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Interface shear behavior between high-strength precast girders and lightweight cast-in-place slabs

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HIGHLIGHTS

- Studying interface shear behavior between lightweight and high-strength concrete.
- Influence of aggregate granular size on slippage and dilation of shear plane.
- Shear capacity of lightweight slab specimens is better than that of normal concrete.
- Both AASHTO and ACI provision underestimate the interface shear strength.

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ABSTRACT

The overall purpose of this study is to examine the shear-friction behavior of shear interface with transverse reinforcement between precast girder using high-strength concrete and cast-in-place slab with lightweight concrete. Eighteen push-off specimens, with testing parameters of lightweight coarse aggregate size, slab concrete type and shear reinforcement ratio, were tested in this investigation. Based on the analysis of the experiment, this study suggests that the granular size of lightweight coarse aggregate did not play a significant role in the shear strength of interface and the shear transfer strength of lightweight slab concrete specimens are greater than that of normal weight slab concrete specimens having the same concrete compressive strength, interface reinforcement ratio and interface treatment. Additional, the transfer reinforcing steel can improve shear capacity and residual resistance obviously. For both sand-lightweight and normal weight cast-in-place slab concretes, the interface shear strengths predicted by the design equations given in AASHTO LRFD 2014 and ACI 318-14 are conservative.

1. Introduction

1.1. Background

More and more bridges now are designed and constructed with precast girder made of high-strength concrete and cast-in-place slab specified with lightweight concrete. This composite construction is an economical way of combining precast and cast-in-place concrete but retaining the continuity and efficiency of monolithic construction. Previous studies have found that behavior of the interface between precast girder and cast-in-place slab of a composite beam influenced the beam behavior significantly, as horizontal shear behavior of such beam was crucial to achieve monolithic action [1–4]. Many studies on composite beam have concluded that some beams did end up failing in flexure, but most failed in horizontal shear and displayed horizontal shear slipping [1–3]. Additionally, Hanson [5] found that large slip at the shear interface exceeded 0.13 mm (0.005 in.) before the beam failed in flexure or in vertical shear can cause a horizontal shear failure to the composite beam, which will result in loss of composite action and a significant reduction of stiffness and flexural capacity. It can also be found that large slips and separations between girder and slab at failure supported the shear-friction theory, which was based on push-off tests by Kriz and Raths [6], Birkeland and Birkeland [7], Mast [8] and Hofbeck et al. [9]. Mattock and Hawkins [10] and Paulay [11] studied the influences of concrete strength, interface preparation, reinforcement ratio and direct stress on the shear transfer strength of reinforced concrete. Mattock [12,13] constructed twenty-three push-off specimens to examine the application of shear-friction hypotheses for shear reinforcement at an arbitrary angle to the shear plane, and performed

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twenty-seven push-off tests to understand the influence of moment on a shear plane, placement of shear reinforcement and tension across the shear interface. Walraven [14] presented the influence of previous load cycles and sustaining loads on shear capacity of cracked concrete members and proposed a news equation considering the influence of concrete strength as a basic parameter. Bass et al. [15] studied the behavior for specimens with different embedment of reinforcement under repeated cyclic loading. Based on the strut-and-tie concept and derived to satisfy equilibrium, compatibility and constitutive laws of cracked reinforced concrete, Hwang and Lee [16] developed a softened strut-and-tie model for determining the shear strength according to the compressive strength of the concrete strut. Recently, Rahal [17] proposed a model considering the influence of steel parallel to the shear interface. Harries et al. [18] provided an empirical formula for better understanding the behavior of ordinary- or high-strength reinforcement based on the non-simultaneous failure of concrete and reinforcement. In addition, this research firstly considered the high-strength steel.

With the increasing application of high-strength concrete, more and more relative works have been done. Walraven [19] carried out an experiment using concretes with compressive strength up to 9000 psi (62.06 MPa), made an analysis of aggregate interlock effect and proposed a more accurate equation for shear transfer. Walraven and Stroband [20] have tested push-off specimens made of 13,500 psi (93.1 MPa) concrete. Mattock [21] focused on the shear-friction behavior between precast girder and cast-in-place slab of composite bridge and examined the available data from shear transfer tests of initially cracked specimens.

Based on the analysis, simple equations for shear-friction design that would more accurately predict the potential shear transfer strength of all strengths of concrete were proposed. Kahn and Mitchell [22] performed fifty push-off tests made of concrete having compressive strengths between 6800 psi (46.89 MPa) and 17,900 psi (123 MPa) and transverse reinforcing ratios between 0.37 and 1.47 percent. It found that both the equation and limitation of the current ACI shear-friction concept were not adapted for the specimens in that study so a more accurate equation was proposed to predict the shear-friction strength of cold-joint and uncracked interfaces for high-strength concrete. Nagle and Kuchma [23] conducted eighteen shear-friction tests and twenty beam shear tests with high-strength concrete and different transverse reinforcement ratios to extend AASHTO LRFD specifications to high-strength concrete.

