



HOKKAIDO UNIVERSITY

Title	MECHANICAL BEHAVIOR OF STUD SHEAR CONNECTOR UNDER SUSTAINED SHEAR AND COMPRESSION FORCES
Author(s)	MAKI, T.; WATANABE, R.
Description	The Thirteenth East Asia-Pacific Conference on Structural Engineering and Construction (EASEC-13), September 11-13, 2013, Sapporo, Japan.
Relation	Proceedings of the Thirteenth East Asia-Pacific Conference on Structural Engineering and Construction (EASEC-13), September 11-13, 2013, Sapporo, Japan, E-4-5.
Citation	Proceedings of the Thirteenth East Asia-Pacific Conference on Structural Engineering and Construction (EASEC-13), E-4-5
Issue Date	2013-09-12
Doc URL	https://hdl.handle.net/2115/54359
Type	conference paper
File Information	easec13-E-4-5.pdf



MECHANICAL BEHAVIOR OF STUD SHEAR CONNECTOR UNDER SUSTAINED SHEAR AND COMPRESSION FORCES

T. MAKI^{1*†}, and R. WATANABE¹

¹ *Graduate School of Science and Engineering, Saitama University, Japan*

ABSTRACT

Push-out shear test of stud shear connector specimens, subjected to sustained shear and compression forces in advance, were conducted and the influence of the sustained forces on shear force-slip displacement relationship was examined. Slip displacement drastically increased due to sustained shear force for 30days, which corresponds to 30% and 60% of shear capacity. However, residual slip displacement after unloading seemed to be uniquely governed by the experienced maximum slip displacement even under sustained shear force. The influence of instantaneous and sustained compression forces corresponding to 30% and 45% of compression capacity of concrete blocks was also examined on shear force-slip relationships. It was clarified that compression force to concrete block influenced on the shape of hysteresis curves, in addition to increase residual slip displacement of the stud connector, regardless of the time duration of applied compression force.

Keywords: Stud shear connector, shear force-slip relationship, sustained load, push-out test.

1. INTRODUCTION

Stud shear connector is one of the popular techniques to be used in the joint connection between concrete and steel members, such as the connection between steel girder and concrete pier, or between prestressed concrete girder and steel girder. Although the shear force-slip relationship of stud shear connector has been widely examined and formulated (Ollgaard et al 1971), slip displacement at shear connector has not been considered in the current design of steel-concrete hybrid structures and nominal design shear force carried by the connector are limited less than 50% of its shear capacity. Thus, the influence of sustained external loads is neither considered because of its low design shear force level and has not been fully studied. However, the applied shear force to the connector in the actual structure is not explicit and the excessive shear force, if any, may result in the additional long-term deformation of the structures.

The objective of this paper is to clarify the influences of sustained shear force to steel girder and of instantaneous/sustained compression force to concrete block on shear force-slip displacement relationships of stud shear connectors.

* Corresponding author: Email: maki@mail.saitama-u.ac.jp

† Presenter: Email: maki@mail.saitama-u.ac.jp

2. PUSH-OUT TEST OF STUD SHEAR CONNECTOR

2.1. Test Specimens and Materials

Figure 1 shows a schematic view of the specimen used in the test. Two $\phi 19$ mm headed studs of 120mm length were welded on both flanges of steel girder (H-200x200x8x12) and the girder was connected to two concrete blocks of 150x300x400mm. The cover thickness of concrete from the top of stud to concrete surface was 30mm. The specimen was designed to fail not due to breaking of stud but due to concrete failure. The direction of concrete placement was in the axial direction of studs, thus, two concrete blocks were individually manufactured on T-shape girders with studs welded on the flange and then the webs of two T-shape girders were welded to each other.

$\phi 10$ mm and $\phi 6$ mm deformed bars were arranged in the concrete blocks as longitudinal and lateral reinforcements, respectively. Two $\phi 32$ mm polyvinyl chloride (PVC) pipes were arranged in each concrete block for subsequent application of compression forces to the blocks through PC tendons. The specimens having completely same configurations were used throughout all test cases.

