END ZONE DESIGN AND BEHAVIOR OF PRESTRESSED UHPC GIRDERS

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INTRODUCTION

The use of ultra-high performance concrete (UHPC) in bridge engineering and highway infrastructure has been gaining momentum in recent years. UHPC can be used in prestressed bridge girders to deliver new benefits for highway bridges compared to conventional concrete including longer spans, shallower superstructure depth, and smaller cross sections. In this study, several full-scale prestressed bridge girders with different depths and web thicknesses were constructed utilizing two commercially available UHPC products. The end zone design methodology was similar to the American Association of State Highway and Transportation Officials (AASHTO) design method except that it allowed the steel and UHPC to concurrently resist cracking stresses in the web. As implemented, the methodology limited the allowable UHPC stress to a conservative estimate of the tensile cracking strength. This paper constitutes a discussion of the end zone behaviors of heavily prestressed UHPC girders and explains the design methodology. The results presented herein focus on end zone behaviors of two representative girders, each made with a different UHPC-class material, and validates the design method through actual strain measurements taken during the release of strands.

END ZONE DESIGN

AASHTO Load and Resistance Factor Design (LRFD) Bridge Design Specifications, section 5.9.4.4 (1), provides a design methodology for end zones of prestressed concrete girders. The design method assumes that four percent of the prestressing force in the bottom bulb of girders contributes to the splitting force in the web. To resist the splitting force, vertical mild steel reinforcement should be placed within the distance of h/4 from the end of the girders, where h is the girder height. For crack control, the size of the reinforcement should be determined so that the stress in the steel does not exceed 20 ksi. The AASHTO design method assumes that the concrete provides no tensile resistance and that only vertical steel reinforcements resist the splitting force. The AASHTO design method can be used as a starting point to design prestressed girders with UHPC-class materials; however, the tensile behaviors of UHPC provide benefits that can also be engaged in the design. In this study, several full-scale prestressed girders were designed with different geometries and web thicknesses using a similar approach as previously described except that the UHPC and steel reinforcement concurrently resist the splitting force in the web. The total splitting force for these girders was assumed to be four percent of the prestress force in the bottom bulb. The allowable UHPC stress in design was 1 ksi, which corresponded to a conservative approximation of the average of the tensile stress of the UHPC-class materials at first cracking, which was determined by direct tension tests (2). The design assumed that the UHPC contributed to the splitting resistance in the web within the distance of h/4 from the girder end and the remaining resistance was provided by vertical mild steel reinforcements while the stress did not exceed 20 ksi. The girder cross-sectional shapes were based on modified versions of the PCEF section with narrower web thickness. The girders were heavily prestressed with 24 0.7-inch diameter strands in the bottom bulb and two 0.7-inch diameter strands in the top bulb with varying levels of vertical mild steel reinforcement in the end zones. Table 1 summarizes the end zone properties of two representative girders designed and constructed using two different UHPC-class materials. In the context of this paper, the girders will be referred to as Girder A and Girder B.

TRANSFER LENGTH

Transfer length is the required length of strands to develop stress in prestressing steel that gradually increases from zero, where bonding starts, to the effective prestress. According to AASHTO LRFD section 5.9.4.3, the transfer length of steel strands in conventional concrete is $60d_b$, where d_b is the nominal diameter of the strands (1). Transfer length highly depends on the bond strength of concrete. UHPC has a higher bond strength compared to conventional concrete; therefore, the transfer length of the strands in UHPC-class materials is expected to be less. Different methods were used to measure the transfer length of 0.7-inch diameter strands in the girders. One method was to place several vibrating wire gauges (VWG) in a stagger pattern in the bottom bulb within 35 inches of the girder ends and record the change in the strain of the VWG gauges before and after release. Figure 1 shows the measured data of the two representative girders, A and B at prestress transfer. The design and geometry of these girders were the same and the only difference was the UHPC-class material. The plots show that the strain in the bottom bulb gradually increased until approximately 15 inches after which it remained constant. According to the AASHTO predictive relationship, the transfer length of 0.7-inch diameter strand in conventional concrete is 42 inches (1) which is more than 2.5 times the measured transfer length in the UHPC girders.

