(32) Experimental Study on Strain Behavior of Pipe Stud Shear Connector Subjected to Various Load Conditions

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The purpose of this study is to investigate the strain behavior of the stud shank at its base experimentally and to develop the relations between the shear force transferred through the stud and the observed strain behavior under different types of load conditions. It is usually troublesome to measure the strain at the base of the stud shank in steel-concrete hybrid structures through the experiment because of welding at the base and necessity of coating for the protection of the strain gauges. To overcome this difficulty, we have introduced the pipe stud instead of the ordinary solid one and then the strain gauges were installed inside the pipe stud near the base of its shank. We employed the push- and pull-out specimen with the pipe stud to which alternating load as well as pulsating load can be applied easily under static and fatigue test.

Key Words : *pipe stud shear connector, static and fatigue test, base strain, push- and pull-out test*

1. Introduction

In steel-concrete hybrid structures, the headed stud shear connectors are frequently applied to connect the steel and concrete members with each other. To predict the shear force transferred through the stud and stress concentration near its base, it is important to observe the strain behavior of the stud at the base. However, it is troublesome to measure the strain at the base of the stud shank in steel-concrete hybrid structures by the experiment because of welding at the base and necessity of coating for the protection of strain gauges.

Matsui et al.[1] evaluated the shear force transferred through the stud in steel-concrete composite slab by investigating the strain of the steel plate near the stud base. Nakajima et al.[2] also measured the strain behavior of the steel plate near its base of the stud shank in the push- and pull-out specimen to predict the stress concentration at the base of the stud shank. However, it is difficult to measure the base strain using above technique. Therefore, Nakajima et al.[3] introduced the pipe stud shear connector for measuring the base strain, in which strain gauges were installed easily inside near the base of its shank.

In this context, providing push- and pull-out specimen[4] to which pulsating as well as alternating load can be applied easily, a series of static and fatigue tests were conducted under the monotonic, pulsating and alternating load conditions. The experimental investigations on push- and pull-out specimen with the pipe stud were the base and mid height strain behavior and relative slip behavior. From the experimental findings, the relations between the shear force transferred through the stud shank and the observed strain are developed under various load conditions.

2. Push- and Pull-out Specimen

The push- and pull-out test specimen having the pipe stud as shown in **Fig. 1** was adopted for the experimental investigation. Two pipe

