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Experimental study on shear behavior of tie-bars in steel-plate concrete composite structure subjected to cyclic loading

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A R T I C L E I N F O

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A B S T R A C T

Tie-bars play an important role in the transfer of the shear between the steel faceplate and the concrete in steel-plate concrete composite structure. Twelve push-out specimens were tested to investigate the shear behavior of tie-bars subjected to monotonic and cyclic loadings in high strength concrete. The primary parameters analyzed in this study included tie-bar diameter, tie-bar strength grade, load procedure and welded joint structural type. The failure modes, shear capacities, shear slips, load-slip curves, shear stiffness, ductility, energy dissipation capacities and tensile strain distributions of tie-bars were studied, in addition to comparing the ultimate shear capacities of tie-bars in this experiment with those calculated by an existing formula. The experimental results indicated that the groove fillet welding significantly improved the shear capacities of tie-bars under cyclic loading with respect to other three welded joint structural types in this experiment (The difference is more than 33%). The shear capacity, shear stiffness and shear slip increased significantly with the increase of tie-bar diameter. The tie-bars subjected to cyclic loading exhibited lower shear capacities and shear slips than those under monotonic loading. The reductions of the shear capacity and the shear slip decreased approximately with the increase of tie-bar diameter, and they were 28–42% and 58–67%, respectively. The tensile strain distributions of tie-bars were affected significantly by the load procedure, and according to the distributions, two recommendations were proposed for the design for out-of-plane shear capacity of steel-plate concrete composite structure subjected to bending moment.

1. Introduction

The steel-plate concrete (SC) composite structure consists of two external steel faceplates, a concrete core, studs anchoring the faceplates to the concrete and tie-bars interconnecting the two faceplates through the concrete core. Currently, the SC composite structure has been used to subway, offshore platform, impact and blast resistant structures, oil and air storage tank and AP1000 enhanced shield building. Investigating the performance of this structural system has been the core issue of concern to researchers [1–9]. The performance of SC composite structure relies on the transfer of shear between the steel faceplate and the concrete in order to ensure the capacity, stiffness as well as ductility. Both of the stud and the tie-bar play an important role in the resistance of longitudinal shear. However, compared with studs, tie-bars resist the vertical shear in the oblique section like stirrups in reinforced concrete structures [10], in addition to preventing steel faceplate buckling [11,12]. Meanwhile, the stud anchored in concrete directly relies on the concrete to offer the shear capacity, which may cause the concrete to crack (Fig. 1). Although the shear behavior of studs had been investigated in many researches, it was deficient that these researches were used to study the shear behavior of tie-bars.

Tie-bar, also known as Bi-Steel, was developed by Bowerman [13], using a high-speed friction weld process to attach the tie-bars to both steel faceplates. Clubley et al. [14] carried out twelve push-out tests, including five standard specimens and seven double panels, to study the shear behavior of 25 mm diameter round bright tie-bars under monotonic loading (Fig. 2). It indicated that the faceplate spacing could affect the shear capacity, and the tie-bar had high ductility and deformation capacity. Xie et al. [15] investigated the shear behavior of friction-welded bar-plate connections with 25 mm diameter round bright tie-bars embedded in concrete under monotonic loading (Fig. 3). The experimental results showed that the ultimate shear capacity of the tie-bar increased by about 25% as the plate thickness increasing from 6 mm to 10 mm, but further increase in plate thickness did not increase their ultimate shear capacities. In addition, a significant tension occurred on the center axis of the tie-bar under shearing, and the tensile strain