END ZONE CRACKING AND STRAIN BEHAVIOR

The end zones of prestressed girders may crack because of the transfer of the prestressing force to concrete. The end zones of the girders were closely inspected after release of strands. No cracks of the size often observed in the end zones of conventional concrete girders were observed. However, UHPC cracks are usually small and barely visible with the naked eye. To find hairline UHPC cracks, denatured alcohol was sprayed at the end zones of the girders. Isolated cracks became visible and were marked while denatured alcohol evaporated. Figure 2 shows the cracking of the end zones of the two representative girders. As indicated in the pictures, the horizontal hairline cracks in the web propagated about 5.5 inches and 10 inches in the girders A and B, respectively. The length of the crack in Girder A was shorter than the length of the crack in Girder B because the UHPC-class material in Girder A was of higher tensile strength. Additionally, electrical resistance strain gauges were installed on the vertical reinforcement in the end zone at different heights to measure strain in the rebar during release of strands. Figure 3-a shows strain distribution along the length of the girders based on the maximum measured strain in the rebar. Results demonstrate that strain in the end zone of the girders linearly reduced within the distance of h/4 from the girder end assuming strain compatibility between vertical reinforcement and UHPC. UHPC first cracking strain is also shown in the plot indicating UHPC reached its allowable stress at first cracking in the h/4 region, as was intended in the design. Results are also consistent with the observed hairline cracks at the end zone.

EVALUATION OF DESIGN METHOD AND CONCLUSIONS

According to the end zone design, the stress in steel reinforcement due to prestressing was limited to 20 ksi. To evaluate the design method, stress in the vertical reinforcement was calculated by multiplying the measured strain by the elastic modulus of the reinforcement. Results are shown in Figure 3-b. The stress in all the steel reinforcement was less than 20 ksi within the distance of h/4 of the girder end except for the nearest rebar to the girder end in Girder B in which the stress was 24 ksi. This could be because of the slightly lower tensile strength of the UHPC-class material in Girder B compared to Girder A. In addition, the contribution of the reinforcement close to the girder end in splitting resistant was more than other reinforcement placed further into the girder. This study showed that the current design method for the end zones of prestressed I-girders is applicable to UHPC girders assuming the steel and UHPC concurrently resist cracking stresses in the web.

Table 1. End Zone Properties of Girders.

Girder Name	Top/Bottom Bulb Width	Height	Web Thickness	Reinforcement Over h/4 Region		UHPC-class
	(in)	(in)	(in)	Vertical Steel	Confinement Steel	
A	28	35	3	2-Bundled #5@3"	#3@3"	H
B	28	35	3	2-Bundled #5@3"	#3@3"	J

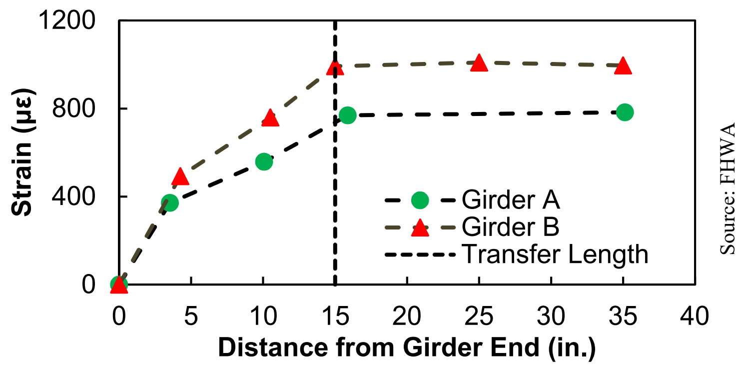

Figure 1. Transfer length of 0.7-inch diameter strands in UHPC girders after release.

