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Headed stud shear connector for thin ultrahigh-performance concrete bridge deck

Jee-Sang Kim [a], Jongwon Kwark [b], Changbin Joh [b], Sung-Won Yoo [c], Kyoung-Chan Lee [d,*]

[a] Seokyeong University, 16-1 Jungneung-Dong, Sungbuk-gu, Seoul 136-704, Korea
[b] Korea Institute of Civil Engineering and Building Technology, 283 Goyangdae-ro, Ilsangseo-gu, Goyang-si, Gyeonggi-do 411-712, Korea
[c] Woosuk University 66 Daehak-ro, Jincheon-eup, Chungcheongbuk-do 365-803, Korea
[d] Korea Railroad Research Institute, 176 Cheoldobangmulgwan-ro, Uiwang-si, Gyeonggi-do 437-757, Korea

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ABSTRACT

Ultrahigh-performance concrete (UHPC) provides much higher compressive and tensile strength than conventional concrete. UHPC is advantageous for use as a bridge slab deck owing to its higher strength, stiffness, and durability. One drawback, however, is the fact that the joint region connecting the deck and girder generally has a thicker cross-section to ensure proper shear connection, which hinders making the overall UHPC deck thinner and lighter. In addition, the shear strength of stud shear connectors embedded in UHPC slab has not been verified to be the same as that in a conventional concrete deck. This study investigates a stud shear connector embedded in a UHPC deck through 15 push-out tests. The ultimate strength of the stud and relative slips are measured. The test parameters were chosen to prove the feasibility of a thinner slab. The stud aspect ratio, overall height-to-diameter, and cover thickness on top of the stud head requirement are also examined to verify the existing geometrical constraints specified in the AASHTO LRFD and Eurocode-4 design codes for UHPC decks. It was shown that the aspect ratio can be reduced from 4 to 3.1 without loss of shear strength of the stud, and the cover could be reduced from 50 mm to 25 mm without causing a splitting crack at the UHPC slab. However, the required ductility demand, 6 mm, was not realized in all cases. Therefore, the stud shear connectors in a UHPC deck should be designed according to the elastic criterion.

1. Introduction

Ultrahigh-performance concrete (UHPC) is an advanced composite material consisting of a high-strength matrix and fibers. It offers significantly superior compressive (>150 MPa) and tensile strength (>5 MPa) compared to conventional concrete, as well as higher modulus of elasticity (>40 GPa) [1]. It is typically made from a mixture of Portland cement, silica fume, filler, fine aggregate, high-range water reducer, water, and steel fibers.

UHPC is being increasingly used worldwide in various components of civil infrastructure. In particular, many studies have investigated its application to bridge components such as girders, decks, and connection joints owing to its higher strength, stiffness, and durability. Many studies have investigated the use of UHPC as a deck slab component. Saleem et al. [2,3] developed a low-profile UHPC deck system as an alternative to an open-grid steel deck. Coreslab Structures Inc. developed a waffle-shaped UHPC panel that was installed in a bridge in Little Cedar Creek, Wapello County, Iowa, US [4], and Aaleti and Sritharan [5–7] investigated the structural behavior and proposed a design guide for this panel system, including connections.

Efforts have also been made to develop a hybrid beam that comprises an FRP girder strengthened with a layer of UHPC slab on top. Chen and El-Hacha [8–10] used 9.5-mm-diameter GFRP studs to join the hollow-box FRP girder and a 53-mm-thick UHPC layer on top. Nguyen et al. [11,12] developed a hybrid composite beam comprising an FRP I-girder topped with a precast UHPC slab, which uses M16 bolts as shear connectors with an epoxy bonding. The UHPC slab was 50 mm thick, and the bolt was embedded to a depth of 35 mm, resulting in only 15 mm of cover on top of the bolt head and stud height-to-diameter aspect ratio of 2.2. This cover thickness and aspect ratio do not satisfy the values of 50 mm and 4, respectively, specified in existing design codes.

A UHPC bridge deck can feasibly have a thinner cross-section than a conventional concrete deck, as shown in previous studies [5–12]. However, the joint region connecting the deck and the steel girder should have thickness comparable to that in the conventional case to ensure that shear connectors can be properly installed and embedded in the deck in order to conform to existing design codes. For example, two previously developed UHPC deck systems have joint connections with thicknesses of 127 mm (5 in.) [2,3] and 203 mm (8 in.) [4,5], which are no less than that of a conventional concrete deck. Because the

* Corresponding author. Tel.: +82 31 460 5391; fax: +82 31 460 5364.
E-mail addresses: zskim@skuniv.ac.kr (J.-S. Kim), origilon@kict.re.kr (J. Kwark), cjoh@kict.re.kr (C. Joh), imysw@woosuk.ac.kr (S.-W. Yoo), eclip77@gmail.com (K.-C. Lee).

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thinnest sections of the UHPC deck are 32 mm (1.25 in.) [2,3] and 63.5 mm (2.5 in.) [4–7], a shear connection requires a significantly thick UHPC deck; this goes against the design objective of reducing the self-weight and lowering the profile of the deck. This study investigates the structural behavior of stud shear connectors embedded in UHPC decks of various thicknesses and confirms the validity of existing design codes for this application.

Since 1960, composite structures have been widely used owing to their structural efficiency. They typically consist of a steel girder and concrete deck that transfers shear force through suitable shear connectors such as angles, channel sections, headed studs, and perforated ribs. Headed studs are used most commonly owing to their simple and quick installation using a stud-welding gun and superior ductility than other types of shear connectors.