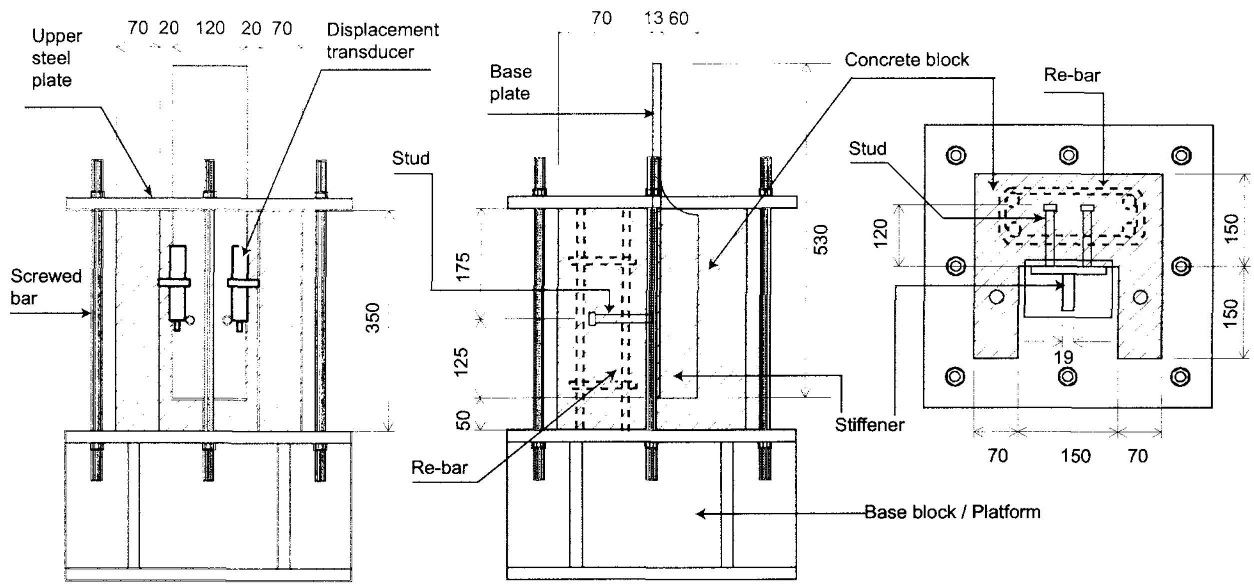

Fig. 1 Outline of the test specimen

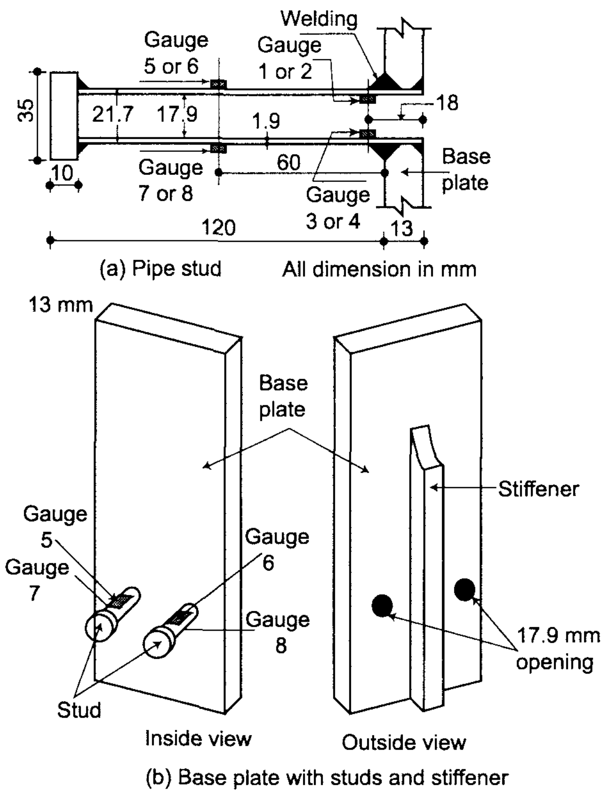

Fig. 2 Strain gauge locations on stud and steel plate

studs with inside and outside diameter 17.9mm and 21.7mm respectively and length of the stud 120mm were arranged on the base plate as shown in **Fig. 2**. The pipe stud embedded through the opening that was previously made in the base plate (530mm×120mm×13mm) and welded from the outside of the pipe as shown in **Fig. 2**(a). To increase the stiffness of the base plate and to provide sufficient resistance against plate bending, another steel plate (350mm×60mm×19mm) was attached to the base plate on the other side as shown in **Fig. 2**(b). The concrete block had a concave section in **Fig. 1** so that the specimen does not rotate in applying the load to the base steel plate.

Four 10mm diameter longitudinal deformed bars and two 6mm diameter stirrups of 200mm spacing were provided to protect the premature cracks in the concrete block. In applying the load, the concrete block was inserted between the steel base block and the upper steel plate and was fixed by eight screwed bars. All the eight screwed bars were subjected to almost equal tensile force that was checked by the torque wrench. The load was applied to the specimen by clamping the top of the base plate at the head of the loading actuator.

Two displacement transducers (**Fig. 1**) were installed to measure the relative slip between the concrete block and the base plate at the same level of the studs. One pair of strain gauges was attached at the base and another pair at the mid height of each pipe stud as shown in **Fig. 2**(a). The main objective of selecting the shape and size of the specimen was to realize easy application of monotonic, pulsating and alternating load condition under static and fatigue test. The inside area of the pipe stud was filled by cement mortar because of minimizing the local deformation of the pipe section during the application of load.

3. Test Setup

Static and fatigue test were carried out on the thirty push- and pull-out specimens. Among thirty specimens, static test was conducted on the twenty one specimens and fatigue test was conducted on the remainder. The static tests were conducted under the monotonic, pulsating and alternating load conditions. The pulsating compression or tension loading cycles were repeated up to the peak load and the peak load was increased up to 80kN then the load was increased monotonically up to the failure of the specimen. On the other hand, complete reversal loading cycles (from compression to tension or vice versa) were repeated up to the failure of the specimen under the alternating load condition. During the loading program, the relative slip between the concrete block and the base plate, strain at the base and mid height of the stud shank were measured at each loading step.

