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Behavior of stud connections between concrete slabs and steel girders under transverse bending moment

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ABSTRACT

The effect of transverse bending moment on stud connections is usually ignored in the design of steel–concrete composite bridges due to beam web flexibility. However, large transverse moment may arise near transverse stiffeners and diaphragms, because they constrain and stiffen the webs and cause tensile forces in stud connectors. Large web spacing and wide cantilevers increase these effects. This study experimentally and numerically investigates this behavior. Four groups of pull-out tests of a single stud connector under tension force are performed, and they provide insight into the behavior of stud connectors under direct tensile loading. Then four stud connections at interfaces near transverse stiffeners are tested to investigate their behavior under transverse bending moment. Numerical models of the stud connections are established to explore local behavior. The pull-out tests show that stud height greatly influences failure mode, tension strength and ultimate separation between the steel flange and the concrete slab. A tension–separation relationship is developed from the test results and used in subsequent numerical simulations. The stud connection tests suggest that longer studs can increase the bending moment and deformation capacities. Reduced longitudinal stud spacing significantly increases the stiffness, but may result in brittle failure of the concrete slab. Stud connectors should not be welded immediately over transverse stiffeners. Numerical simulations and test data compare well, and numerical results predict tensile forces in studs located near the steel web and in the region near stiffeners and other web restraint. The stud connectors in the two innermost rows on either side of a transverse stiffener provide the restraint to develop the tensile force in the studs caused by transverse bending moments. The force in a stud increases as its distance from the steel web increases and its distance from the transverse stiffener decreases. Shear–tension interaction should be checked for these connectors. Details of transverse stud arrangements with various stud heights are provided.

1. Introduction

Steel–concrete composite girders are extensively used in bridge construction due to their light weight, large load capacity and relatively shallow girder depth. Headed stud connectors are usually welded to the top flange of the steel girder and embedded into the concrete slab to develop the composite action [1,2]. The studs resist the horizontal and vertical relative movements between the steel flange and the concrete slab [3,4]. Thus, the studs will resist both the horizontal shear force and any tensile force that develops.

Extensive studies [5–14] on the behavior of the stud connections between concrete slabs and steel girder top flanges under shear force are described in the literature, but few studies evaluate the behavior of stud connections under transverse bending moment at this interface. Xu et al. [15] performed biaxial load experiments on stud connectors using push-out tests, and showed that the bending-induced cracks in the slab adversely affect stud performance. Their research focused on the influence of the local transverse bending moment in the concrete slab on a single stud connector. The effect of transverse bending moment at the interface on stud connections is seldom investigated and usually ignored in the design of a composite bridge, because the high flexibility of steel webs limits any moment transfer between the slab and the girder flange. However, large bending moment transfer may arise near transverse stiffeners and diaphragms since the local stiffness is increased. The increased local stiffness may cause increased tensile stress in concrete slabs and tension force in stud connectors [16]. This may be further increased by composite girders with large web spacing and wide cantilevers in the concrete

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Nomenclature

A_s	area of the shank of the headed stud
d	separation between steel beam and concrete block in pull-out tests
d_{cp}	separation at peak transverse support bending moment
d_s	diameter of the shank of a stud connector
d_p	separation at peak tension load in pull-out tests
d_u	separation at 90% of the peak tension load on the post-peak descending branch in pull-out tests
E_c	elastic modulus of concrete
E_s	elastic modulus of steel
f_c	cylinder compressive strength of concrete
$f_{c,cube}$	cube compressive strength of concrete
f_t	tensile strength of concrete
G_f	energy required to open a unit area of crack
f_u	tensile strength of headed stud material
f_{us}, f_{ur}	ultimate strength of structural steel and reinforcements, respectively
f_{ys}, f_{yr}	yield stress of structural steel and reinforcements, respectively
h_s	overall height of a stud connector
h_{ef}	effective embedment depth of a stud connector
k_c	bending stiffness of stud connection at the interface
k_s	shear stiffness of a stud connector
k_t	tension stiffness of a stud connector
M_u	applied maximum transverse support bending moment
n_l	number of stud connectors in the longitudinal direction
s_l	stud spacing in the longitudinal direction
T	tension force in a stud connector
T_u	tension strength of a stud connector
σ_u	ultimate strength of steel material
σ_y	yield stress of steel material
ε'_c	strain corresponding to the compressive strength of concrete
ω_c	failure cracking displacement

