An experimental study on shear force distribution among studs in grouped and ungrouped arrangements

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Grouped stud arrangement is often used in the composite girder bridges with the prestressed concrete slab. Proper experimental investigation needs to ensure that all the studs in grouped arrangement will transfer the almost equal magnitude of shear force or not. Base strain behavior is the most appropriate media for predicting the shear force transmission through the stud shank. Pipe studs are provided for measuring the base strain. A series of static as well as fatigue tests were carried out on the push- and pull-out test specimens with the grouped and ungrouped stud arrangements under the pulsating and alternating load conditions. It is revealed that all the studs are not transfer equal magnitude of shear force.

Key Words : *experiment, pipe stud shear connector, grouped and ungrouped stud arrangements, push- and pull-out test specimen, base strain, shear force distribution*

1. INTRODUCTION

In the steel-concrete composite girder bridges, shear connectors are employed to connect the concrete slab and the steel girder. Conventionally, headed studs are the popular shear connectors and arranged almost uniformly on the top flange of the steel girder. However, nowadays the prestressed concrete slabs have been adopted frequently in the composite girder bridges. The prestressing along the longitudinal direction of the concrete slab transfers large extra stress in the steel girder simultaneously by the conventional jack up-down method. The extra stress is unnecessarily confined both in the concrete slab and steel girder. On the other hand, the grouped stud arrangement[1] technique can be employed effectively for prestressing across the transverse direction of the concrete slab, where the prestressed force is applied without connection between the concrete slab and the steel girder.

In this regard a number of pockets are left for the studs in the grouped stud arrangement as shown in **Fig. 1** in the concrete slab at the time of concreting. After concreting except the pockets, the prestressed force is applied to the concrete slab alone and finally the concrete slab is connected with the steel girder through the pockets by non-shrinkage mortar. Okubo et al.[2] employed the push-out test[3] specimens with the grouped stud arrangement and investigated the behavior of the studs in the grouped arrangement