The static strength of stud shear connectors was originally evaluated based on Ollgaard et al.'s [13] early experimental work. They showed that the static strength of a stud shear connector is controlled by two different failure mechanisms: surrounding concrete crushing failure, related to concrete's compressive strength, f_c', and shearing failure of the shank of the stud, related to the stud's ultimate tensile strength, F_u. The smaller value between the two different mechanisms controls the design shear strengths of a stud shear connector. The AASHTO LRFD provision 6.10.10.4.3 [14] defines the design static strength of a stud shear connector, Q_r, as

$$Q_r = \phi_{sc} Q_n = \phi_{sc} 0.5 A_{sc} \sqrt{f_c' E_c} \leq \phi_{sc} F_u A_{sc} \quad (1)$$

where the resistance factor, ϕ_{sc}, is taken as 0.85. Eurocode-4 [15] defines the design static shear strength, P_{Rd}, as

$$P_{Rd} = \frac{0.29 \alpha d^2 \sqrt{f_c' E_c}}{\gamma_v} \leq \frac{0.8 F_u A_{sc}}{\gamma_v} \quad (2)$$

where the partial factor, γ_v, is taken as 1.25, and an aspect ratio factor, α, which depends upon the stud height-to-diameter ratio, h_{sc}/d, is taken as $0.2(h_{sc}/d + 1)$ for $3 \leq h_{sc}/d \leq 4$ and 1 for $h_{sc}/d \geq 4$.

Different design codes have different resistance or partial factors. However, they are similar in that the left-hand side terms of Eqs. (1) and (2) refer to concrete crushing failure in terms of the surrounding concrete strength (f_c') and modulus of elasticity (E_c) but not the mechanical property of the embedded stud. Furthermore, the right-hand side terms of Eqs. (1) and (2) refer to stud shank failure in terms of the ultimate tensile strength (F_u) of the stud but not the mechanical property of the surrounding concrete. The concrete crushing failure controls when the compressive strength of the concrete is low or moderate, and the stud shank failure does when the strength is high. The threshold between the two failure modes usually lies at a concrete compressive strength of 30–40 MPa.

Considering that the compressive strength of UHPC exceeds 150 MPa, the stud shank failure mode obviously always controls the static strength of the stud shear connector. Ollgaard et al. [13] reported that the concrete strength of their specimens was 18–35 MPa. Therefore, the validity of existing design codes for stud shear connectors should be confirmed for UHPC applications because it provides much higher concrete strength than before.

Geometrical constraints are another important issue with regard to UHPC decks in that they must be as thin as possible to reduce their weight and construction costs. The constraints of existing design codes may result in a UHPC deck with a thicker cross-section at the joint region between the deck and the girder. The thickness of waffle deck panels [4–7] is 63.5 mm at the thinnest region between ribs but 200 mm at the joint region. Saleem [2,3] developed a low-profile deck system that is as thin as 31 mm between ribs but is 125-mm-thick at the joints. This study investigates a joint region with a thickness of only 75 mm to overcome the stocky joint region resulting when applying a current design code to the shear connectors embedded in a UHPC deck.

The first geometrical constraint is the aspect ratio between the overall stud height and the shank diameter. The AASHTO LRFD [14] and Eurocode-4 [15] design codes require an aspect ratio of at least four and three, respectively. The second constraint is the concrete cover thickness over the stud head to prevent a longitudinal splitting crack on top of the shear connector. The AASHTO LRFD provision 6.10.10.1.4 [14] regulates that the clear depth of the concrete cover over the top of a shear connector should not be less than 50 mm and should penetrate at least 50 mm into the concrete deck. For example, when using the most common diameter of 17 mm for a stud for a bridge deck and

Table 1
Push-out test specimens.

Specimen group	Deck thickness (mm)	Stud shear connector			Cover thickness (mm)	EA
		Height (mm)	Diameter (mm)	Aspect ratio (height/diameter)		
Normal	150	100	22	4.5	50	3
UHPC-I	150	100	22	4.5	50	3
UHPC-II	100	65	16	4.1	35	3
UHPC-III	100	50	16	3.1	50	3
UHPC-IV	75	50	16	3.1	25	3

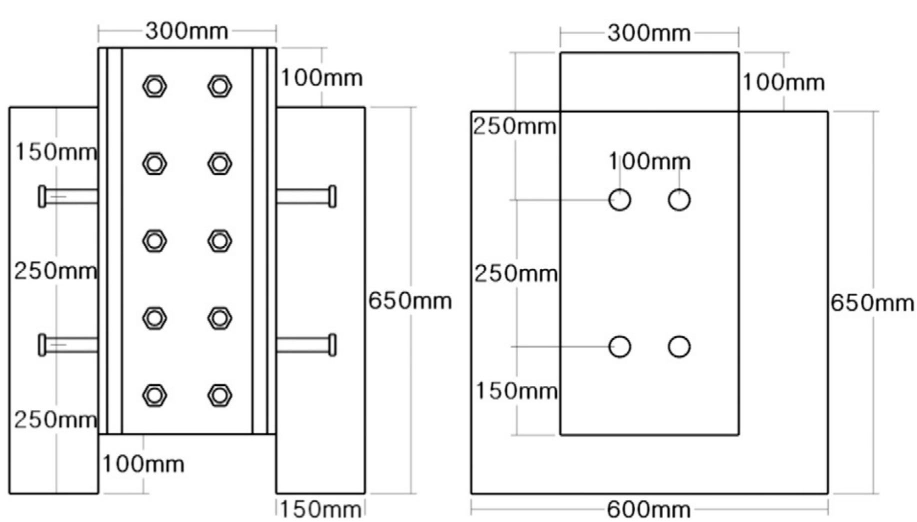

Fig. 1. Push-out specimen dimensions.