slab. The approach bridges of Shanghai Yangtze River Bridge in Shanghai, China, are steel–concrete composite bridges that illustrate this concern. Each composite bridge consists of two separate parallel composite box girders, each of which is comprised of a steel U-girder attached to a concrete slab through stud connectors. The details of the cross section at mid-span are shown in Fig. 1. The full width of the concrete deck slab is 17.15 m and is divided into three traffic lanes. The outmost traffic lane is reserved for light rail trains in the future. The web spacing and the width of each concrete cantilever are about 9.15 m and 4 m, respectively, which is very uncommon in existing composite bridges and is a great concern during the design. Web stiffeners are required at some locations, and significant stiffening of the web occurs at these locations. The stiffened web results in significant increases in the rotational stiffness of the flange and web, and increased local restraint to the slab at this local region. Hence, local moment transfer and significant tensile forces in the studs may occur in this region. Therefore, this research studies the behavior of stud connections between concrete slabs and steel girder top flanges under transverse bending moment located near transverse stiffeners.

In this paper, the static behavior of stud connections is investigated both experimentally and numerically. The experimental work consists of pull-out tests and concrete slab-to-steel girder top flange connection tests. Four groups of pull-out specimens are tested to study the behavior of a single stud as a function of stud height under direct tensile force. Then, four concrete slab-to-steel girder top flange connections are tested to investigate their global behavior under transverse bending moment at a stiffener.

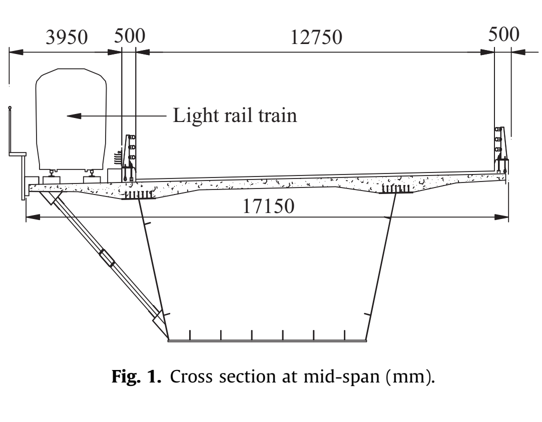

Fig. 1. Cross section at mid-span (mm).

The chosen variables are stud height, longitudinal stud spacing and stud location. Based on the pull-out test results, the effect of overall stud height on the tension stiffness, tension strength and ductility of a stud connector is evaluated. An expression relating tension to separation between the stud and beam flange is developed and used in subsequent numerical simulations. The global behavior of the four stud connections are analyzed with this analytical model, compared to experimental results, and then used to evaluate the effect of key parameters. Then, finite element models are established to derive the local behavior within these connection regions. Distribution of contact stress at the steel–concrete interface and distribution of tensile force in stud connectors are discussed in detail.

2. Pull-out tests

Tensile force arises in some stud connectors when a stud connection is subjected to transverse bending moment; thus, pull-out tests are carried out at first to study the behavior of a single stud connector under direct tensile force.

Four groups of three identical pull-out specimens, denoted as T1, T2, T3 and T4, respectively, were tested. Previous researches [17–19] have shown that stud height has a great influence on stud behavior under tensile force, and stud height is the primary variable for the pull-out tests. The overall stud height, h_s, is 100 mm, 200 mm, 300 mm and 400 mm for Groups T1, T2, T3 and T4, respectively. The stud shank diameter is 22 mm for all the specimens.

The details of the pull-out specimens are shown in Fig. 2. Each specimen consists of a steel beam, a concrete block and a single stud connector. The steel beam is designed with sufficient strength and stiffness to ensure it remains in the elastic range through the load needed for stud fracture or cone failure of the concrete. The concrete block is cast in the horizontal position, as is done for composite girders in practice. Bond stress at the steel–concrete interface is diminished by greasing the contact surface between the steel beam and the concrete block.

2.1. Material properties

Six 150 mm × 150 mm × 150 mm concrete cube specimens are cast at the same time as the concrete blocks for the pull-out test specimens to provide material properties of the concrete. The