The 2023 World Congress on
Advances in Structural Engineering and Mechanics (ASEM23)
GECE, Seoul, Korea, August 16-18, 2023

Experimental Study of Sharply Curved Ultra-high Performance Concrete Beams

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ABSTRACT

Modern highway bridges are commonly built on a horizontal curve and are made of either concrete or structural steel (Nutt et al., 2008). In comparison with straight bridges, the addition of curvature introduces torsion to the structural system that results in significant warping and distortional stresses in girder sections (Davidson et al., 2002). For sharply curved bridges, the common practice is to use steel I-beams or tub girders because conventional concrete girders are structurally ineffective. There are several disadvantages in the existing steel bridge system, including: 1) steel beams may experience buckling failure during construction; and 2) steel beams require frequent maintenance or repair as steel is susceptible to corrosion, particularly in aggressive environments. Therefore, the implementation of advanced materials is imperative to tackle challenges in design and construction of sharply curved bridges.

Recent advances in concrete materials technology have led to the development of a new generation of cementitious composite materials, called ultra-high performance concrete (UHPC), which can increase structures' service life due to its exceptional durability (Tadros and Voo, 2016). This paper presents an early stage of an experimental study of sharply curved UHPC beams. It addresses the development of various specimens and initial test results. It also discusses the experimental findings and compares the test results with an existing equation on torsional strength.

1. INTRODUCTION

When sharply curved beams are required in structures, the current practice is primarily limited to the steel option because conventional concrete girders are structurally ineffective. Specifically, the torsional design criterion due to the sharp curvature is challenging to satisfy, which may demand excessively congested reinforcement or undesirably heavy concrete girders. Meanwhile, there are several disadvantages in the

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use of curved steel beams, including: 1) steel beams may experience buckling failure during construction; 2) steel beams require frequent maintenance or repair as steel is susceptible to corrosion, particularly in aggressive environments (Reese 2010); and 3) steel prices keep rising and have nearly tripled in the past three years. Therefore, the implementation of advanced materials is imperative to tackle challenges in design and construction of sharply curved beams.

Recent advances in concrete materials technology have led to the development of a new generation of cementitious composite materials, referred to as ultra-high performance concrete (UHPC) (Graybeal 2006, Graybeal 2011, Graybeal and Tanesi 2007). UHPC has a strength about 5 times that of conventional concrete and can increase structures' service life up to 100 years due to its exceptional durability As a result, UHPC has strong potential to address infrastructure deterioration. A few states, including Iowa and Virginia, has implemented UHPC in bridges in a few demonstration projects and validated its feasibility and effectiveness. As a result, the Federal Highway Administration (FHWA) and many state departments of transportation (DOTs) are working tremendously to promote the use of UHPC bridges. Because UHPC is a relatively new material in the United States, no design guidelines or specifications are available for bridge engineers to follow. Further, very limited research has been conducted to study the behavior of sharply curved UHPC beams. Therefore, this research project features an initial attempt to explore sharply curved UHPC beams. This paper presents the ongoing research efforts and reports the preliminary results on material and beam tests.

2. LABORATORY TESTING

Laboratory testing was conducted on both UHPC's material properties, particularly compressive and direct tension tests, and conventionally reinforced beams.

2.1 Material tests

A UHPC mix design was developed that included 0.2-mm diameter by 13-mm-long steel fibers at a ratio of 2% by volume. An IMER 750 mixer was adopted to mix the UHPC (Fig. 1). Both compressive and direct tension tests were conducted (Fig. 2 and Fig. 3). At 28 days, the compressive strength reached up to 131 MPa and the post-cracking tensile strength was 6.9 MPa.

2.2 UHPC Beam tests

A number of specimens were made and tested, including 5 curved beams and 6 straight beams. Fig. 4 and Fig. 5 show the forms of the curved beams and the cured beams after removal of forms, respectively. These beams have a radius of curvature of 15.24 m. This paper presented the test results of two sharply curved beams that were 1,800 mm long with depths of 101 mm. These simply supported beams were restrained torsionally at both ends and a concentrated force was applied at its midspan through a hydraulic cylinder. No shear reinforcement was provided to assess the effect of steel fibers on the beams' shear and torsional capacities. Strain gauges were installed at the critical sections to monitor the structural response. Fig. 6 and Fig. 7 depict the curved beams during testing.

Fig. 1 UHPC during mixing

Fig. 2 76 mm x 152 mm UHPC cylinders

Fig. 3 Direction tension test

Fig. 4 Forms for curved UHPC beams

Fig. 5 Curved UHPC beams after form removal

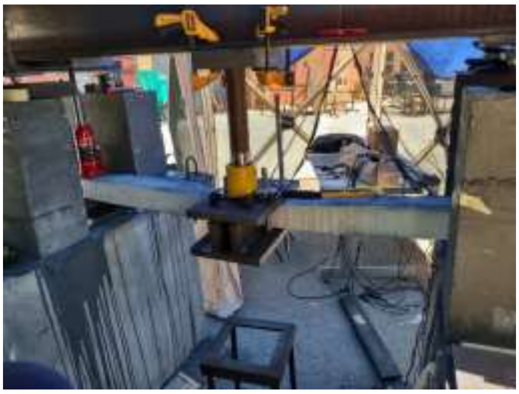

Fig. 6 First test of a UHPC beam

Fig. 7 Second test of a UHPC beam

Torsional response is one of the most important items when a UHPC beam is studied. One recently proposed equation (Kwahk et al. 2015) is listed below for comparison purposes.

$$T_u = 2A_0 f_{tu} t_d cot\theta \qquad (1)$$

The maximum applied force at midspan was 34.6 kN, which corresponded to a torsional moment of 3.85 kN.m at each beam end. Assuming of an angle of 40 degrees, the collected torsional strength was very comparable to the predicted strength using Eq. (1). The test results demonstrated the significant increase of torsional strength as compared to that of convention concrete. Additional tests will be conducted to further verify the above equation and relevant equations proposed by other researchers (Rao and Seshu 2003, Ismail 2015, Kwahk 2015, Zhou et al. 2022, Mitobaba et al. 2022, Yousef et al. 2023). In addition, the effects of combined shear and torsional responses will be investigated.

3. CONCLUSIONS

Laboratory testing was conducted to evaluate the behavior of curved UHPC beams. The test results revealed that UHPC beams exhibited substantial torsional capacities as a result of provide steel fibers, preliminarily demonstrating the suitability of using UHPC in curved beams in comparison with the conventional concrete.

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