High-early Portland cement was used for concrete production. Water to cement ratio (W/C) was 53.5% and maximum gravel size was 20mm. Measured value of slump was 12cm. Compressive strength of hardened concrete at the date of first loading (cured for 52 days) was 43.9MPa. High strength headed stud (SM570), having Young's modulus of 196GPa, yield strength (0.2% offset) of 500MPa and tensile strength of 623MPa, was used in the specimens.

2.2. Test Parameters, Loading and Measurement

In this experiment, totally seven specimens were tested as summarized in **Table 1**. Test parameters were sustained shear and compression force levels. Sustained shear force levels were 30% and 60%

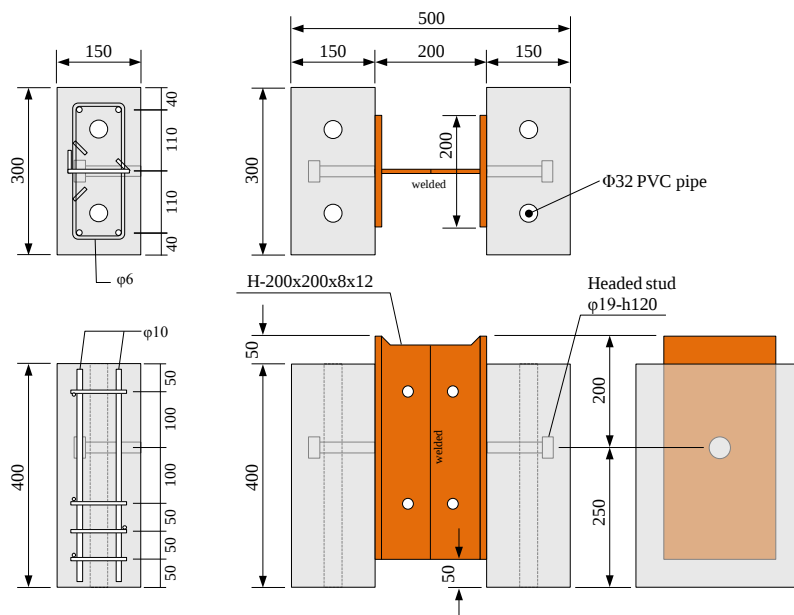


Figure 1: Configuration of Test Specimen

of the calculated shear capacity of the specimen for the cases A3-L and A6-L, respectively. Applied compression force levels were 30% and 45% of the calculated compression capacity of the concrete block in B3-S (instantaneous) / B3-L (sustained) and B6-S (instantaneous) / B6-L (sustained), respectively. The time duration of sustained load was about one month in the four cases under sustained loads (denoted as “-L”). The calculated values of shear capacity for $f'_c = 43.9$ MPa (52days) and 50.1MPa (93days) using equations (1), (2) and (3) (JSCE 2009) are also tabulated in **Table 1**. The test specimen was designed such that the capacity was determined by equation (2).

$$V_{su} = \min(V_{su1}, V_{su2}) \quad (1)$$

$$V_{su1} = 31A_{ss} \sqrt{\frac{h_{ss}}{d_{ss}}} f'_c + 10000 \quad (\text{N}) \quad (2)$$

$$V_{su2} = A_{ss} f_{su} \quad (\text{N}) \quad (3)$$

where, V_{su} : shear capacity (N), A_{ss} : cross sectional area of stud (mm^2), h_{ss} : height of stud (mm), d_{ss} : diameter in cross section of stud (mm), f'_c : compressive strength of concrete (MPa), and f_{su} : tensile strength of stud (MPa).