In fatigue test, a set of maximum and minimum load was selected in order to apply the required amplitude of the shear force of 40, 55 and 75kN with the loading frequency of 3.0Hz. Constant minimum load amplitude of 2.5kN was applied to the specimen under the pulsating load condition and equal magnitude of the maximum and minimum load was set under the alternating load condition. During the fatigue test, the magnitude of the load, relative slip and strain on the stud shank were measured by the dynamic data acquisition system at each 5 to 60s interval for recording the expected fatigue life of each specimen.

4. Experimental Findings and Discussion under Static Tests

4.1 Shear force-relative slip relations

The typical shear force-relative slip relation under the monotonic load condition is shown in **Fig. 3** in associated with the similar one of the solid stud under the pulsating load condition. The ordinate indicates the shear force applied to the one stud and the abscissa indicates the average value of the relative slip between the concrete block and the base plate. The outline of the pipe stud relation agrees well with the envelop of the solid one. The typical shear force-relative slip relation under the pulsating and alternating load conditions are shown in **Fig. 4**. These relations are compared with the one under the monotonic load condition in **Fig. 4-a** and **Fig. 4-b** and the envelops of the relations under the pulsating and alternating load conditions almost agree with the one under the monotonic load condition. Furthermore, the shear force-relative slip relation of the solid stud is also compared with the one of the pipe stud in **Fig. 4-b**. The correlation between the shear force-relative slip relations of the pipe stud and the one of the solid stud is well.

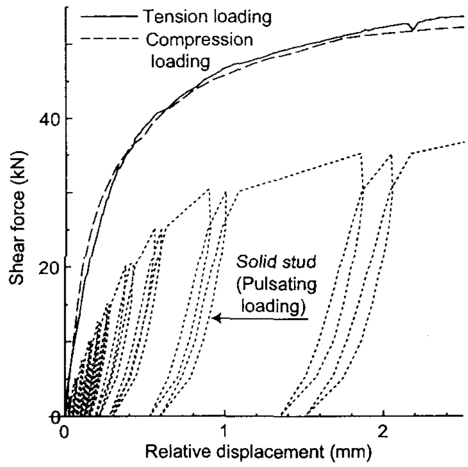

Fig. 3 Shear force-relative slip relation under the monotonic load condition

The maximum shear strength, yield shear strength, shear stiffness are estimated for the specimens under each type of load condition and the material properties of steel and concrete are summarized in **Table 1**. The shear stiffness is defined as the slope of the secant at the point of one-third of the maximum shear strength on the shear force-relative slip relation. The yield shear strength is defined as the point where a 0.2mm offset of the relative slip parallel to the shear stiffness crosses the shear force-relative slip relation. In **Table 1**, the 'Status' column under the alternating load condition means load started from compression or tension and was followed by tension or compression. The shear stiffness under tension loading is less than that under compression loading in all load conditions.

The reasons of variation of compression and tension shear stiffness are explained here briefly. During compression loading, a rotation of the base plate was occurred and the bottom edge of the base plate contacted the concrete block then some percentage of the applied load transmitted directly to the concrete block. On the other hand, during tension loading, an inverse rotation was occurred and the base plate contacted on the top of the concrete block. Therefore, the direct shear transmission of percentage of the applied load in case of compression loading is larger than the one under tension loading. So that, the actual transferred shear force through the stud during the compression loading is smaller than the one

