bulb with the crack spacing near midspan being less than 0.2 inches. Failure of the girder occurred when the fibers bridging an individual crack at midspan in the south bulb began to pullout. This forced a redistribution load into the prestressing strands, resulting in the necking and rupture of the strands.

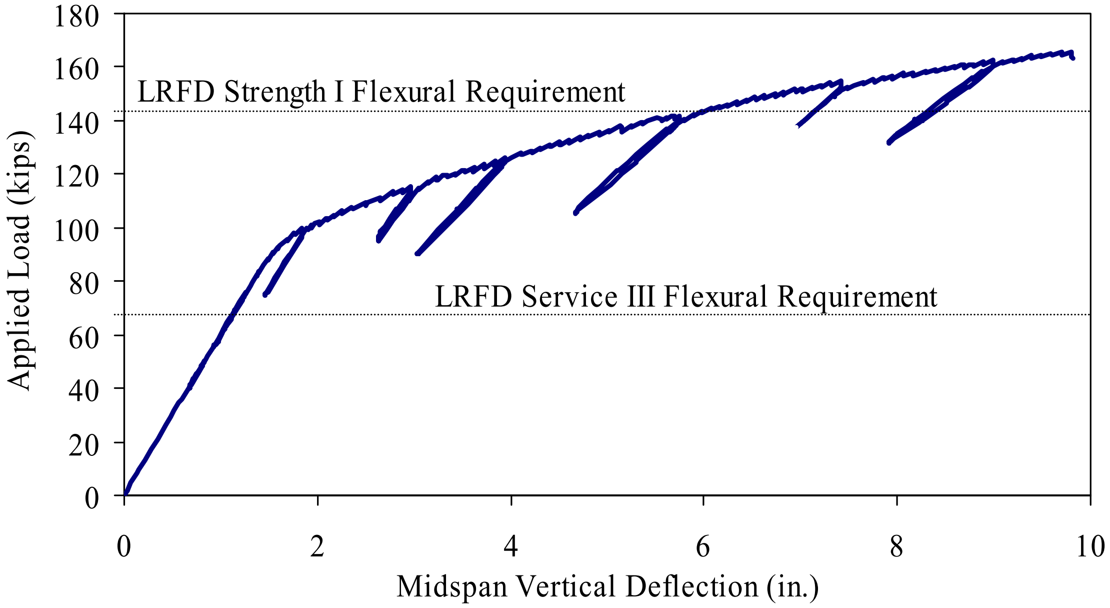

Figure 4. Load-Deflection Response for a UHPC Girder Subjected to Flexure.

SHEAR BEHAVIOR

Shear testing was completed on a shorter span of the girder that was broken in flexure as described above. The setup for the shear tests included three-point loading with an overall span of 21 feet and a shear span of 7 feet. Loads were applied vertically downward onto the deck of the girder above the webs.

The initial tests under this loading arrangement focused on the lateral distribution of shear forces within the girder. Loads were applied above one web, and load cells recorded reactions at the supports. Figure 5 shows the result of this test wherein a load of 81 kips was applied to the girder. Nearly 93% of the load was reacted by the leg of the girder on which the load was originally applied.

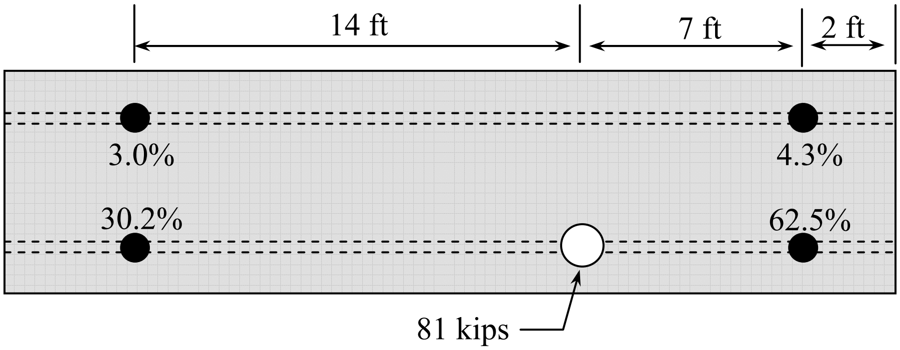

Figure 5. Elastic Lateral Shear Distribution.

A final shear test was completed to determine the ultimate shear capacity of this UHPC girder cross-section. Figure 6 shows the applied load versus load point deflection results from this test. The first shear cracks were observed in a web of the girder at an applied shear force of 175 kips. As the load continued to increase, hundreds of parallel shear cracks formed. The ultimate shear capacity of this girder was reached at a load of 640 kips which corresponds to a shear force of 425 kips. The figure shows that the girder exhibited significant reserve load and deflection capacity after initial shear cracking.

SUMMARY AND CONCLUSION

Structural optimization of prestressed concrete bridge girders for use with UHPC has been completed. The resulting cross-section for a 70-foot span is a 33-inch deep bulb-double-tee shape. Four of these girders were fabricated using a 28 ksi compressive strength, steel-fiber reinforced UHPC. Two of these girders were used to construct a bridge at the Turner-Fairbank Highway Research Center, while the remaining two girders are undergoing structural testing to determine a baseline behavior for this material/girder combination.