Figure 2 shows the loading apparatus in the test. Specimens were fixed to the steel base block using cement paste and shear (push-out) force was applied to the specimens through $\phi 17$ PC bars and two 350kN center-hole jacks. For B-series, prior to the final push-out loading, compression force was introduced to concrete blocks through $\phi 26$ PC bars with the help of 500kN center-hole jack. In the push-out loading, the specimens were unloaded by every 10% of the calculated shear capacity.

The applied loads were measured by load cells as shown in **Figure 2**, and these values were checked through the PC bar strain (multiplied by cross sectional area and Young’s modulus). Slip displacement at stud location was measured at both sides of steel girder using displacement transducers. In addition, axial strain in stud, vertical strain at flange of girder and vertical/horizontal strain at the surface of concrete block were measured through strain gauges.

Table 1: Test cases

Case	Pre-loading			Age at Final Shear (push-out) Loading (days)	Compressive Strength ^{*3} f'_c (MPa)	Shear Capacity V_{su} (kN)	
	Type	Level (%)	Duration (days)			Calculated	Measured
A0-S	-	-	-	52	43.9	156.4	165.0
A3-L	Shear (push-out)	30 ^{*1}	31	89	50.1	166.3	142.0
A6-L	Shear (push-out)	60 ^{*1}	31	89	50.1	166.3	150.5
B3-S	Compression	30 ^{*2}	-	54	43.9	156.4	158.0
B6-S	Compression	45 ^{*2}	-	57	43.9	156.4	127.2
B3-L	Compression	30 ^{*2}	29	92	50.1	166.3	103.8
B6-L	Compression	45 ^{*2}	28	92	50.1	166.3	181.6
NOTE							
*1 Percentage of calculated shear capacity of the specimen at 52days							
*2 Percentage of calculated compression capacity of the concrete block at 52days							
*3 Measured at around the time of final loading							

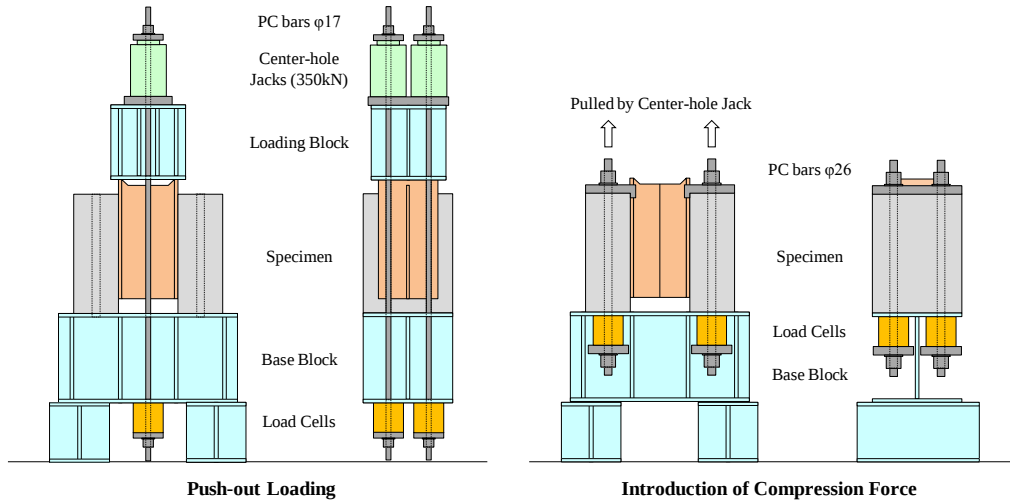


Figure 2: Loading Apparatus

2.3. Shrinkage and Creep Test of Concrete

Shrinkage strain in concrete had been measured using mold gauges embedded in the prism specimens (100x100x400mm) since the next day of concrete placing until the end of final loading tests. The measured values of shrinkage strain were 230μ , 327μ and 458μ at 51, 65 and 93days, respectively. Furthermore, creep strain in concrete cylinders ($\phi 100 \times 200$ mm) was also measured for a month under sustained compressive stress at 30% and 60% of compressive strength at 51days (43.9MPa). The measured values of creep strain for 30days were 466μ and 854μ , respectively. Note that these values of creep strain also contain shrinkage strain because the cylinders under sustained load were not sealed. Compressive strength, Young's modulus and the strain at peak stress (creep strain was excluded) of the cylinders under sustained load were almost same as those measured at 93days in the cylinders without sustained load. The average environmental temperature and relative humidity during the above measurement were 8.6°C and 57.4%, respectively.