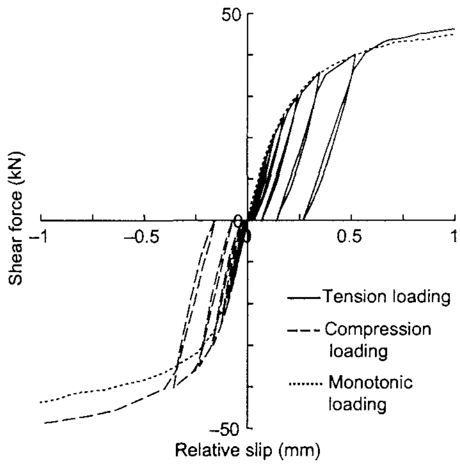

Fig. 4-a Pulsating load condition

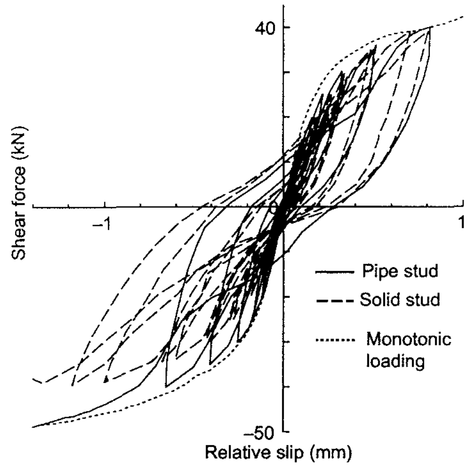

Fig. 4-b Alternating load condition

Fig. 4 Shear force-relative slip relations under the static test

Table 1 Summary of the static test results

Loading condition	Status	Maximum shear strength (kN)	Yield shear strength (kN)	Shear stiffness (kN/mm)	Concrete strength (N/mm^2)	Yield stress of stud (N/mm^2)
Monotonic	Compression	52.7	36.3	190.2		
Monotonic	Tension	53.2	36.4	162.3		
Pulsating	Compression	55.8	41.3	219.7	33.4	235
Pulsating	Tension	52.5	38.0	140.2		
Alternating	Compression	53.2	37.3	208.8		
Alternating	Tension	58.0	38.5	151.7		

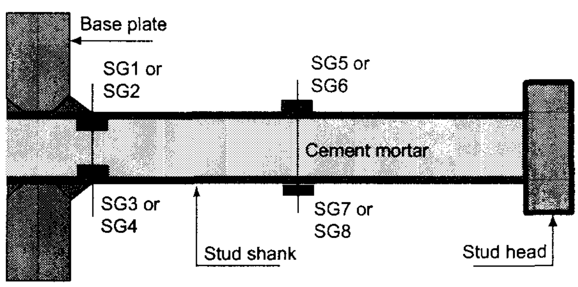

Fig. 5-a Strain gauges location

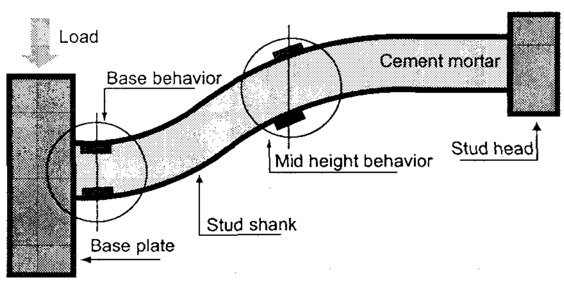

Fig. 5-b Behavior of stud under loading

Fig. 5 Deformation characteristics of pipe stud

during tension loading. Moreover, while the reaction force was subjected to the base block during compression loading, the reaction force was subjected to the top steel plate, which was supported by the eight screwed bars during tension loading. In the latter case, a small elongation of the bolts may enhance the relative slip between the base plate and the concrete block.

4.2 Strain behavior of stud shank

The experimental investigations on the strain behavior were limited to recording the base and mid height strain of stud shank under each type of load condition. Under compression loading, the deformation of the stud shank may become the one as shown in **Fig. 5-b** from **Fig. 5-a**. The typical relations between shear force amplitude and the direct strain amplitude for both the top and bottom strain at the base and mid height under pulsating compression and tension loadings are shown in **Fig. 6**. The amplitude of the shear force is taken as the difference of the maximum and minimum peak values of the applied load and the corresponding strain amplitude is taken into account.

