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Design considerations for headed shear studs embedded in ultra-high performance concrete as part of a novel bridge repair method

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ABSTRACT

This paper presents design parameters and considerations for headed studs embedded in UHPC as part of a novel bridge repair method. The method is developed for retrofitting of steel bridge girders with severe corrosion at the ends. In this repair method, headed shear studs are welded to the undamaged portion of the web plate at the girder end and encased with Ultra-High Performance Concrete (UHPC). The end bearing capacity is increased by transferring shear forces from the web to UHPC casts through the studs. Sixteen push-out tests were performed to evaluate design considerations prior to field implementation. The effects of a) eccentric loading, b) concrete material variations, c) clear and side cover, d) welding/surface preparation, and e) curing of UHPC on shear capacity of studs were studied. The results were used to establish design and installation recommendations for the proposed repair.

1. Introduction

There is a growing need for more efficient and effective repair methods to rehabilitate the rapidly deteriorating infrastructure. To improve the efficiency of repairing deteriorated bridge girders with section loss at the ends, a new repair method has been proposed, in which headed shear studs are embedded in ultra-high performance concrete (UHPC) [1]. UHPC is the ideal candidate material for this repair because of its flowability, excellent corrosion resistance, superior tensile capacity. No additional reinforcement is needed other than the steel fibers present in the mix. Additionally, studies have shown that headed studs exhibit superior fatigue performance when embedded in UHPC compared to regular strength concrete (RSC) [2]. In this repair, the headed shear studs are welded to the non-corroded portion of the web plate near the bearing region and encased in a panel of UHPC. This panel of UHPC extends down to the bottom flange, enabling a force transfer mechanism to alleviate the weakened web (Fig. 1).

It is estimated that there is a backlog of approximately $123 billion in bridge rehabilitation projects in the United States [3]. The current procedure to repair damaged girder ends is expensive, time consuming, difficult to implement, and leads to bridge closures. First, the superstructure must be jacked to relieve the dead load from the affected portion of the girder. This procedure is costly and sensitive, as improper jacking can result in bridge collapse, serious structural damage to the components, injury to workers, or traffic accidents [4]. Next, the damaged section of the steel must be cut out so that a new section can be welded into place. Lead abatement may be necessary if the girder was treated with a lead-based paint. After the damaged portion is removed, a new section of steel is carefully welded into place such that the girder remains straight and upright. Finally, the superstructure is lowered back into place. While this repair procedure is commonly accepted as the standard protocol for repairing corroded girders, there is a growing need for an alternative method which decreases the time needed for lane closures, minimizes cost, and improves the effectiveness of the repair.

Corrosion is one of the most prevalent issues facing steel superstructures. A typical expansion joint for new construction in small-span bridges lasts less than 15 years [5]. However, leakage of the joints can occur prior to the expected lifespan of the joint, exposing the superstructure to water and deicing chemicals. Additional inhibitors that induce corrosion in steel girders include high temperature, salt concentration in the air, presence of sulfur oxides, and wind velocity [6]. Exposure to these hazards may cause significant corrosion of the load-bearing components (Fig. 2). Experimental studies have been conducted to evaluate the bearing capacity of steel girders with section loss due to corrosion near the bearing region [7]. The studies revealed that a 70% section loss in the web and flange area decreased the bearing capacity of the girder by 76%. When corrosion damage is present in the web and stiffener, the failure mode shifts from buckling of the web plate to local crippling at the reduced region [8].

The proposed repair method utilizing headed studs and UHPC has been proven as a viable option to restore the bearing capacity of a weakened girder. Experiments were performed with one-third scale bridge girders to validate this concept [9]. The results showed that the capacity of a damaged steel girder increased by approximately 25% compared to the undamaged section when the proposed repair was applied. When