3. TEST RESULTS

3.1. Processing of Measured Data

Figure 3(a) shows the shear force-slip displacement hysteresis curve of A0-S specimen. Here, shear force was assumed as a half of the applied load, and the slip displacement was the averaged value of the measured slip displacements at four points. A set of maximum shear force and slip displacement in each loading cycle was picked up from this result and plotted in **Figure 3(b)** as envelope curve. Residual slip displacement was defined as a displacement when the applied load was removed in each cycle. The residual slip displacement in each cycle was also plotted as shown in **Figure 3(c)**. Similar way of data processing was also applied to the results in all test cases. The black break lines in **Figure 3** show the existing model proposed by Shima et al. 2008 for the compressive strength of 43.9MPa (52days), as has been formulated by the following equations (4), (5) and (6):

$$V = V_{su} \{1 - \exp(-\alpha \delta / \phi)\}^{2/5} \quad (4)$$

$$\alpha = 11.5 \{1.1(\gamma - 1)^2 + 1\} f'_c / 30 \quad (5)$$

$$\delta_p = \delta - 0.04\phi \{1 - \exp(-24\delta / \phi)\} \quad (6)$$

where, V : shear force (N), V_{su} : shear capacity (N), δ : slip displacement (mm), ϕ : diameter of stud (mm), f'_c : compressive strength of concrete (MPa), $\gamma = V_{su2} / V_{su1}$: capacity ratio, δ_p : residual slip displacement (mm).

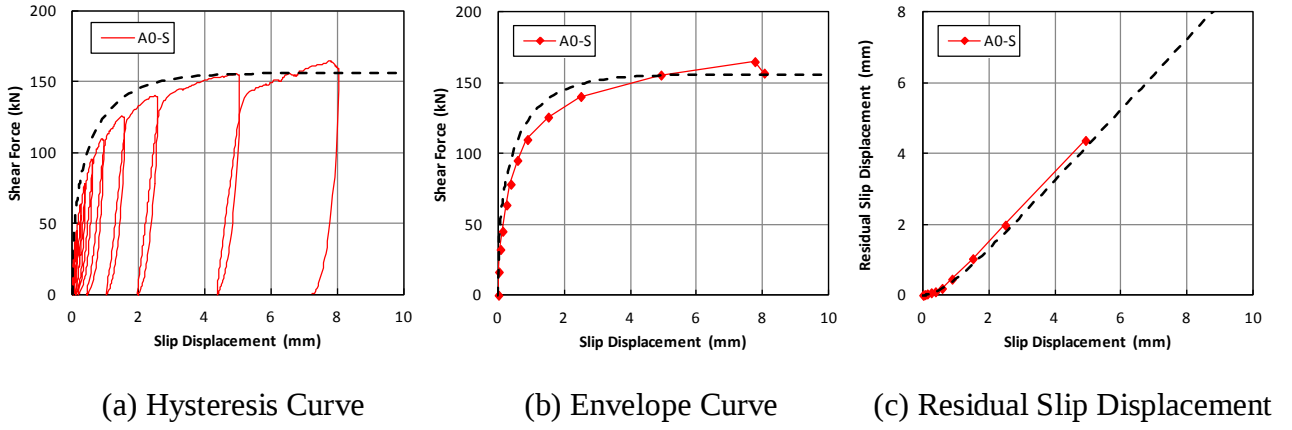


Figure 3: Shear Force-Slip Displacement Relationship (A0-S)

