EXPERIMENTAL STUDY ON SHEAR FORCE-SLIP RELATIONSHIP OF HEADED STUD CONNECTORS UNDER CONTROLLED SHEAR AND AXIAL FORCES

Y. TAIRA[1*], S. SAITO[2], T. WATANABE[3], Y. MIZOE[4], H. SHIMA[5],

A. NAKAJIMA[6] and K. FURUICHI[1]

[1]*Civil Structures Group, Technical Research Institute, Kajima Corporation, Japan*
[2] *Department of Civil and Environmental Engineering, Faculty of Engineering, Yamanashi University, Japan*
[3] *Hokubu Consultants Corporation, Japan*
[4] *Engineering Department, Bridge Structure Division, KAWADA Industries*
[5] *Department of Infrastructure Systems Engineering, School of Systems Engineering, Kochi University of Technology*
[6] *Graduate School of Engineering, Utsunomiya University*

ABSTRACT

Headed studs are widely used as shear connectors for various steel-concrete composite structures. In the design of such structures, it is necessary to determine not only the shear capacity but also the shear force-slip relationship of headed studs, both of which are dependent on the loading applied. In standard push-out tests, the actions of axial force and shear force depend on the support condition of concrete blocks of the push-out test specimen. However, the nature of these actions has not yet been clarified. In push-out tests of headed studs, it is therefore important to determine shear capacity and the shear force-slip relationship in consideration of the axial force as well as the shear force acting on studs.

In this study, push-out tests of headed studs were conducted with axial compressive force controlled by using hydraulic jacks, and the shear force-slip relationships of such studs under both shear force and axial compressive force were determined.

Keywords: headed stud connector, push-out test, shear capacity

1. INTRODUCTION

Headed studs are widely used as shear connectors for steel-concrete composite structures, and it is necessary to determine their shear capacity when steel-concrete composite members are designed. Such structures can be designed more rationally in consideration of the shear force-slip relationship.

* Corresponding author and presenter: Email: ytaira@kajima.com

It has been shown that forces acting axially on headed studs affect their shear capacity and shear force-slip relationship (Shima 2011). These design values based on the available experimental results are specified in Standard Specifications for Hybrid Structures (JSCE Committee on Hybrid Structures). However, these formulas do not consider the effects of axial forces acting on studs. In actual structures, studs are simultaneously subjected to the axial tensile force or the axial compressive force as well as the shear force. To evaluate the behavior of the composite structure with studs adequately under various conditions, it is necessary to determine shear force-slip relationships in consideration of the effects of axial forces acting on the stud. However, the performance of headed studs is usually determined via push-out tests of specimens consisting of steel H-beams with welded studs and concrete blocks. In such tests, axial (restraining) force and shear force act at the interfaces between H-beam flanges and concrete blocks because the bottom of the specimen is restrained. In conventional push-out tests, however, such axial forces cannot be identified.

In this study, three push-out tests were conducted using the method proposed by Shima *et al*. (2011), in which the bottom of the concrete block of the specimen is supported with bearings capable of horizontal movement and rotation, and the axial compressive forces acting on the studs were controlled with hydraulic jacks as shown in Figure 1. Figure 1 shows the specimen set-up for testing.

The results were used to examine the effects of these axial forces on the shear capacity and shear force–slip relationship of studs.