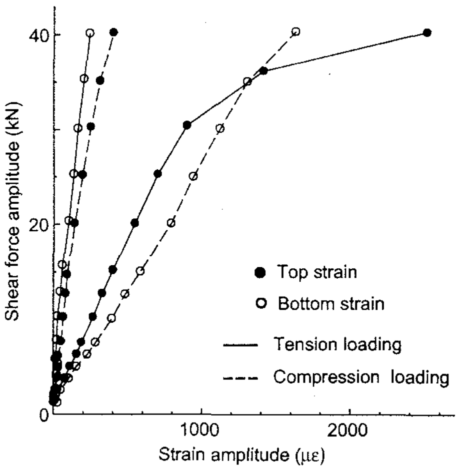

Fig. 6-a At base

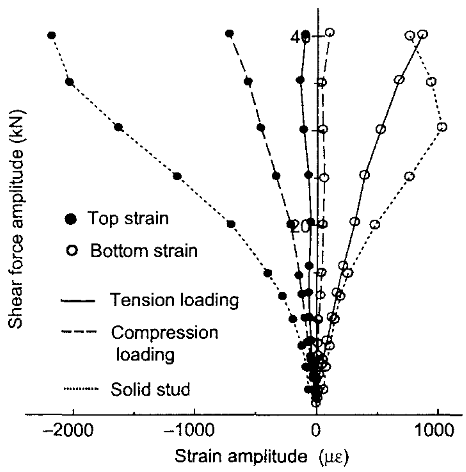

Fig. 6-b At mid height

Fig. 6 Direct strain amplitude relations under the pulsating load condition

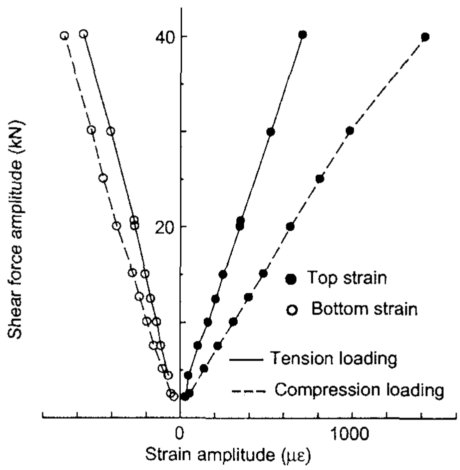

Fig. 7-a At base

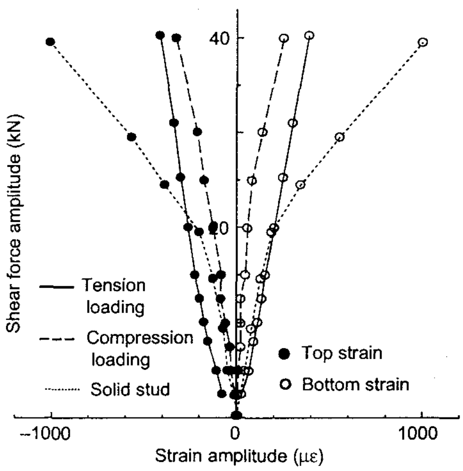

Fig. 7-b At mid height

Fig. 7 Direct strain amplitude relations under the alternating load condition

Under compression loading, the amplitude of the bottom sided strain is greater than the one of the top strain with same sign at the base, while at the mid height, the top sided strain amplitude is greater than the bottom one with reserve sign and the opposite behavior is observed under tension loading. The bottom strain at the base and the top strain at the mid height are composed of the tensile axial strain and tensile bending strain respectively, whereas the top strain at the base and the bottom strain at the mid height are composed of the tensile axial strain and compressive bending strain. At the base the axial strain is greater than the bending strain and at the mid height the axial strain is less than the bending strain irrespective of the loading direction. In **Fig. 6**, it can be seen that the amplitude of the base strain is also larger than the one at the mid height in a certain shear force amplitude.

The relation between the shear force amplitude and direct strain amplitude of the solid stud under pulsating compression loading is also shown in **Fig. 6**(b). In this case, the magnitude of the top sided strain amplitude is also larger than the bottom one and this tendency is almost same as the one with the pipe stud. However, the magnitude of strain amplitude at any shear force amplitude level differs from the one of the pipe stud, because the flexural rigidity of the pipe stud is about 3.75 times larger than the solid ones. **Fig. 7** shows the typical relations between shear force amplitude and direct strain amplitude at the base and mid height under the alternating load condition. The top and bottom strain amplitude at the base and mid height under a certain shear force amplitude are almost same irrespective of the loading direction, but the base strain amplitude is greater than the mid height one at the top and bottom of the stud shank.