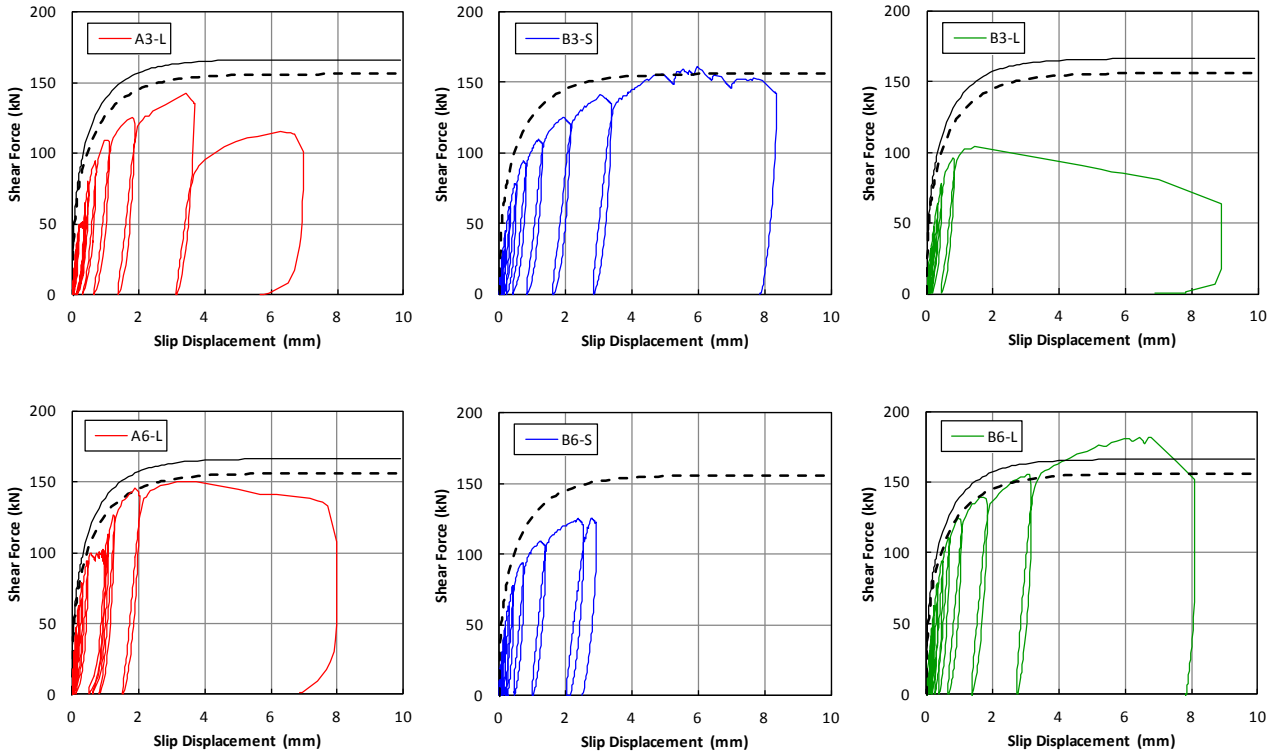


Figure 4: Measured Shear Force-Slip Displacement Relationships (other cases)

Figure 4 shows the measured shear force-slip relationships in all the other test cases. Here, the figures for the sustained load cases include the black solid line, which is given by the equations (4) and (5) with the compressive strength of 50.1MPa (93days). The maximum shear force in each case was scattered due to the rotation of steel girders during push-out loading, because the specimen had only one stud in one side of the specimen. Thus, the push-out shear capacity was excluded from the discussion in this paper.

3.2. Influence of Sustained Push-out Shear Force

Figure 5 shows the close-up view of shear force-slip displacement relationships of A-series specimens. The sustained shear force was about 50kN and 100kN in A3-L and A6-L, respectively. The increase in the slip displacement, which might be due to the creep deformation of the concrete around the studs, was clearly observed in both cases during the 31days under the sustained loads.