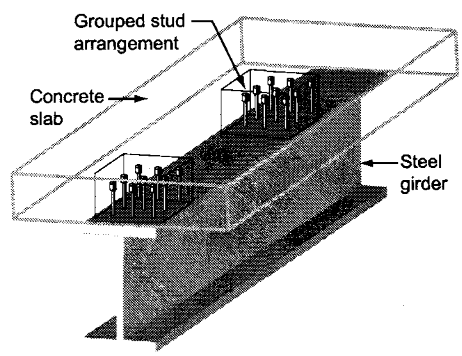

Fig. 1 Grouped stud arrangement

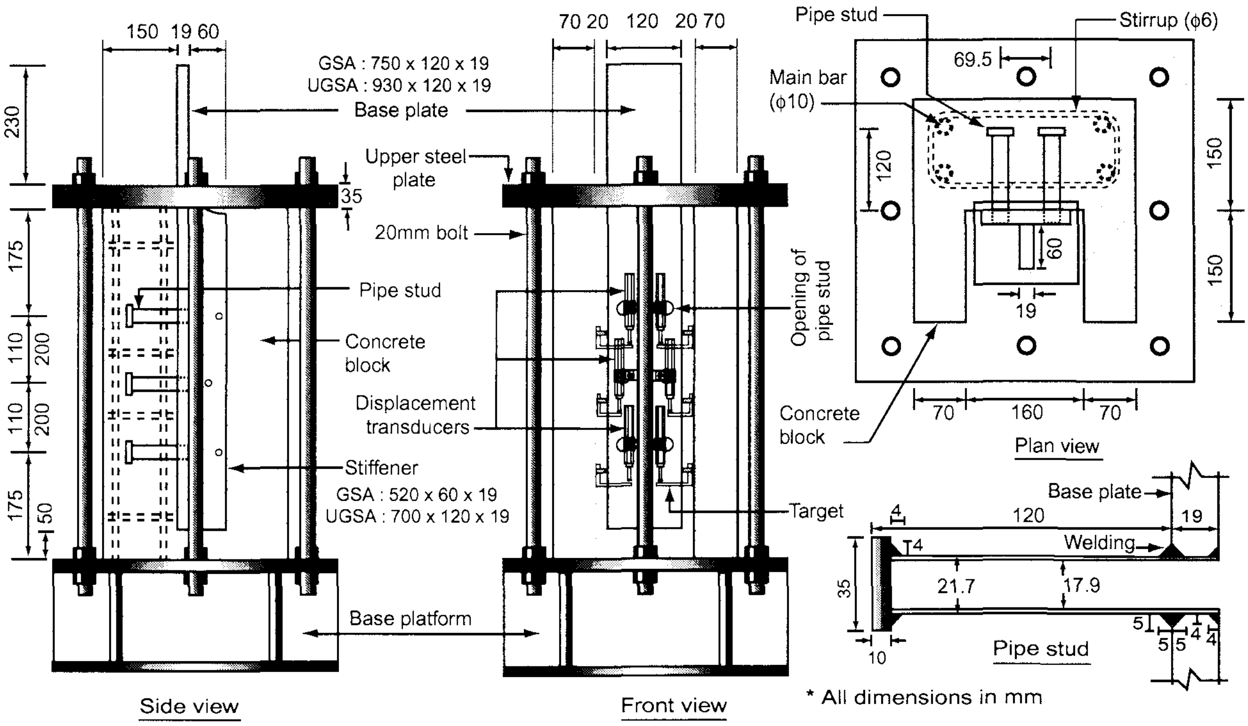

Fig. 2 Specimen details

and the effect of concreting in the pockets with the same concrete or the non-shrinkage mortar. Okada et al.[4] investigated the influence of the stud arrangement by employing the push-out test specimens with the grouped stud arrangement parallel to the standard arrangement. The above observations were carried out on the grouped action and they concluded that all the studs in grouped arrangement showed almost same performance.

In this study, the authors point their attention towards the investigation on the shear force distribution among the studs provided as the grouped (GSA) and ungrouped (UGSA) arrangement in the push- and pull-out test specimens in **Fig. 2** instead of conventional push-out test[3] specimen. Parallely a difference between the GSA and UGSA is observed from the viewpoint of the experimental records. Pipe studs[5,6] are used as the shear connectors in both the GSA and UGSA. The main purpose of employing the pipe stud is to measure the base strain of stud shank, which is quite impossible in the generally used solid studs[7,8] because of welding provided to connect the studs with the base plate, and coating provided to protect the strain gauge. A series of the static tests as well as the fatigue tests are carried out on the push- and pull-out test specimens with the GSA and UGSA under the pulsating and alternating load conditions.

The entire research is carried out in four phases. Firstly, the relations between the shear force and slip among the studs in different levels in **Fig. 2** with the GSA and UGSA are investigated under the static loadings. Secondly, the strain behavior of the pipe stud at the base as well as the mid height is investigated, and the relations between the observed strain and the shear force transferred through the stud shank in different levels are constructed for the static loadings. Thirdly, the percentage of the total shear force transferred through the stud in different levels is estimated. Finally, the behavior of the pipe stud shear connectors for the GSA and UGSA is also investigated for the fatigue tests.

2. TEST SPECIMEN

The push- and pull-out test specimen with pipe studs is shown in **Fig. 2** was employed for the experimental investigation. Three pairs of pipe studs with inside diameter 17.9mm, and outside diameter 21.7mm and height 120mm were welded on the base plate. In the GSA, to satisfy the studs pitch specified in the Japanese Specification for