Moreover, for example, the sign of the amplitude of the top sided strain at the base is opposite to the one at its mid height. This implies that the

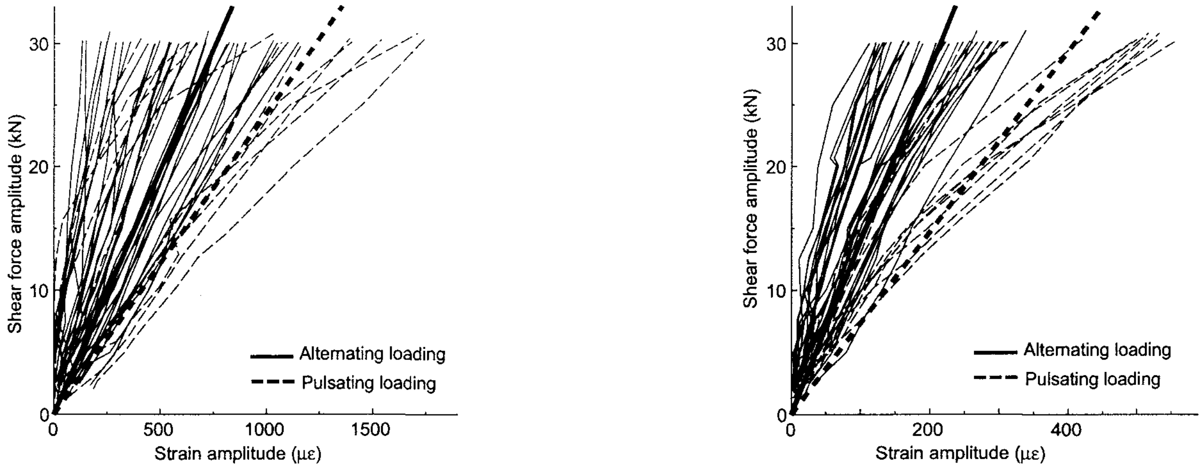

Fig. 8-a At base **Fig. 8-b** At mid height

Fig. 8 Shear force-direct strain amplitude relations

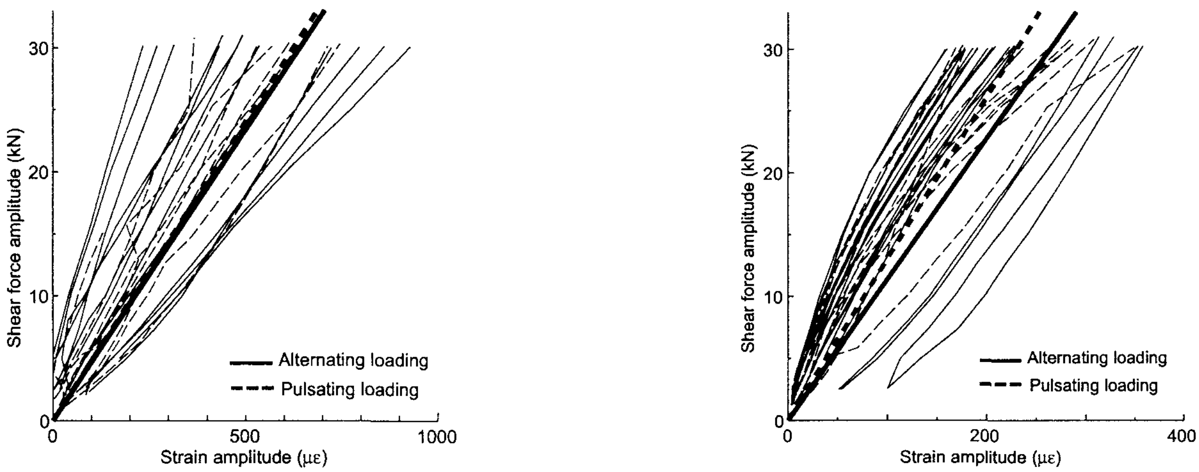

Fig. 9-a At base **Fig. 9-b** At mid height

Fig. 9 Shear force-bending strain amplitude relations

curvature of the base section of the pipe is opposite to the one at mid height section. The difference between the axial force at peak shear force and the axial force at zero shear force becomes large under the pulsating load condition. Then, the axial strain as well as the axial strain amplitude becomes large under the pulsating load condition. On the other hand, the difference between the axial force at tension peak shear force and axial force at compression peak shear force or vice versa under the alternating loading becomes small. So that, the axial strain as well as the axial strain amplitude also becomes small under the alternating load condition.

