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INFLUENCE OF BOUNDARY CONDITION TO PUSH-OUT TEST OF HEADED STUD SHEAR CONNECTOR

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ABSTRACT

The accurate prediction formula for the shear force-slip curves is required that can consider the multi directional stress state in actual structures. The push-out test used as the standard method to get load-slip curves of headed stud shear connectors provides unclear force conditions of studs because the rotation of concrete blocks in the specimen is restrained by floor supports. In this study push-out tests are conducted under boundary conditions using roller supports or restraint bars. Test results under these conditions show horizontal and diagonal cracks and the brittle failure. Using restraint bars shows no brittle failure and similar load-slip curves to the condition using floor supports. Failure behaviors under conditions using roller support and restraint bars are discussed.

Keywords: Headed stud shear connector, push-out, crack, boundary condition.

1. INTRODUCTION

Because shear connectors are a key of the structural performance of steel-concrete composite structures, it is important for the design verification to grasp the dynamic behavior of shear connectors. Combinations of the axial force and the shear force act on headed shear connectors in practical structure. Therefore, the accurate verification requires the dynamic behavior under clear force conditions. The push-out test (**Figure 1**) is a standard method to get load-slip curves of headed stud shear connectors, which are ones of shear connectors widely used. A problem of the current push-out test is that the rotation of concrete blocks is strongly restrained by floor supports. This boundary condition gives unclear conditions of forces acting studs and a possibility to overestimate the shear strength of the stud depending on actual situations where studs are used. In this study, push-out tests with two kinds of boundary conditions are conducted to investigate an influence of the boundary conditions to the shear behavior of stud shear connectors.

2. OUTLINE OF PUSH OUT TEST

2.1. Test specimen

Shape and size of all test specimens displayed in **Figure 2** were same as specimens of the previous experiment (Shima and Watanabe 2008) that was based on the draft of push-out test method of

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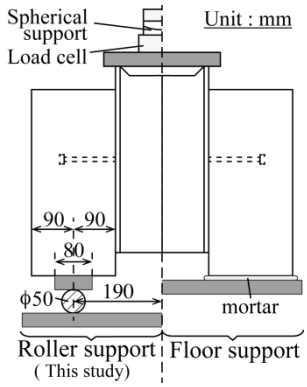


Figure 1: Test setup

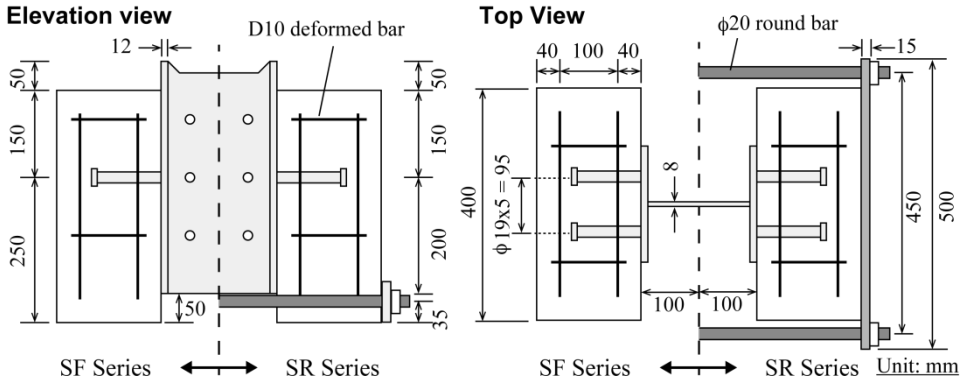


Figure 2: Shape and size of test specimen

headed stud shear connector developed by Japanese society of steel construction (JSSC 1996). Two studs were welded on a flange of a T shaped steel. Then T shaped steels were welded after casting of concrete to be the H shaped steel. Concrete was casted in the parallel direction to the stud axis to reduce an influence of the bleeding. Headed stud shear connectors used in this study apply to the normal strength class specified in JIS B 1198. Properties of the stud are shown in **Table1**.

Two boundary conditions were prepared in this study. Conditions of all test specimens are shown in **Table 2**. All tests were conducted under the roller support condition (**Figure 3**). This condition gives no restraint to concrete brocks because blocks rotate and displace outwards freely and the equilibrium of forces acting on the concrete block provides clear force conditions. Specimens of series SR have round bars connecting bottom parts of two concrete blocks (**Figure 2**). This condition can provide the restriction of the rotation and the horizontal displacement depending on the spec of round bars keeping clear force condition. Specimens of series SF have no restraint bars.