Figure 6 shows the envelope curves and the variations of residual slip displacement in the three cases. A slight recover in the stiffness just after the slip displacement increase due to sustained loads could be observed in A3-L and A6-L. However, the increase in the slip displacement and in the stiffness do not influence on the residual slip displacement variation. The residual slip displacement is governed only by the experienced maximum slip displacement in each cycle even under sustained shear force, and it follows the unique variation formulated by the equation (6).

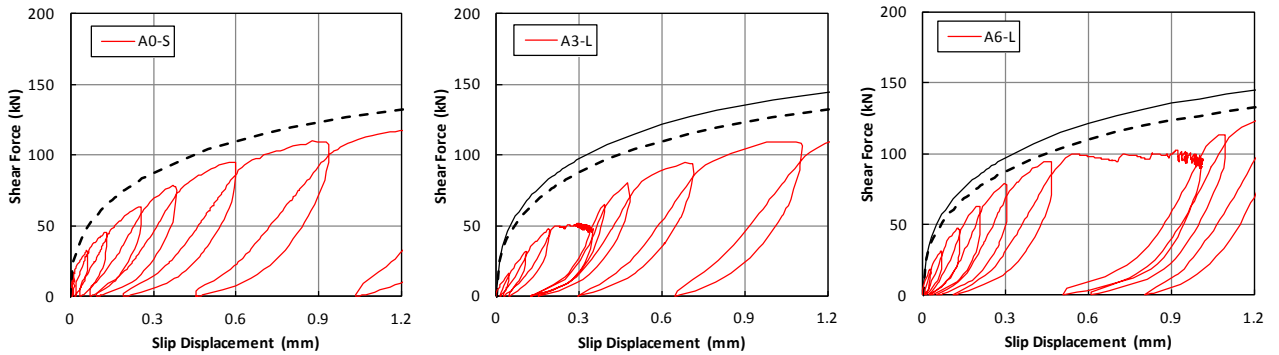


Figure 5: Close-up View of Shear Force-Slip Displacement Relationships (A-series)

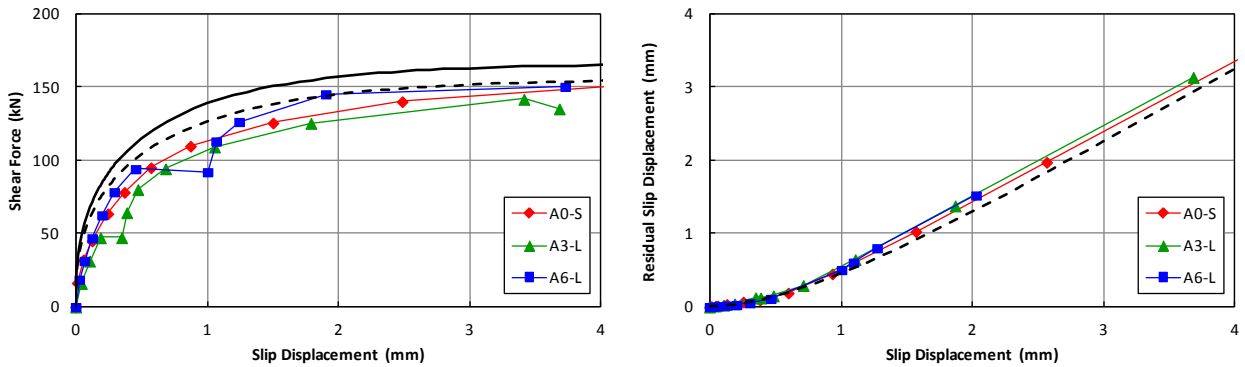


Figure 6: Envelope Curves and Variations of Residual Slip Displacement (A-series)

3.3. Influence of Instantaneous and Sustained Compression Forces

Figure 7 shows the close-up view of shear force-slip displacement relationships in B-S series (under instantaneous compression forces). The measured axial strain of stud just before the push-out loading was about 60μ and 120μ in B3-S and B6-S, respectively. This indicates the existence of normal stress from concrete block to flange surface because the lateral expansion of concrete due to the applied compression forces was confined by the stud. Thus, frictional stress at the flange surface during push-out loading was considered to be different in these cases.

