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Shear failure analysis on ultra-high performance concrete beams reinforced with high strength steel

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ABSTRACT

A new deck system for moveable bridges was developed that makes use of ultra-high performance concrete (UHPC) reinforced with high strength steel (HSS) rebar to achieve the light weight and high strength requirements in moveable bridge applications. However, the typical deck strips of this deck system failed predominantly due to shear cracks in simply supported beam proof tests. This paper investigates the mechanism of the deck strip shear failure experimentally and analytically. Experimental studies were performed at several scales, including material characterization, bond strength tests, small-scale prism tests, and full-scale beam tests. Specimens with traditional shear strengthening techniques were also tested. Several existing formulas were utilized to predict the shear strength, and the results were compared to the experimental results. The accuracy and limitations of these formulas are discussed. The shear failure of UHPC–HSS beams is not characterized by brittle response or catastrophic load reduction as with normal reinforced concrete. Therefore, this particular shear failure mode is regarded as acceptable. However, the additional shear resistance caused by the localized deformation of the longitudinal reinforcement is not recommended to be considered for design capacity formulas.

1. Introduction

Ultra-high performance concrete (UHPC) is a fiber-reinforced concrete (FRC) with high compressive strength cement matrix and high tensile strength fibers. It exhibits the strain hardening effect in uniaxial tension tests due to the existence of the fibers with volume fraction at about 2%. According to the classification method introduced by Naaman and Reinhardt [1], UHPC can be regarded as one kind of high performance fiber-reinforced cement composite (HPFRCC). Several UHPC products are commercially available worldwide, and Ductal® is one widely available in the US. The material properties of Ductal® were fully investigated by Graybeal [2]. The high strength and good durability were confirmed based on the experimental results. Compressive strengths as high as 221 MPa are ensured by applying a heat treatment process, which is recommended by Lafarge, the manufacturer of the UHPC material used in this paper; otherwise, lower strengths will result. The benefits of this recommended heat treatment process were also confirmed by Graybeal [2]. The tensile strength was experimentally investigated by Chanvillard and Rigaud [3] using both uniaxial and four-point bending tests. The ultimate tensile strength from the direct tension test was found to be around 10.8 MPa, while the equivalent strength obtain from the flexural test was usually higher due to the scale effect. The fibers blended in the UHPC matrix provide a bridging effect across the micro cracks and thus increase the tensile strength and ductility. The punching shear resistance of the UHPC slab was investigated by Harris and Roberts-Wollmann [4], and the minimum deck thickness to prevent the punching shear failure under the factored wheel load (165 kN) for a 200 mm by 500 mm patch is predicted to be 25 mm. In Europe, Ductal® has been investigated by Toutlemonde [5] to build a full depth waffle shape bridge deck system. In US, the Pi-girder and two-way waffle shape full depth deck system are currently being investigated in Iowa state [6–9] under the research projects sponsored by the Federal Highway Administration (FHWA).

The term high strength steel (HSS) used in this paper refers to structural steel material that has a minimum yielding stress over 517 MPa (75 ksi). Several types of Grade 75 stainless steel rebar are commercially available [10] that meet the requirement of ASTM A955 [11]. Although the superior corrosion resistance of stainless steel rebars makes them the best choice for deck applications, the material cost is usually several times higher than that of normal Grade 60 carbon steel rebar. High strength microcomposite steel rebar (MMFX2) is an uncoated, high strength rebar made from a low carbon, chromium alloy steel. It meets the requirement of ASTM A1035 [12] for Grade 100 rebar with yielding stress of 690 MPa and ultimate strength as high as 1200 MPa. Although

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