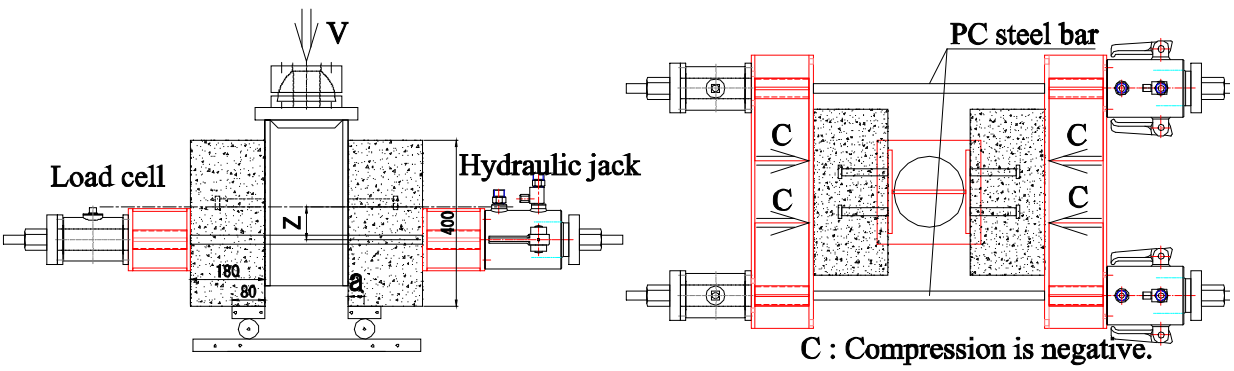

Figure 1: Test set-up

2. EXPERIMENT METHOD

2.1. Specimen Configuration and Test Method

Figure 2 shows the specimen details, which was determined in accordance with the Push-out Test Method for Headed Stud Shear Connectors (JSSC) and was identical to that adopted by Shima (2011). Four headed studs with the shank diameter of 19 mm and their height of 120 mm were welded to each steel H-beam. Table 1 shows the stud dimensions and strength. As mentioned above, in the push-out test method the concrete block of the specimen is supported with bearings capable

of horizontal movement and rotation. In the standard test method, mortar is placed between the concrete blocks and the reaction floor for flatness adjustment. In push-out test method, a bending moment causes opening along the lower parts of the concrete blocks due to the difference between the locations at which shear force and reaction force act (Figure 3). When this occurs, the concrete blocks are restrained horizontally by the friction force arising between them and the reaction floor, and axial compressive force acts at the steel-concrete interface.

However, this force cannot be identified. Against such a background, restraining force in the horizontal direction was eliminated in this study using the bearings mentioned above. Further, in order to cancel out the bending moment discussed here, axial compressive force was applied to the specimen using hydraulic jacks to tension (i.e., pull) prestressing bars placed on both sides of it.

Unidirectional incremental cyclic loading was applied, and unloading was carried out during the loading process to check residual displacement (slip).

The quantities measured were the applied load (shear force) and axial compressive force, the lateral slip and opening between the H-beam and the concrete block, and the axial strain at a distance of 30 mm from the head of the stud.

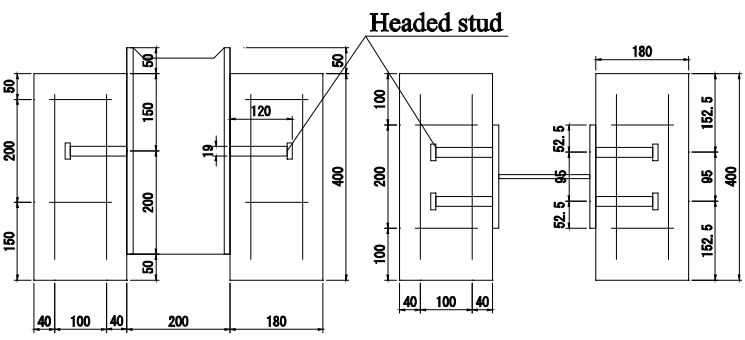

Figure 2: Specimen details

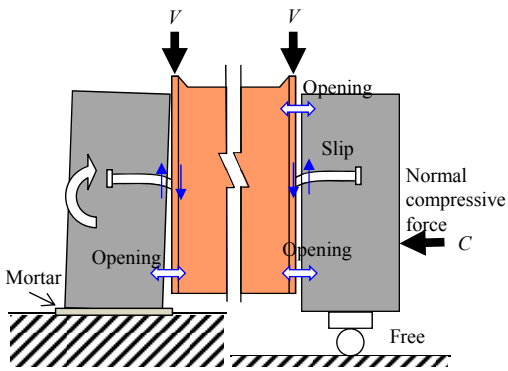

Figure 3: Specimen deformation during the test

Table 1: Dimensions and strength of headed studs

Diameter mm	Height mm	Head diameter mm	Head thickness mm	Yield strength N/mm^2	Tensile strength N/mm^2
19	120	32	10	373	496

2.2. Experimental Factor

The main experimental factor is the axial compressive force applied to the studs, and three test specimens were used (Table 1). In the loading of Specimens 1 and 3, the axial compressive force

(C) per stud corresponding to the shear force (V) acting on each stud was applied simultaneously and proportionally. In the loading of Specimen 2, a predetermined amount of axial compressive force was applied in advance, and shear force was applied while keeping the axial compressive force constant. The amount of axial compressive force applied was the same as that acting under the maximum shear force in the test on Specimen 1. Figure 4 shows the relationship between the shear force and axial compressive force applied to each specimen. Table 2 shows the measured compressive strength of concrete.