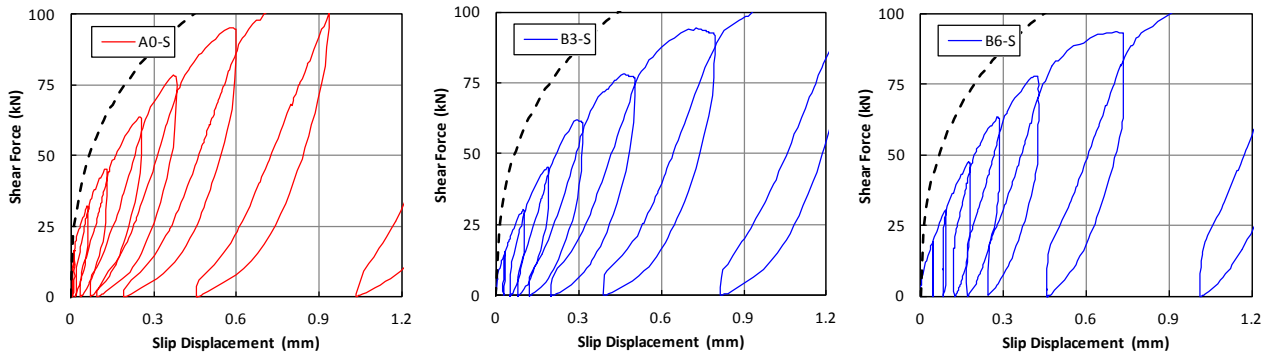


Figure 7: Close-up View of Shear Force-Slip Displacement Hysteresis Curves (B-S series)

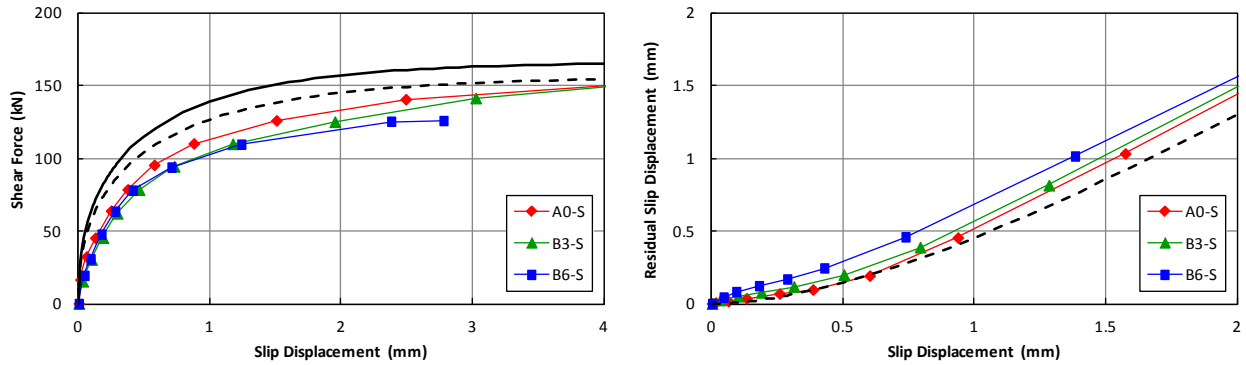


Figure 8: Envelope Curves and Variations of Residual Slip Displacement (B-S series)