The concrete compressive strength is also a parameter. Each series contains the lower compressive

Table 1: Property of headed stud

Specimen	Diameter [mm]	Height [mm]	Diameter of head [mm]	Thickness of head [mm]	Tensile strength [N/mm^2]	Yield strength [N/mm^2]
SFL	18.9	120	32.0	10.5	451	346
SFH, SRL, SRH	18.9	120	32.0	10.5	450	345
19-120-437-31, 53	19.0	120	32.0	10.0	437	326

Table 2: Specimen properties and test results

Specimen	Restraint condition	f_c' [N/mm^2]	Calculated shear capacity			Test results		Failure mode
			$V_{su\text{-}c}$ [kN]	$V_{su\text{-}s}$ [kN]	V_{su} [kN]	$V_{su\text{-}exp}$ [kN]	$\delta_{su\text{-}exp}$ [kN]	
SFL1	Free	29.4	129.0	126.5	126.5	75.3	0.54	Concrete
SFL2	Free	28.6	131.5	126.5	126.5	75.6	0.49	Concrete
SFH1	Free	53.8	175.4	126.2	126.2	101.4	1.98	Concrete
SFH2	Free	53.6	175.1	126.2	126.2	88.0	1.11	Concrete
SRL	Restraint bar	27.8	128.9	126.2	126.2	142.0	12.92	Stud
SRH	Restraint bar	54.9	177.0	126.2	126.2	147.3	8.47	Stud
19-120-437-31	Rotation	31.4	133.8	123.9	123.9	118.5	10.00	Stud
19-120-437-53	Rotation	52.5	170.0	123.9	123.9	139.8	11.55	Stud

strength, 30N/mm^2 and the higher compressive strength, 50N/mm^2. "L" is added at the end of specimen name when the specimen has the lower strength concrete. "H" is added in the case of the higher strength. The specimen 19-120-437-31 and 19-120-437-53 are specimen in the previous study (Shima and Watanabe 2008). Test condition of these specimens is almost equal to specimens in this study except the boundary condition. These specimens were put on a bed of the testing machine. Cement paste was laid between concrete blocks and the bed as shown in **Figure 1**. Therefore concrete blocks of these specimens are restrained to displace in horizontal direction by the friction and to rotate by the floor. Test results of these specimens are referenced in this study as the result of the boundary condition of the friction and the rotation restraint by floor supports.

Predicted shear capacities are also displayed in **Table 1**. Following equations presented in JSCE standards (JSCE 2002, JSCE 2007) were used for prediction.

$$V_{su\_c} = 31 A_{ss} \sqrt{f_c' \, h_{ss} / d_{ss}} + 10000 \quad \text{[N]} \tag{1}$$

$$V_{su\_s} = A_{ss} f_{su} \quad \text{[N]} \tag{2}$$

Where, V_{su_c} is the shear capacity of a headed stud shear connecter decided by the interaction between concrete and the stud (Hiragi et al 1989). V_{su_s} is the shear capacity of the connecter decided by the stud strength. A_{ss} is the stud cross sectional area [mm^2]. h_{ss} is the stud height [mm]. d_{ss} is the stud diameter [mm]. f_{su} is the stud tensile strength [N/mm^2]. f_c' is the concrete cylinder strength [N/mm^2].

The standards decide that the larger value of **Eq.1** and **Eq.2** is the shear capacity of the stud shear connecter, V_{su}. All specimens are predicted to be failed by the stud rapture.

2.2. Measurement

The slip of stud shear connectors, the horizontal displacement of concrete blocks, the separation between a flange and a concrete block, the axial strain of studs and web strains were measured by using displacement transducers and strain gauges. Locations of measurement are displayed in **Figure 4**. Only SFL series has π shape gauges striding across stud positions to obtain the crack behavior around studs.