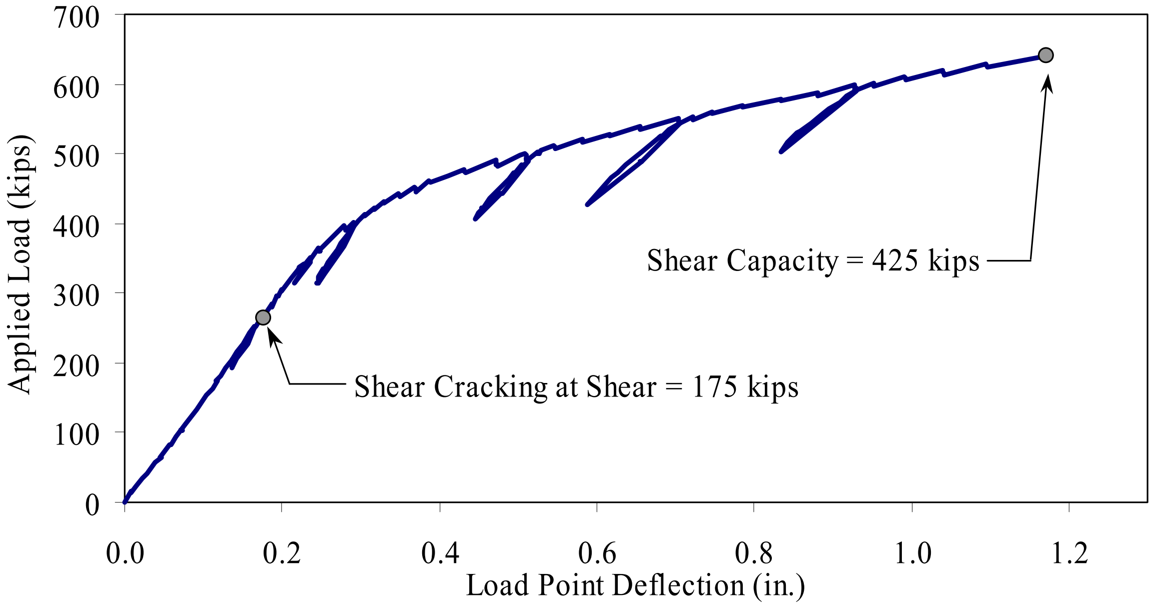

Figure 6. Load-Deflection Response for a UHPC Girder Subjected to Shear.

The elastic lateral load distribution tests indicate that this girder cross-section does not transfer significant flexural or shear loads between girders, or even within an individual girder. Loading above the outer leg of a two girder bridge resulted in over two-thirds of the flexure in the bridge being carried by said girder leg, with most of the remainder being carried by the adjacent leg. Loading above one leg of an individual girder with a shorter span resulted in nearly 93% of the shear force being reacted by that particular leg. Clearly, this girder cross-section has a restricted ability to laterally transfer loads between girder legs and to adjacent girders.

The ultimate capacity tests showed that this cross-section possesses sufficient capacity to resist primary flexure and shear forces. The ultimate flexural capacity of 3070 k-ft was 118% of the required ultimate capacity. The ultimate shear capacity of 425 kips significantly exceeds any shear loading that could realistically occur given the flexural capacity of the girder.

Further testing of this optimized girder cross-section is ongoing. Although the structural capacities of this girder seem to be sufficient, additional testing is planned to determine if the relatively slender nature of this cross-section is going to be detrimental to the girders overall behavior. Additional shear, primary flexure, transverse flexure, and shear fatigue tests are planned. The capability of the longitudinal shear key to transfer forces across the bridge and maintain its structural integrity will also be investigated.

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This paper is intended as an academic discussion, not as engineering advice, and no reliance upon this paper is permitted. Independent advice by the professional of record as to the application of the concepts and opinions contained herein to any specific project should be sought.

REFERENCES

1. Bonneau, O., C. Vernet, M. Moranville, and P.-C. Aïtcin, “Characterization of the Granular Packing and Percolation Threshold of Reactive Powder Concrete,” *Cement and Concrete Research*, V. 30, No. 12, 2000, pp. 1861-1867.

2. Cheyrezy, M., V. Maret, and L. Frouin, “Microstructural Analysis of RPC (Reactive Powder Concrete),” *Cement and Concrete Research*, V. 25, No. 7, 1995, pp. 1491-1500.

3. De Larrard, F., and T. Sedran, “Optimization of Ultra-High-Performance Concrete by the Use of a Packing Model,” *Cement and Concrete Research*, V. 24, No. 6, 1994, pp. 997-1009.

4. Richard, P., and M. Cheyrezy, “Composition of Reactive Powder Concretes,” *Cement and Concrete Research*, V. 25, No. 7, 1995, pp. 1501-1511.

5. Graybeal, B., and J. Hartmann, “Ultra-High Performance Concrete Material Properties,” *Proceedings, Transportation Research Board Conference*, January 2003.

6. Graybeal, B., “Strength and Durability of Ultra-High Performance Concrete”, *Proceedings, International Symposium on High Performance Concrete*, Orlando Fla., October 2003.

7. Graybeal, B., “Characterization of the Behavior of Ultra-High Performance Concrete,” Ph.D. Dissertation, University of Maryland, May 2005, 360 pp.

8. Park, H., E. Chuang, and F.-J. Ulm., “Model Based Optimization of Ultra-High Performance Concrete Highway Bridge Girders,” *MIT-CEE Report R03-01*, Massachusetts Institute of Technology, March 2003.

9. Soh, M., "Model-Based Design of a Ultra High Performance Concrete Prototype Highway Bridge Girder," *M.S. Thesis*, Massachusetts Institute of Technology, June 2003.

10. American Association of State Highway and Transportation Officials (AASHTO), *AASHTO LRFD Bridge Design Specifications*, 2002.

11. Graybeal, B., and J. Hartmann, "Lateral Load Distribution in Optimized UHPC Bridge Girders," *Proceedings, International Conference on Advanced Materials for Construction of Bridges, Buildings, and other Structures, IV*, Maui, Hawaii, August 2005.