Table 2: Specimen properties

Specimen	External normal force C (kN) per stud	Position of jack z (mm)	Position of support a (mm)	Concrete strength f'c (N/mm^2)
1	-V	90	90	24.5
2	-180	40	0	28.2
3	-0.5 V	40	80	29.2

*V : shear force

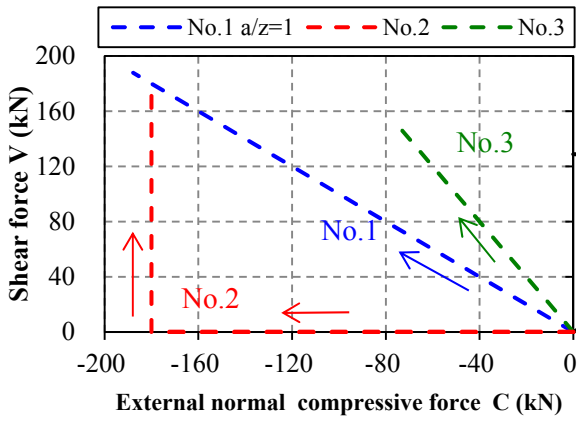

Figure 4: V-C relationship

3. EXPERIMENTAL RESULTS

3.1. Shear Force–Slip Relationship

Figure 5 shows the shear force (V_{ss})-slip (δ_{ss}) relationship of each specimen, and Figure 6 shows the same with slip on an enlarged scale. The vertical axis is the shear force figures per-stud values obtained by dividing the applied load by the number of studs.

In all specimens, stiffness decreased as shear force increased, and shear force was maximized when the lateral slip was between 5 and 7 mm. The degree of change in stiffness varied from specimen to specimen. Comparison of Specimen 1 and Specimen 3, both of which were subjected to axial

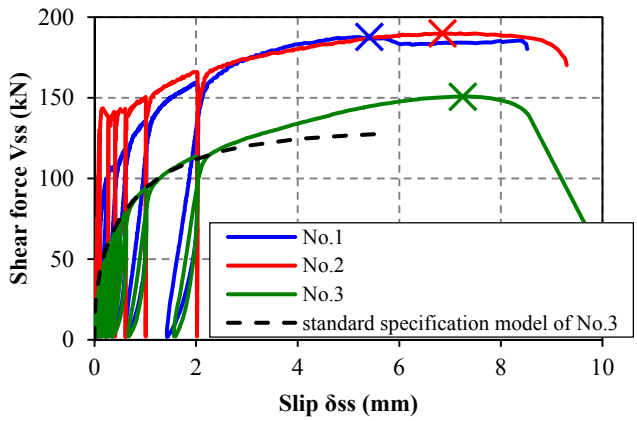

Figure 5: V-δ relationships of specimens

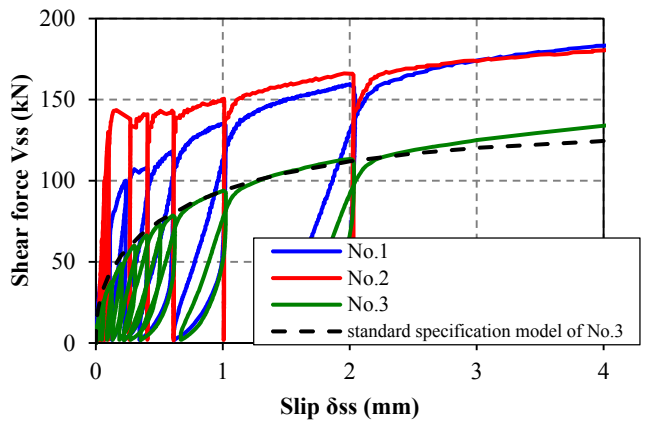

Figure 6: V-δ relationships of specimens

compressive force increasing in proportion to shear force, revealed that Specimen 1, for which the ratio of axial compressive force to shear force was higher than that for Specimen 3, showed higher initial stiffness. Specimen 2, to which axial compressive force was applied prior to shear force, had high initial stiffness and underwent little slip until shear force reached about 150 kN. This is presumably due to the friction force acting along the interface between the H-beam flange and the concrete block.

The unloading curves show that lateral slip decreased with shear force in Specimen 1 and 3, while pre- and post-unloading lateral slip in Specimen 2 showed little difference. This is also thought to have been because friction force was large relative to the restoring force of the studs.