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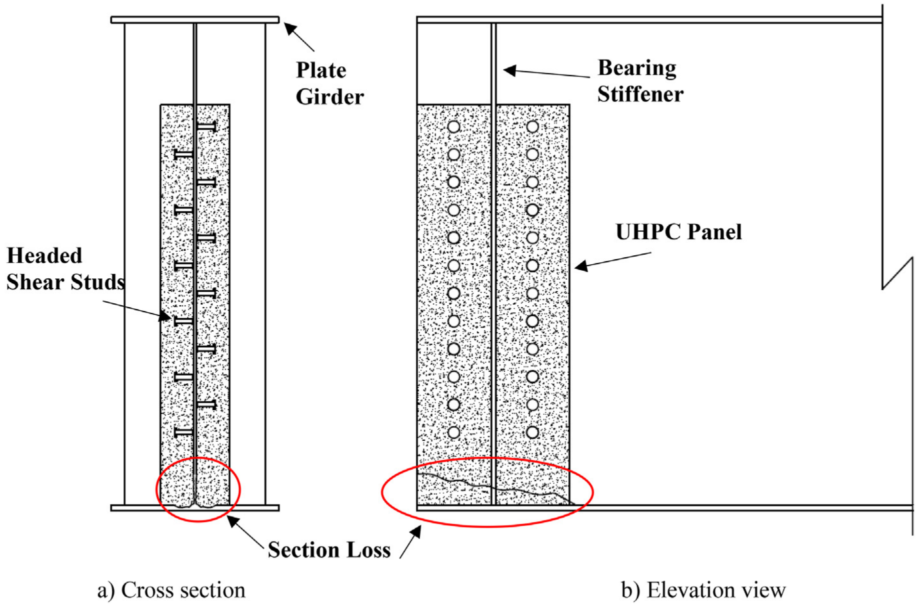

Fig. 1. Schematic of proposed repair concept.

the damaged girder was tested, high levels of axial strain concentrations were observed at the reduced section of the web plate. However, when the UHPC repair was implemented, these strains were drastically lowered and instead transferred to the UHPC, demonstrating the success of the repair. A critical component of the proposed repair is the interaction between the web plate, the headed shear studs, and the UHPC panel. A study was conducted by the authors to examine the performance of headed shear studs welded onto 9.5-mm thick web plates. Parameters such as stud diameter, stud spacing, stud arrangement, and UHPC compressive strength were assessed [10]. The results showed that when studs are embedded in UHPC, stud shank failure always governs, with no damage to the UHPC. These results were consistent for all patterns tested, including vertical stagger, horizontal and vertical stagger, and tight spacing.

Although experimental studies have proven that this repair method is a promising alternative to the current repair procedure, design parameters must be established to ensure proper application and longevity of the repair. In this research, push-out experiments were designed to evaluate potential design parameters that may be considered by the bridge owner. Factors studied include a) eccentric loading, b) concrete variations, c) clear and side cover, d) welding/surface preparation, and e) presence of vibration while curing. The results from each push-out test are compared against the baseline sample, which represents typical behavior of headed studs embedded in UHPC. The data obtained from the tests was used to provide design recommendations for implementing the proposed repair method in the field.

Fig. 2. Corrosion at girder end.

2. Review of prior studies

Extensive literature exists on the shear capacity of headed shear studs. However, there is still a need for validation of the proposed parameters as part of the UHPC repair. No data was found on the performance of headed studs when subjected to a combination of shear and in-plane torsion. This scenario may be relevant in the field when there is a moment applied to the stud group. Therefore, the effect of eccentric loading must be studied, as it is currently unknown. The influence of concrete embedment material has been more commonly studied. Lam et al. [11] reported that when conducting push-out tests using regular strength concrete (RSC) with a compressive strength of 20 MPa, the failure mechanism was governed by conical failure of the surrounding concrete with partial yielding of the stud. When studs are embedded in higher strength concrete, larger capacities are generated with a failure mode resulting in stud shank rupture [12]. It was found that the stiffness and deformability of headed studs embedded in RSC is also dependent on the concrete strength [13]. When studs are embedded in UHPC, a spacing of 3.5 stud diameters (d_b) generates at least 90% of the shear strength of a single stud, while in RSC a spacing of $6d_b$ is required [14]. However, transverse reinforcement is necessary for RSC panels, as the tensile resistance of concrete is insufficient to accommodate the splitting forces generated by the studs [15]. In the context of the UHPC repair, bridge owners may opt for an alternative embedment material and therefore experiments must be performed to validate their use.

Another important design parameter for the proposed repair is clear and side cover of the studs. Due to the nature of the repair, the studs may be welded close to the end of the girder or adjacent to a bearing stiffener. Therefore, minimum clear distance and cover must be established. A study has shown that a UHPC cover of 25 mm is sufficient to generate full capacity of the studs (i.e. stud shank failure) [16]. However, no studies have evaluated side cover or minimum clear distance to the edge of the concrete.