The difference between the bending moment at peak shear force and the bending moment at zero shear force under the pulsating load condition becomes same as the difference between the bending moment at tension peak shear force and the bending moment at compression peak shear force or vice versa under the alternating load condition. Then, the amplitude of the direct strain under the pulsating load condition is larger than the one under the alternating load condition in any shear force amplitude. The shear force amplitude and the direct strain amplitude relations at the mid height of the solid stud under the alternating load condition is also shown in **Fig. 7-b**. The tendency of the relation is same to the one of the pipe stud.

4.3 Shear force-strain amplitude relation

The above relations between the shear force amplitude and the strain amplitude are typical examples of the test results. For predicting the shear force transferred through the stud shank from the strain behavior, all the strain relations must be investigated under the pulsating and alternating load conditions. **Fig. 8** shows the relations between the shear force amplitude and the absolute value of the direct strain amplitude at the base and mid height under the pulsating and alternating load conditions. The ordinate shows the shear force amplitude per one stud and abscissa shows the absolute amplitude of the direct strain.

Regression lines are plotted for both the load conditions to observe the correlation among the plotted data. The amplitude of the shear force is taken as the difference of the maximum and minimum peak values within the range of 30kN shear force amplitude. All strain gauge records at the base and mid height are taken into account under the alternating load condition and only larger ones are considered under the pulsating load condition. It has been observed that the scattering at the base and mid height of the plotted data is so large for a certain shear force level. This scattering may be occurred due to the variation of the location of inside gauges and the base welding size of the pipe.

The slope of the regression lines under the pulsating load condition at the base and mid height are about 57% and 53% respectively of the ones under alternating load condition. This is due to the effect of axial strain described earlier. With respect to the relations shown in **Fig. 8** at the base, the correlation coefficients are about 0.83 and 0.47 respectively under the pulsating and alternating load conditions and the ones at the mid height are about 0.87 and 0.72 respectively.

Other relations between the shear force amplitude and the bending strain amplitude are shown in **Fig. 9** at the base and mid height. The slope of regression lines under the pulsating load condition are about 1.03 and 1.15 times of the ones under the alternating load condition. From the regression lines in these figures, it can be seen that the bending strain amplitude under the pulsating and under the alternating load conditions is almost same, but that the bending strain amplitude at the base is larger than the one at its mid height in any shear force amplitude.

The correlation coefficients of the regression lines related to the bending strain amplitude are about 0.91 and 0.63 at the base and 0.89 and 0.65 at the mid height respectively under the pulsating and alternating load conditions. Among the strain amplitude relations as shown in **Fig. 8** and **Fig. 9**, although the scattering in the relations is not so small, the bending strain amplitude relations at the base and also at the mid height under both the pulsating and alternating load conditions are acceptable for the prediction of the shear force transferred through the pipe stud.

Table 2 Average strain amplitude ($\mu\epsilon$) at the base and mid height under the fatigue test

Shear force ampli.	Pulsating comp. loading	Pulsating tension loading	Alternating loading
20.0 kN	725(170)	900(300)	413(180)
27.5 kN	1000(425)	1000(625)	250(240)
37.5 kN	1500(550)	1500(850)	200(475)

5. Experimental Findings and Discussion under Fatigue Tests

Nine specimens were employed for the fatigue test. Among them, six specimens were conducted under the pulsating load condition and the others were conducted under the alternating load condition. The shear force amplitudes were 20, 27.5 and 37.5kN per one stud with the loading frequency of 3.0Hz. The average strain amplitudes at the base and mid height under the fatigue test are shown in **Table 2**, and the values in the parenthesis are for the mid height. The relations between the strain amplitude and the number of cycles at the base and mid height under the pulsating load condition are shown in **Fig. 10-a** and **Fig. 10-b**. The variation was observed under the constant shear force amplitude.

At the base, the bottom strain is greater than the top one while, at the mid height, the top strain amplitude is greater than the bottom one under pulsating compression loading. Reverse observations were also recorded under pulsating tension loading. This behavior (**Fig. 10-a** and **Fig. 10-b**) agree well with the one under the static test (**Fig. 6**). The relations between the strain amplitude and the number of cycles at the base and mid height under the alternating load condition are shown in **Fig. 10-c**. The top and bottom strain amplitudes at the base and mid height are almost same. Moreover, the base strain amplitude is greater than the one at the mid height. This behavior supports the static one (**Fig. 7**).