3.2. Shear Capacity and Failure Mode

The measured shear capacities of the specimens were compared with values calculated using the equations provided in the Standard Specifications for Hybrid Structures:

$$V_{ssu} = min(V_{ssu1}, V_{ssu2}) \tag{1}$$

$$V_{ssu1} = 31A_{ss}\sqrt{\frac{h_{ss}}{d_{ss}}f'_c} + 100 \tag{2}$$

$$V_{ssu2} = A_{ss}f_{su} \tag{3}$$

where V_{ssu} is the shear capacity of a headed stud, A_{ss} is the cross-sectional area of the stud shank, h_{ss} is the stud height, d_{ss} is the stud shank diameter, f'_c is the compressive strength of concrete, and f_{su} is the tensile strength of a stud.

Table 3 shows the measured and calculated values for each specimen. Specimen 1 and Specimen 2 had similar shear capacities, indicating that the value stays the same if axial compressive force remains unchanged, regardless of axial compressive force or shear force history. The measured values were larger than the calculated values by a factor of more than 1.5. In Specimen 3, in which axial compressive force was small relative to shear force, the measured value was greater than the calculated value by a factor of 1.18, but the difference was smaller than that in Specimen 1 and Specimen 2.

3.3. Residual Slip

In considering the serviceability limit state of structural members joined with shear connectors, it is necessary to ensure that excessive residual displacement does not occur and to check such displacement as part of stud performance evaluation. Figure 7 shows the relationship between experimentally determined pre-unloading slip (δ_{ss}) and post-unloading slip (δ_{ssr}) as well as the calculation results obtained from the equations provided in the Standard Specifications for Hybrid Structures.

Specimen 1 and Specimen 3, both of which were subjected to proportionally applied shear force and axial compressive force, produced similar results. In contrast, Specimen 2 showed residual slip values greater than those of Specimen 1 and Specimen 3. The pre-unloading slip values and residual slip values showed little difference, and the ratio between them was roughly 1:1 regardless of slip magnitude. Comparison with the Specification Model shows that the values for Specimen 2 as well as those for Specimen 1 and Specimen 3 were somewhat greater than the calculated values. This is presumably because the axial compressive forces applied in this experiment were greater than those in the experiment conducted by Shima and Watanabe (2008) for the development of the Specification Model. Shima and Watanabe reported that compressive stress values obtained by dividing axial compressive force by the cross-sectional area of the stud were used as an indicator, and that the values thus determined for a total of six specimens were 70 to 125 N/mm^2. In the experiment conducted in the study reported here, compressive stress was 670 N/mm^2 in Specimen 2, which was subjected to axial compressive stress prior to loading.

It was thus found that when large axial compressive force relative to the shear force applied keeps acting, stiffness is high and slip is small under shear force, but any slip that has occurred remains.

3.4. Opening

Figure 8 shows the opening between an H-beam flange and a concrete block. The vertical axis shows shear force normalized by shear capacity. It can be seen that the opening at the top changed very little in Specimen 1 until the end of the test. In the other regions and specimens, however, the opening grew as shear force increased. In Specimen 3, in which axial compressive forces were relatively small, the opening began to increase gradually after the shear force/shear capacity ratio exceeded 0.4. In Specimen 1, in which axial compressive forces were relatively large, the opening began to grow gradually after the ratio exceeded 0.6, while in Specimen 2 it grew considerably after the ratio reached 0.7. These observations were consistent with the slip changes seen.

3.5. Stud Strain

Figure 9 shows the relationship between stud head strain and lateral slip. It can be seen that strain increased with slip, and the three specimens show similar curves. In Specimen 2, compressive strain

Table 3: Shear capacity

Specimen	Exp. (kN)	Cal. (kN)		Exp. / Cal
		Eq. (2)	Eq. (3)	
1	187.8	120.0	145.0	1.57
2	190.0	125.2	145.0	1.52
3	150.7	127.2	145.0	1.18

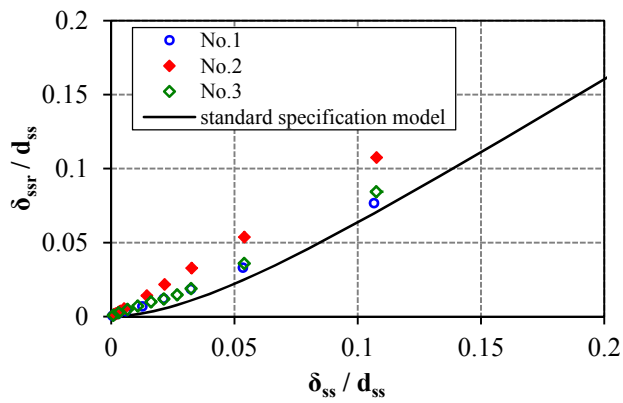

Figure 7: δ_{ssr}-δ_{ss} relationships of specimens

occurred because of the initially introduced axial compressive force, but the strain level was similar to those of the other specimens when the slip was about 0.4 mm. The maximum values of tensile strain ranged from 360 to 480 μ, while the maximum values of yield strain were considerably smaller. This is because these are values of strain occurring near stud heads. Strain decreased just before failure, presumably because the lower part of the stud yielded.