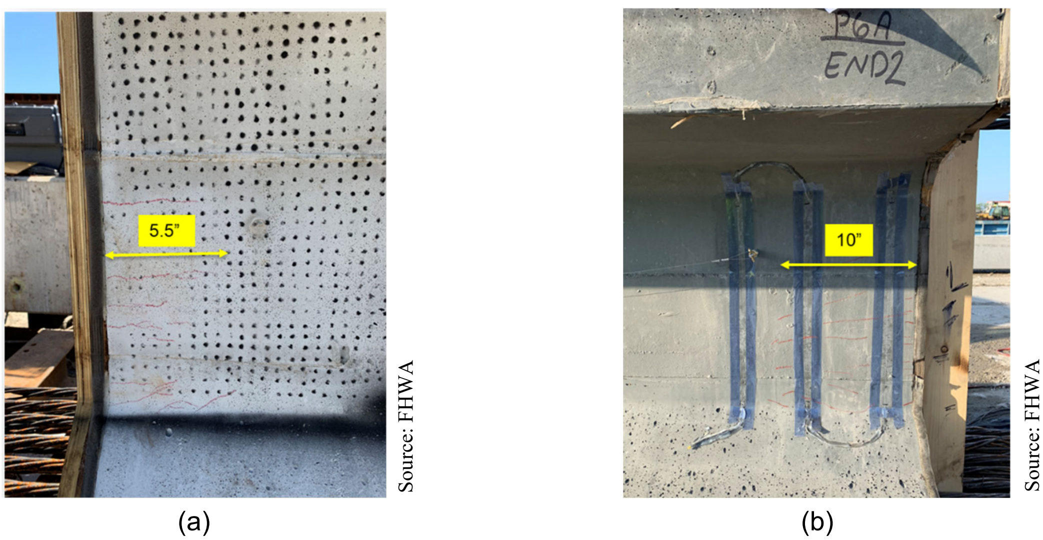

Figure 2. End zone cracking after release (a) Girder A (b) Girder B.

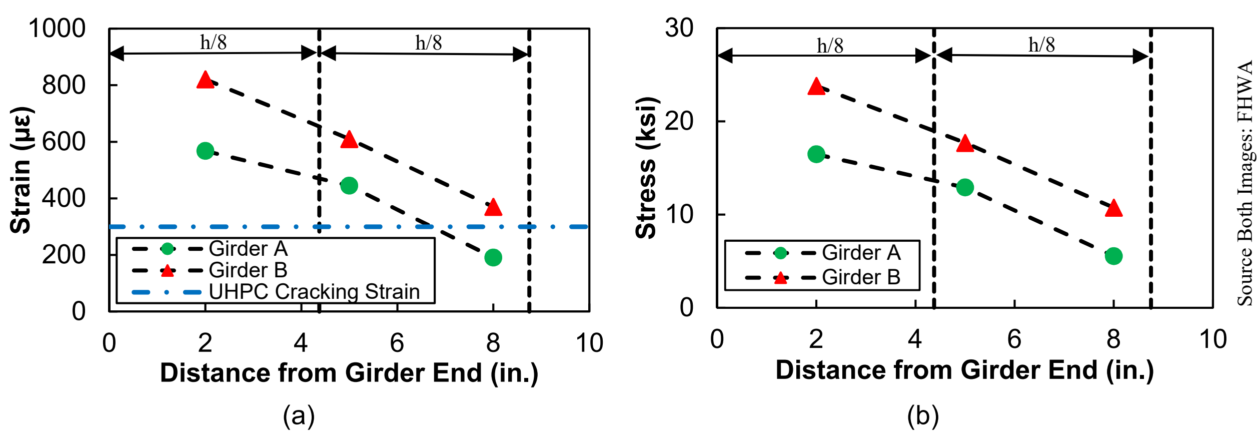

Figure 3. End zone behavior after release (a) Strain distribution (b) Stress distribution.

REFERENCES

1. AASHTO, "LRFD Bridge Design Specifications," 8th Edition, Washington, DC, 2017.
2. Haber, Z., De la Varga, I., Graybeal, B., Nakashoji, B., and El-Helou, R. "Properties and behavior of UHPC-class materials," FHWA, U.S. Department of Transportation, Report No. FHWA-HRT-18-036. Office of Infrastructure Research and Development, 2018.