The S-N relations of all the specimens are shown in **Fig. 11**. The regression lines are plotted under all the load conditions. From **Fig. 10** and **Table 2**, it can be seen that the strain amplitudes under the pulsating load condition is greater than the ones under the alternating load condition. Then, we can expect longer fatigue life under the alternating load condition than the pulsating load condition. From **Fig. 11**, it is ob-

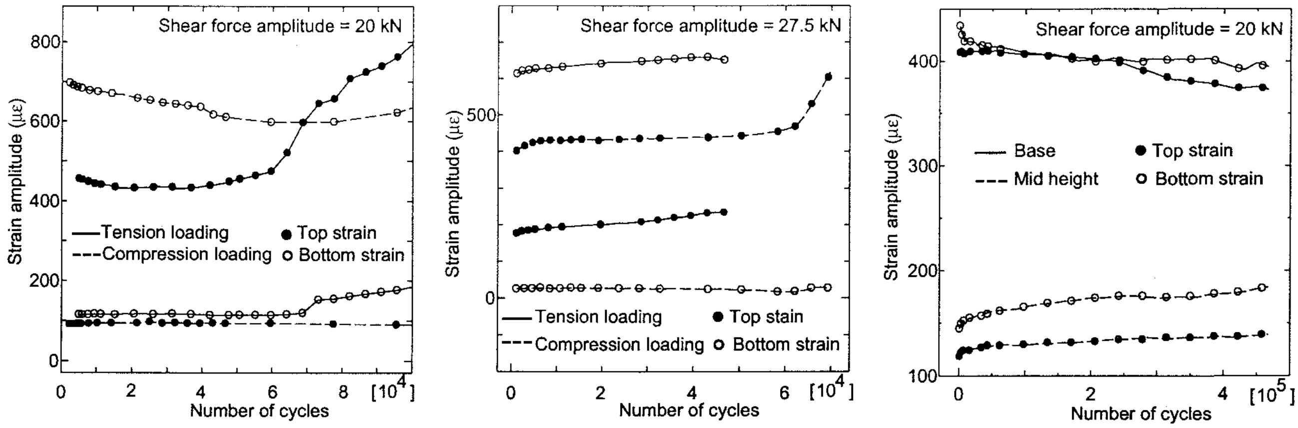

Fig. 10-a Pulsating load condition (at base) **Fig. 10-b** Pulsating load condition (at mid height) **Fig. 10-c** Alternating load condition

Fig. 10 Direct strain behavior under the fatigue test

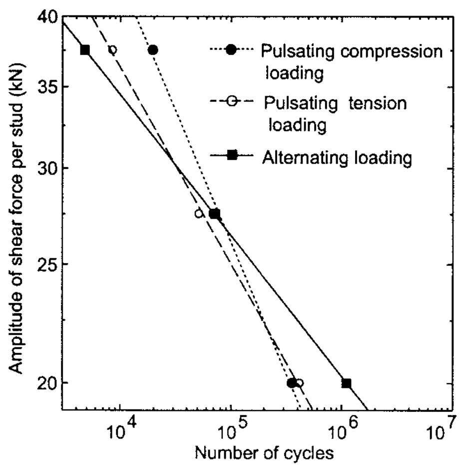

Fig. 11 S-N curve under the fatigue test

served that the fatigue life under the alternating load condition does not always longer than the one under the pulsating load condition. This may be due to the scattering of the strain behavior.

6. Conclusions

In this research, we carried out a series of the test employing the push- and pull-out specimen with the pipe stud. As a result, the following conclusions may be drawn based on the observations through the experimental study.

1. For recording the base strain of the stud shear connector, we introduced the pipe stud by which the base strain of the stud shank can be measured under the monotonic, pulsating and alternating load conditions.
2. The outline of the shear force-relative slip relations of the pipe stud resembles to the one with the general solid stud.
3. We observed that the measured strain at the base of the stud shank is much larger than the one at its mid height and that the curvature at the base of the stud shank is opposite to the one at its mid height.
4. We developed the relation between the shear force transferred through the stud and the strain behavior. These relations can be used for predicting the transferred shear force of the stud experimentally.
5. The strain amplitude relations under the fatigue test almost agree well with the ones under the static test.

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