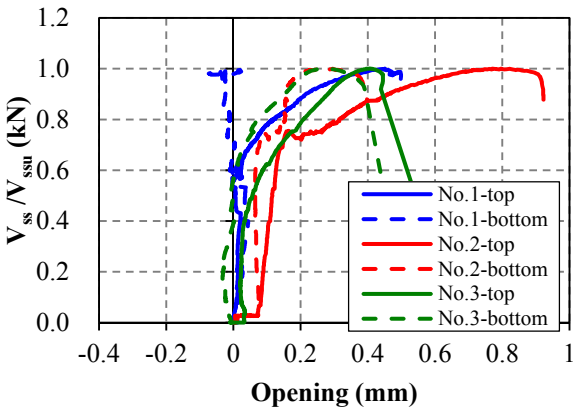

Figure 8: V_{ssr}/V_{ssu} - opening relationships of specimens

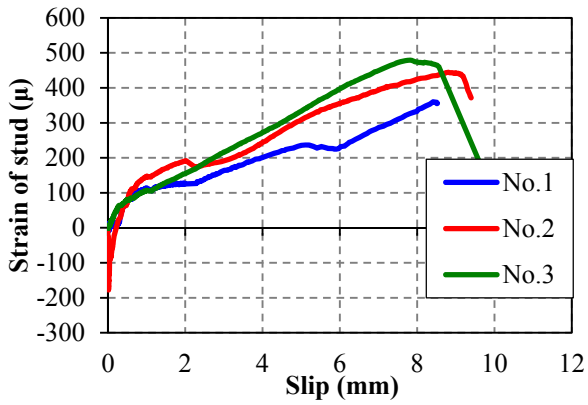

Figure 9: Strain -slip relationships of specimens

3.6. Comparison with Calculated Values (Shear Force–Slip Relationship)

The curves showing the calculated values obtained using the equations shown below, which are provided in the Standard Specifications for Hybrid Structures, were compared with the measured values. Figure 5 also shows the calculation results by the black dashed line. As these equations do not allow for the effects of axial compressive force, using them for calculation in regard to the three specimens reflects only differences in the compressive strength of concrete. Consequently, the results obtained are almost the same. Figure 5 therefore shows values calculated using the compressive strength of Specimen 3.

$$V_{ss} = V_{ssu}\left(1 - e^{-\alpha\delta_{ss}/d_{ss}}\right)^{\beta} \tag{4}$$

$$\delta_{ssu} = 0.3d_{ss} \tag{5}$$

$$\alpha = 11.5(f'_c/f'_{c0})\{1.1(\eta - 1)^2 + 1\} \tag{6}$$

$$\eta = V_{ssu1}/V_{ssu2} \tag{7}$$

where V_{ss} is the shear force acting on the headed stud, δ_{ss} is the lateral slip, δ_{ssu} is the ultimate lateral slip, $\beta = 0.4$; and $f'_{c0} = 30$ (N/mm^2) .

The curve for Specimen 3 shows close agreement with the calculated values until lateral slip reached 2 mm. This suggests that the relationship between axial compressive force and shear force

in the experiment conducted to derive the formula may have been practically the same as the relationship for Specimen 3.

4. CONCLUSIONS

A series of push-out tests was conducted on three specimens subjected to varied axial compressive forces to investigate the effects of axial compressive forces acting on headed studs. The results showed that shear capacity increases with axial compressive force, and the measured values were greater than the calculated values obtained using the equations provided in the Standard Specifications for Hybrid Structures. When axial compressive force was applied in proportion to shear force and shear force was applied with constant axial compressive force, similar values were obtained from maximum shear force-axial compressive force combinations, and shear capacity was determined by the magnitude of axial compressive force regardless of loading history. Similarly, in the shear force-lateral slip relationship, stiffness increased with axial compressive force, and differences in slip were small when shear force was the same. However, when axial compressive force was large, slip did not return after unloading, resulting in large residual slip displacement.

As both the shear capacity and the shear force-slip relationship outcomes differed from the Specification Model results, it is necessary to use shear capacity and shear force-slip relationship values corresponding to the state of loads acting on studs.

5. ACKNOWLEDGMENTS

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