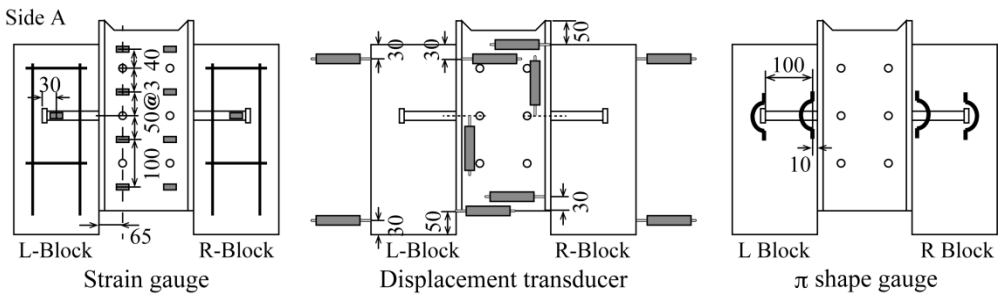
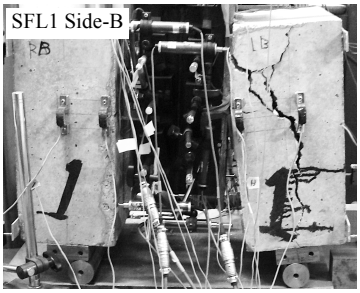


Figure 4: Location of gauges and displacement transducers



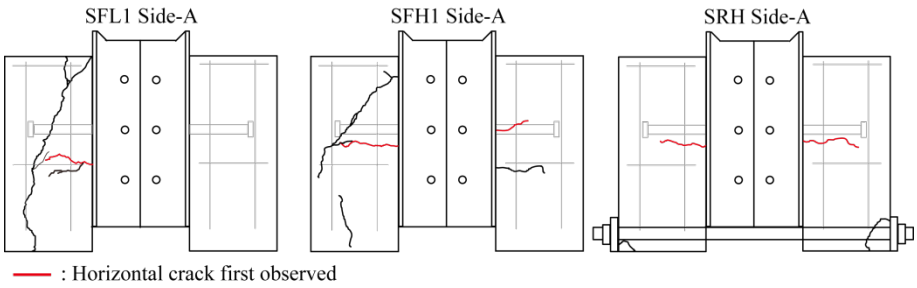


Figure 5: View at failure

Figure 6: Crack pattern

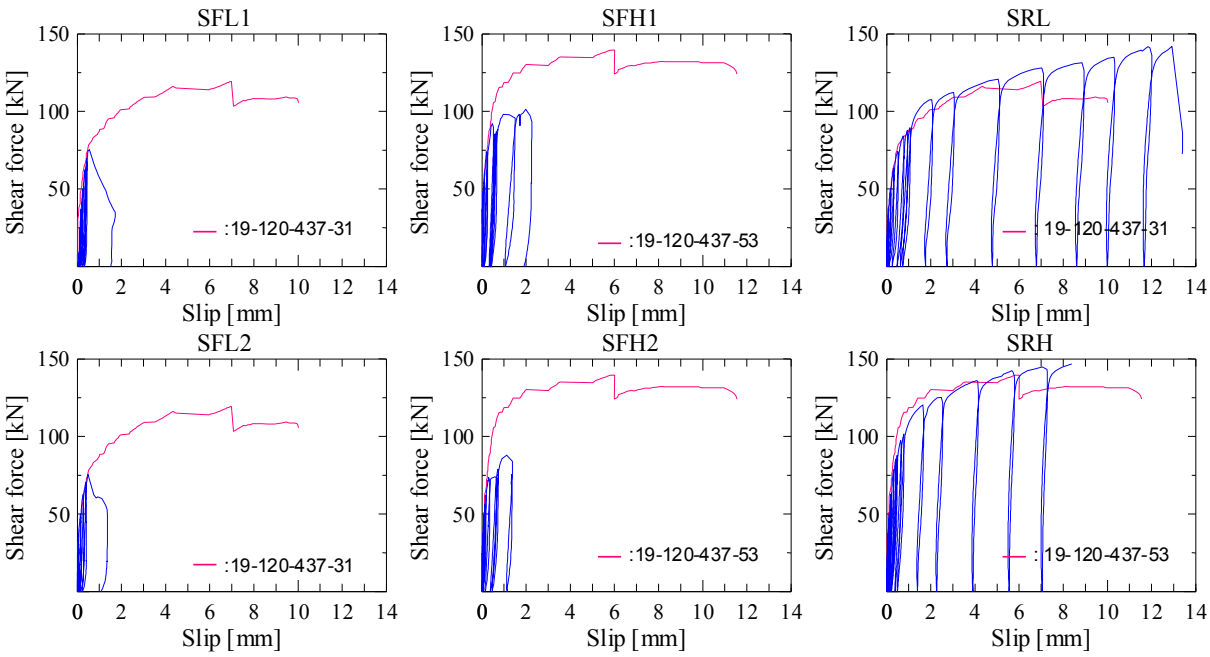


Figure 7: Applied shear force-slip relationship.