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Nomenclature

A_s	gross area of shear connector
b	parameter in V_c formulas
c	parameter in V_c formulas
d	tie-bar diameter
E_c	modulus of elasticity of concrete
E_{cm}	secant modulus of elasticity of concrete
f_c	concrete compressive strength
f_c', f_{ck}	specified compressive strength of concrete
f_{yp}	steel-plate yield strength
f_y	shear connector yield tensile strength
f_u	shear connector ultimate tensile strength
K_e	equivalent shear stiffness of shear connector
K_s	secant shear stiffness of shear connector
k_L	reduction factor
L	distance between the stain gauge and the welded joint
L_o	overall length of tie-bar
m	the ratio of the distance between two outside steel-plates versus the tie-bar diameter
P	peak value
r	correlation coefficient
S	shear slip of shear connector
s_{max}	shear slip corresponding to maximum shear capacity in a cycle
s_{min}	shear slip corresponding to minimum shear capacity in a cycle
s_m	maximum shear slip of shear connector
s_y	shear slip corresponding the yield shear capacity of shear connector
$s_{y,m}$	shear slip corresponding the yield shear capacity of shear connector under monotonic loading
$s_{y,c}$	shear slip corresponding the yield shear capacity of shear connector under cyclic loading
s_u	shear slip corresponding the ultimate shear capacity of shear connector
$s_{u,m}$	shear slip corresponding the ultimate shear capacity of shear connector under monotonic loading
$s_{u,c}$	shear slip corresponding the ultimate shear capacity of shear connector under cyclic loading
T	time
t	steel-plate thickness
V	shear capacity of shear connector
V_{max}	maximum shear capacity in a cycle
V_{min}	minimum shear capacity in a cycle
V_y	yield shear capacity of shear connector
$V_{y,m}$	yield shear capacity of shear connector under monotonic loading
$V_{y,c}$	yield shear capacity of shear connector under cyclic loading
V_u	ultimate shear capacity of shear connector
$V_{u,m}$	ultimate shear capacity of shear connector under monotonic loading
$V_{u,c}$	ultimate shear capacity of shear connector under cyclic loading
V_{uc}	ultimate shear capacity of shear connector depend on the concrete
V_{us}	ultimate shear capacity of shear connector depend on the tie-bar
Q	quantity of tie-bars at the same interface in push-out specimen

varied according to the relative stiffness of the tie-bar, the steel faceplates and the concrete. These results show the shear behavior of 25 mm diameter round bright tie-bars under monotonic loading, but there is no research investigating the shear behavior of tie-bars with different diameters in cyclic loading condition. Natural cyclic loads, such as earthquakes, sea ices and sea waves, can vary the bending moment signs in steel-plate concrete composite structural sections, so the tie-bars and studs at the interface between the steel and the concrete would be subjected to fully reverse cyclic shear forces. Currently, results from the existing literatures on the shear behavior of other shear connectors indicated that shear connectors subjected to fully reversed cyclic loading exhibited lower shear capacities and ductility than those under monotonic loading [16–20]. Meanwhile, the maximum shear slips of the shear studs under cyclic loading in the existing literatures were all far below the ductility criterion of 6 mm stipulated in Eurocode 4 [21]. These experimental results showed that the reduction of shear capacities of studs was significant and varied, and it was affected by some parameters, including the stud diameter, the stud tensile strength, the load procedure, the weld procedure and the tensile force. Pallares and Hajjar [22] reviewed many push-out tests from the past literatures on the shear capacities of studs and proposed 25% reduction in the monotonic shear capacity to account for cyclic loading. The reductions of shear capacity and shear slip of tie-bars subjected to cyclic loading are certain, but they also has not been investigated.

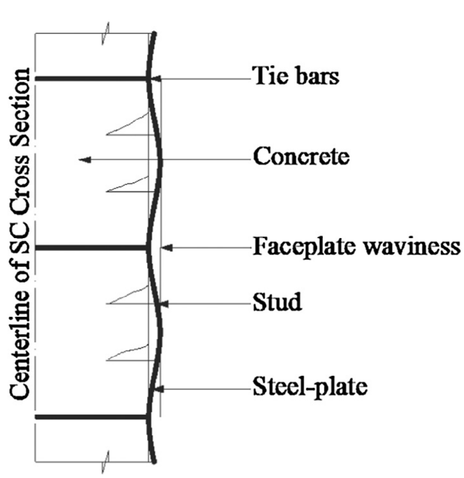

Fig. 1. Faceplate waviness. (The faceplate waviness and the variation in tie-bar dimensions has been exaggerated for illustration purposes.)

Obviously, the tie-bar diameter and strength grade can affect their shear behavior under cyclic loading. The reductions of shear capacity and shear slip of shear connector mean a waste of resources. For increasing the shear capacity of a tie-bar under cyclic loading, one of the most effective methods is to improve the welded joint structural type. It had been determined that different weld procedures could vary the resistances to fracture for studs [23,24]. For tie-bar, the common welded joint structural type is formed by friction stir welding. Civjan and Singh [18] compared the shear capacities of 13 mm diameter studs using stud welding and SMAW-fillet welding. Their results showed that the SMAW-fillet welding did not improve the ultimate shear capacities of studs under cyclic loading, but significantly improved the ultimate shear capacities of the studs under monotonic loading. Researches on the welded joint structural types indicated that the groove fillet welding was better than fillet welding in some cases [25–27]. In addition, tie-bars resist shear at the interface, thus slotting at the faceplate may improve the tie-bar shear capacity. The friction stir welding, the fillet welding, the groove fillet welding and the slotting fillet welding were adopted in this test, in order to investigate the effect of welded joint structural type on the shear behavior of tie-bars under cyclic loading. As