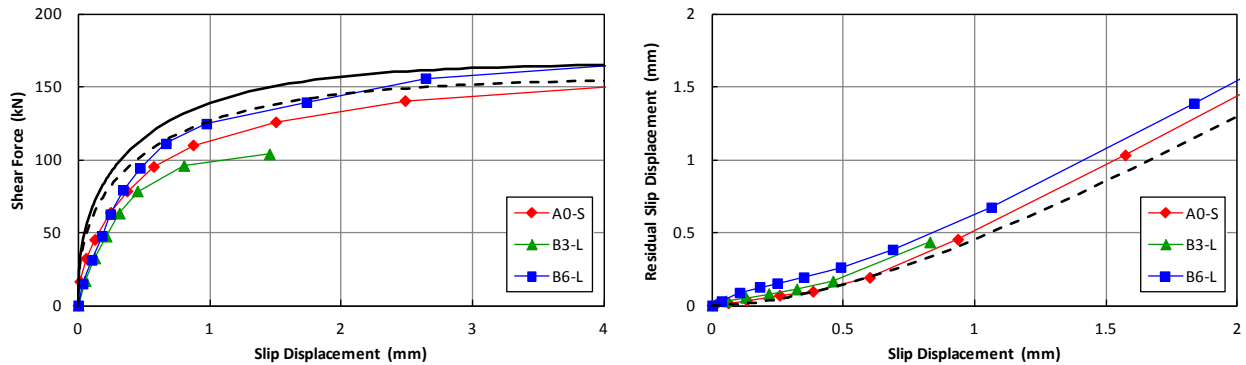


Figure 9: Envelope Curves and Variations of Residual Slip Displacement (B-L series)

The reloading stiffness in each cycle was very high in B3-S and B6-S up to a certain level of shear force (approximately 8kN in B3-S, and 15kN in B6-S). It is known that similar shape of hysteresis curves can be observed in the hysteretic behavior of the material having frictional damping. That is to say, when the applied shear force was zero in unloading process, the restoring force of stud was equalized to the negative frictional force between concrete and flange surface. This remaining negative frictional force was released during the initial stage of reloading process with no or very small increment in the slip displacement, resulting in the high reloading stiffness. Similar behavior could also be observed in B3-L and B6-L.

Figure 8 and **Figure 9** show the envelope curves and the variations of residual slip displacement in B-S and B-L series, respectively. Regardless of the applied shear force level, both in B-S and B-L series, the higher the applied compression force, the larger the residual slip displacement. This tendency might also be due to the existence of frictional stress between concrete and steel flange. When no compression force is applied, the restoring force of stud is canceled by relatively low negative frictional force. However, under a certain level of compression force, the slip displacement returns to the displacement where the restoring force of stud is equalized to the negative frictional force, resulting in the relatively large residual displacement.

4. CONCLUSIONS

Sustained shear (push-out) force increases slip displacement of stud shear connector with the increase in the applied shear force level. However, the relationship between maximum experienced slip displacement and residual displacement after unloading is not influenced by the increase in the slip displacement due to the sustained force.

Compression force to the concrete block prior to the application of shear (push-out) force seems to increase residual slip displacement after unloading, regardless of its duration time of application. It may be because of the increase in the negative frictional force at the interface between concrete and steel flange due to the lateral confining pressure induced by the tensile force in the studs. No clear influence of sustained compression force to the concrete block on shear force-slip displacement relationship can be observed.

REFERENCES

- Ollgaard, J., Roger, R. and Fisher, J. (1971). Shear strength of stud connectors in lightweight and normal-weight concrete, AISC Engineering Journal. April, pp.55-64.
- Japan Society of Civil Engineers (JSCE) (2009). Standard Specifications for Hybrid Structures -2009. Japan Society of Civil Engineers. (in Japanese)
- Shima, H. and Watanabe, S. (2008). Formulation for load-slip relationships of headed stud connector, Doboku Gakkai Ronbunshuu A (Journal of JSCE), 64(4), pp.935-947. (in Japanese)
- Shima, H. and Watanabe, S. (2010). Formulation for load-slip relationships of headed stud connector, Proceedings of the 34th IABSE International Symposium on Bridge and Structural Engineering, Venice, 2010, pp.630-631.