2.3. Loading method

The hydraulic universal testing machine (capacity: 1000kN) was used to load. Test setup is displayed in **Figure 3**. One directional cyclic loading and only pushing were adopted. Unloading was done when the load was 50kN, 100kN, 150kN, 200kN and 250kN or the average slip of studs was 0.3mm, 0.5mm, 0.75mm, 1.0mm, 1.4mm, 2.0mm, 3.0mm 5.0mm 7.0mm 11.0mm and 13.0mm.

3. TEST RESULT AND DISCUSSIOIN

3.1. Influence of boundary condition to failure behavior

Boundary conditions give great influences to the failure behavior of headed stud shear connecters. Specimens of series SF, the rotation of whose concrete brocks is unrestrained, were failed by cracking of the concrete block (**Figure 5**). Example crack patterns are shown in **Figure 6**. Load-slip relationships at studs are displayed in **Figure 7**. Shear forces presented here are the average shear force per a stud and the slip is also the average of measured slips of studs. Horizontal cracks drawn by red lines in **Figure 6** were the first crack and occurred irrespective of boundary conditions.

These cracks developed from the interface between the flange and the concrete block. The flexural moment acting on concrete blocks or vertical tensile stress in the concrete block caused by the stud pushing concrete down are guessed as a cause of the horizontal cracking from crack patterns. A diagonal crack occurred after the horizontal cracking and the load dropped suddenly in the case of no restraint, SF series. As the result SF series shows the brittle behavior and much lower shear capacities than specimens using floor supports. In the case of roller supports and using restraint bars, SR series, no diagonal crack occurred and load-slip curves are more similar to the curves of the case using floor supports. Instead, the failure load of SR series is higher than the case using floor supports. If specimens having the same concrete strength are compared, the shear capacity of the case using restraint bars is 120% or 105 % of that of the floor support condition.

Boundary conditions influences crack propagations and that causes different failure mode to effect directly. Therefore, mechanisms of these crack propagations are important to clarify how stress conditions the stud is.

3.2. Relationship among rotation, cracks and boundary conditions

Horizontal cracks seem like the flexure crack. The existence of the bending moment in the concrete block can be estimated from the rotation of concrete blocks. The rotation of the concrete block is calculated by dividing the relative horizontal displacement between the top and the bottom of the concrete block by the height of the concrete block. The rotation which separates both sides of the bottom parts of concrete blocks is defined as the positive rotation. Examples of shear force-rotation curves are shown in **Figure 8**. SFL1, SFH1 and SRH have the same intension as curves observed in SFL2, SFH2 and SRL. Both specimens having no restraint condition, SFL2 and SFH1, show the increase of the rotation with the increase of shear force. The specimen using restraint bar, SRL, shows little rotation. Contrary to loading, rotation increases by unloading. Specimen with the floor support and devices that restrain the horizontal displacement shows same characteristics of the rotation in previous study (Shima 2011). The study explained this phenomenon was caused by the concrete wedge formed by a diagonal crack from top of the stud collar to the flange.

It is confirmed that concrete blocks rotates in condition of no restraint but does not rotate in condition of bar restraint. However this is not proof of no flexure of concrete brocks because the