At the same time, lightweight aggregate concrete slabs are being used increasingly in precast concrete construction to reduce member weight and costs, so that there are several studies on the interface shear transfer of lightweight concrete. Mattock, et al. [24] studied the effects on horizontal shear capacity of lightweight concrete with the variables of aggregate type, concrete strength, shear reinforcement amount and precracking of an interface. Loov and Patnaik [2] proposed an applicable equation for lightweight and semi-lightweight concrete, based on the testing of sixteen composite beam. Shaw and Sneed [25,26] examined the direct shear transfer across an interface of lightweight concrete cast at different times, with the variables of lightweight aggregate material, concrete unit weight, compressive strength, shear interface preparation, reinforcement ratio and crack interface condition. Banta [27] performed twenty-four push-off specimens to study the effects of surface treatments, reinforcement ratios and aspect ratio on shear interface behavior between ultra-high performance concrete and lightweight concrete. Scott [28] constructed thirty-six push-off tests to determine if the current code equations accurately predicted the horizontal shear strength of precast girders and cast-in-place decks for both lightweight and normal weight concrete. Three type of combinations and four variations in the amount of horizontal shear reinforcement for specimens with permanent net compressive force normal to the shear plane were studied. Some of the deck specimens failed before failure at the interface. Generally, few relative studies focus on the shear behavior of interface between high-strength concrete and lightweight concrete, including the variables of granular size of lightweight aggregate, slab concrete type and shear reinforcement ratio.

1.2. Current design codes

Currently, the calculation of shear transfer force in design is usually based on the provisions of Section 5.8.4-Interface Shear Transfer Shear Friction of AASHTO LRFD 2014 [29] or of Section 11.6-Shear-friction of ACI 318-14 [30]. The current AASHTO LRFD 2014 equation for nominal shear resistance at the interface of precast concrete girder with cast-in-place concrete slab is computed as a function of the cohesion factor c, the area of concrete shear interface A_{cv}, the friction factor μ, the area of interface shear reinforcement A_{vf}, the yield stress of interface shear reinforcement f_y, and the permanent net compressive force P_c:

$$V_{ni} = cA_{cv} + \mu(A_{vf}f_y + P_c) \quad (1)$$

Section 5.8.4 also specifies that V_{ni} shall not exceed $K_1 f_c' A_{cv}$ nor $K_2 A_{cv}$ and the f_y shall not exceed 414 MPa. The values for the cohesion factor c, friction factor μ, fraction of concrete strength available to resist interface shear K_1 and limiting interface shear resistance K_2, which depend on surface preparation and how the composite system is constructed, are listed in Table 1.

The other current design provision is the ACI 318-14, which the equation is given by:

$$V_{ni} = \mu A_{vf} f_y \quad (2)$$

An upper limitation of $K_1 f_c' A_{cv}$, $K_2 A_{cv}$ and $K_3 A_{cv}$ was proposed for V_{ni} and of 414 MPa for f_y in the provisions. The values of coefficient of friction μ, K_1, K_2 and K_3 are also summarized in Table 1. The modification factor λ is the reduced coefficient of the mechanical properties of lightweight aggregate concrete respective to normal weight concrete of the same compressive strength, which is taken as 1.0 for normal weight concrete and may be 0.85 for sand-lightweight concrete [30,31]. For this research, the values of parameters for case II in Table 1 were used to calculate the capacity of two type of sand-lightweight slab concrete specimens, and for case III in Table 1 were used to calculate the shear resistance load for normal weight slab concrete specimens.

As mentioned previously, the shear friction theory has been studied extensively by others, especially for normal weight concrete with various reinforcement ratios, compressive strengths, and interface conditions. Relatively, little work has been done, however, to investigate the shear friction mechanism for the surface between lightweight concrete and high-strength normal weight concrete with the variables of lightweight aggregate size, concrete type and reinforcement ratio. This condition can be the result of actual project that a high strength bridge girder casts in advance and then pours the lightweight fresh concrete onto it as bridge slabs when the girder were set in specified locations. Accordingly, this study was aimed at studying the shear transfer of lightweight aggregate slab concretes across a cold joint with a roughened interface (cases II in Table 1). Results are compared with those from normal weight slab concrete of the same strength and interface condition (cases III in Table 1).

2. Experimental program

2.1. Test specimens and materials

The experimental program included 18 push-off specimens used to investigate direct shear transfer across an interface