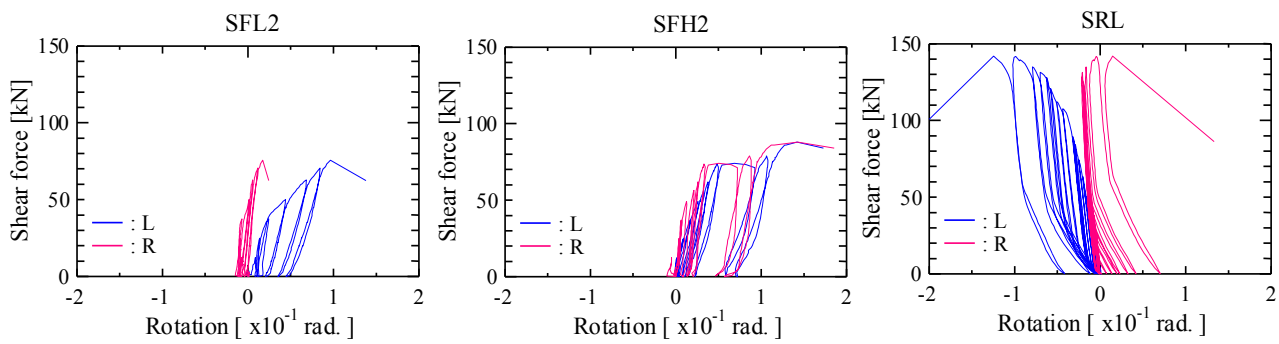


Figure 8: Rotation of concrete blocks

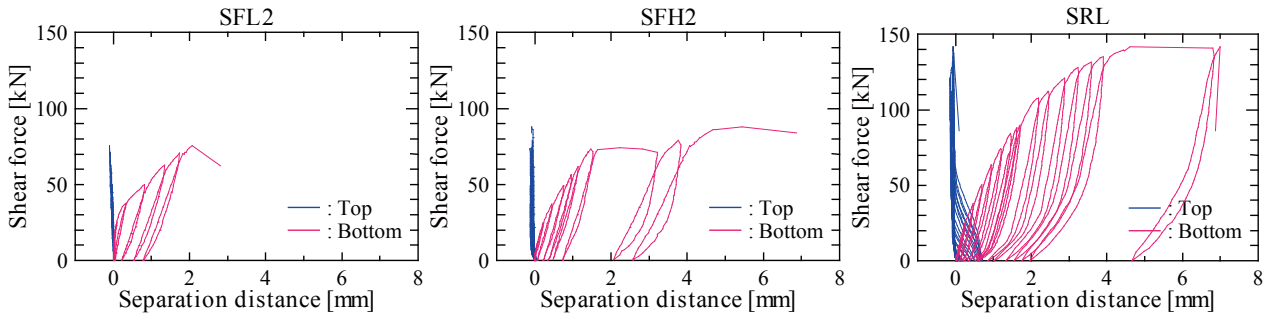


Figure 9: Separation distance between flange and concrete block

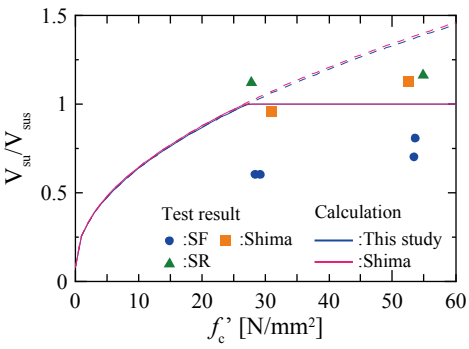
rotation calculated in this study is based on the relative horizontal displacement between the top and the bottom of the concrete block.

Figure 9 shows the shear force-separation distance relationship. The separation distance is the distance between the concrete block and the flange at the top or the bottom part of the H shaped steel. The separation distance at the bottom side increases with the increment of the shear force in all cases. Top of concrete blocks in all specimens do not separate from the flange. These separation behaviors indicate that concrete blocks rotate to separate the bottom side of concrete blocks regardless of restrain bars. As mentioned above, for the specimen SRL, which uses restraint bars the rotation calculated relative horizontal displacement shows opposite results. It is very complicate to explain this confliction with only results in this study. To clarify the mechanism of horizontal and diagonal cracking further investigations are required that relate to the flexure of concrete blocks are required such as push-out tests under the condition that no bending moment acts on concrete blocks.

3.3. Influence of concrete strength to shear capacity under difference boundary condition

The relationship between the compressive strength of concrete and the shear capacity is compared among test and calculation results (**Figure 11**). Solid lines are calculated shear capacities V_{su}, which are decided by the lower shear capacity between V_{su_s} or V_{su_c} as displayed in **Eq.1** and **Eq.2**. Dot lines are V_{su_c} displayed to compare the effect of the concrete strength. Calculated lines of V_{su_c} represent the effect of the concrete strength under the boundary condition of the floor support. All shear capacities in this figure are normalized by the calculated stud strength V_{su_s} to eliminate the difference of the stud strength among specimens.

Shear capacity of specimens supported by the floor almost agrees with calculation because the formulas were based on test results under the same boundary condition. The prediction formula much overestimates the shear capacity of specimens using roller supports and no restraint bar. Test results are form 60 % to 80 % of the calculated capacities. Moreover, the tendency of the effect of the concrete strength disagrees with the calculation. As described on characteristics of cracking, the failure mechanism under no restraint boundary condition is much different from the mechanism formed by the interaction between concrete and the stud due to the diagonal crack.



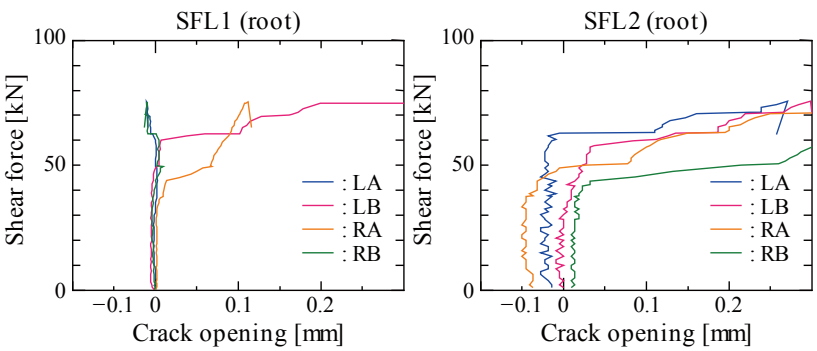


Figure 11: Effect of concrete strength **Figure 12: Horizontal crack opening**

Table 3: Load of first horizontal cracking

Specimen	SFL1	SFL2	SFH1	SFH2	SRH	SRL
Shear force [kN]	40.0	40.0	50.0	61.0	50.0	75.0

The predicted shear capacity underestimates the capacities of specimens restrained by round bars but the tendency in test results that the concrete strength has no relation to the shear capacity agrees with the tendency of calculations. The failure mode also agrees with the calculation. The axial restraint on the stud by round bars is supposed to influence the rapture of the stud and cause the underestimation of the prediction. These results show that the push-out test under the boundary condition of using roller supports and restraint bars can provides similar performance of the stud connector under the boundary condition of using the floor support depending on the condition of the restraint by round bars. The push-out test under the boundary condition of using roller supports and restrain bars has a possibility to be an appropriate method to obtain the shear behavior of the headed stud connector under several load conditions.

3.4. Influence of concrete strength to horizontal cracking

Figure 12 shows the opening displacement of horizontal cracks in SFL series near the root of studs, which was measured by π gauges. The sudden increment of the crack opening displacement indicates that the first horizontal crack occurs at approximately 40kN in both SFL1 and SFL2. Load-slip curves of these specimens show no clear change around 40kN. The horizontal cracking is thought as a trigger of the diagonal cracking but gives a quite small effect on the load-slip curves.

Horizontal cracking loads of all specimens are displayed in **Table 3**. All loads except specimens using π gauges are results of visual observations. in comparison among SF series, the compressive strength influences the cracking load like shear capacity. However, π gauges can catch the opening of invisible cracks. If results by the visual observation are compared, no rule relating to the concrete strength is seen. For example, if results are compared among same boundary condition, SRL and SRH, the specimen having high concrete strength SRH shows lower cracking load than the specimen having low concrete strength SRL. No rule relating to boundary condition is also seen in

comparison among specimen having the same concrete strength. It is said that the compressive strength of concrete and boundary conditions little influences the load of horizontal cracking.

4. CONCLUSIONS

The findings in this study are listed below.

1) The horizontal crack occurs first in the concrete block near stud regardless of using restrain bar if roller support is used. Load of the occurrence is little depended on concrete compressive strength. The flexure of concrete block or vertical tensile stress due to stud is thought as a main cause of this crack. However, the mechanism of cracking was not clarified in this study.

2) The diagonal crack occurs in the concrete block after horizontal cracking under the unrestrained boundary condition provide by using roller supports and no restraint bar. The crack causes the brittle failure. The shear capacity becomes approximately 60% of the predicted capacity.

3) The compressive concrete strength influences to the shear capacity of the failure mode causing the diagonal crack. However the tendency of the influence is different from the prediction formula. This is because the failure due to the diagonal cracking is much different from the failure due to interaction between concrete and the stud observed in previous studies.

4) The shear capacity under the boundary condition provided by roller support and restraint bar is higher than the shear capacity under the condition provided the floor support and the predicted capacity nevertheless of horizontal cracking. Moreover the failure mode agrees with the floor support condition and the prediction. Therefore, the push-out test under the boundary condition provided by roller supports and restrain bars seems to be an appropriate method to obtain the shear behavior of the headed stud connector under several load conditions.

Influence of the boundary condition presented in this study clearly show that the push-out test using the current specimen is not "elemental" test but "structural" test. It is very important to consider structural conditions as boundary conditions to develop the appropriate test method.

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