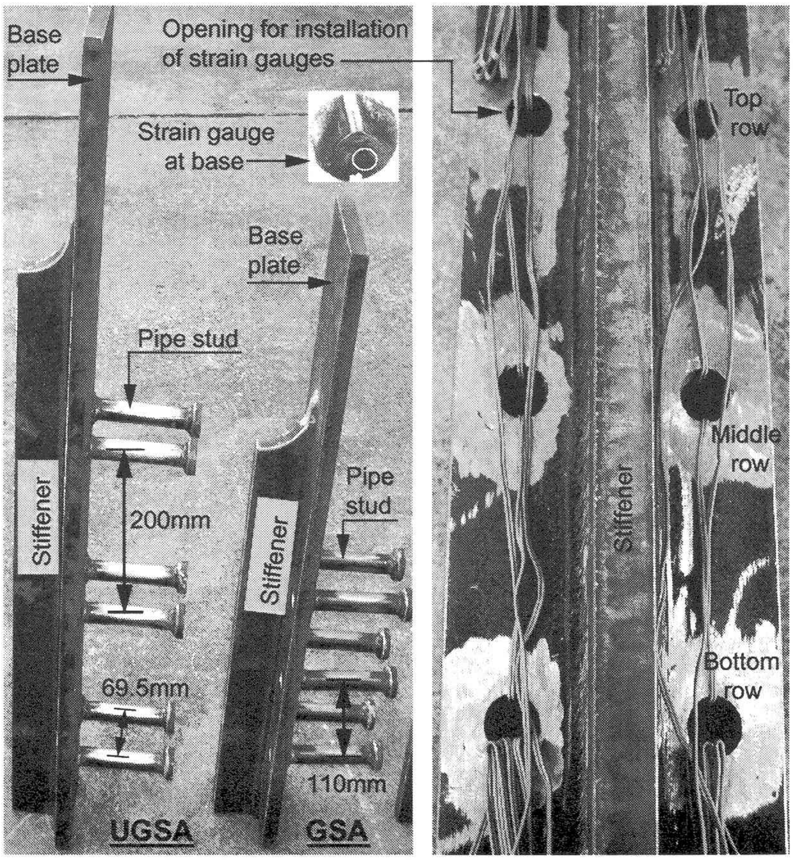

Photo 1 GSA & UGSA and opening at base plate for strain gauges

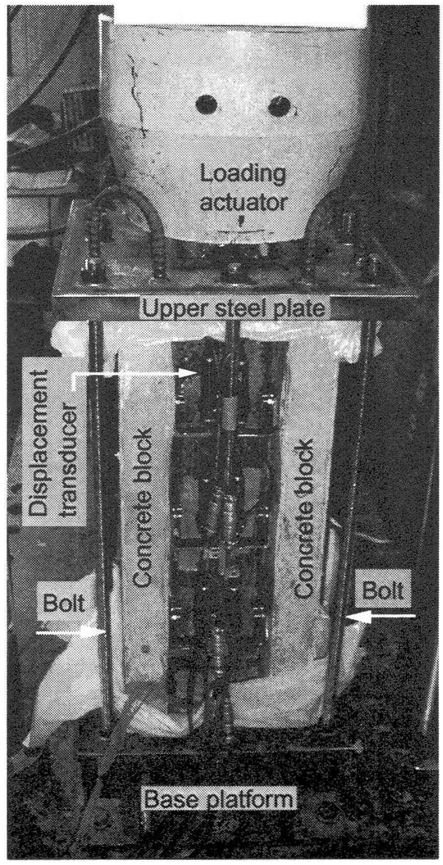

Photo 2 Specimen under loading

Highway Bridges[9]), 110mm and 69.5mm spacing were selected for the longitudinal and transverse directions. On the other hand, the longitudinal and transverse spacing of studs in the UGSA were set to 200mm and 69.5mm respectively. The pipe studs were embedded through the opening at the base steel plate and welded from the outside of the pipe as shown in **Fig. 2** and **Photo 1**. To provide sufficient resistance to the base steel plate against plate bending, another steel plate (stiffener) was welded to the base steel plate on the other side. The size of the base plate as well as the stiffener plate is mentioned in **Fig. 2**.

One pair of strain gauges was installed at the base and another pair at the mid height of each pipe stud as shown in **Fig. 3**. Four 10mm diameter longitudinal deformed bars and four 6mm diameter stirrups with unequal spacing (155mm and 110mm) in the GSA and equal spacing (200mm) in the UGSA were provided to protect the premature cracks in the concrete block. The compressive strength, tensile strength and modulus of elasticity of the concrete used for making the specimen were 46N/mm^2, 4.1N/mm^2 and 35.2kN/mm^2 respectively. The inside area

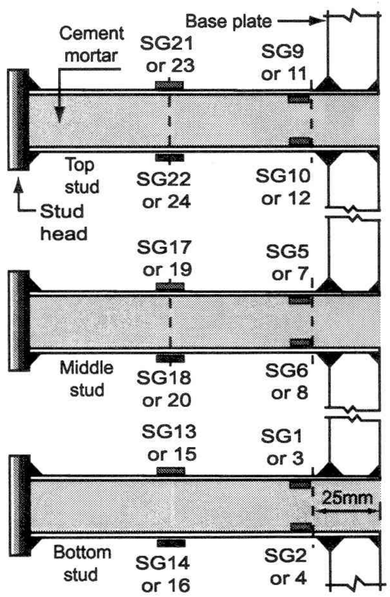

Fig. 3 Strain gauge locations on pipe stud shank

of the pipe stud was filled with cement mortar having compressive strength of 41N/mm^2 to minimize the effect of local deformation of the pipe section during the tests. Before applying the load, the concrete block was inserted between the steel base platform and the upper steel plate those were tightened by eight screwed steel bars having diameter of 20mm. All the eight screwed bars were subjected to almost equal tensile force that was ensured by the torque wrench. The load was applied to the top of the base plate of the specimen by the loading actuator as shown in **Photo 2**. Three pairs of displacement transducers were fastened at the same level of the studs to measure the slip between the concrete block and the base plate. The main objective of selecting the shape and size of the specimen was to realize easy application of the pulsating and alternating loadings for the static and fatigue tests.

3. TEST PROCEDURE

A series of experiments was carried out on the twenty-four push- and pull-out test specimens with the GSA and UGSA. Twelve of them were employed for the static tests and the rest twelve specimens were employed for the fatigue tests under the pulsating and alternating load conditions. The pulsating compression loading cycles were repeated with several incremental peak loads up to 180kN. Then the load was increased monotonically up to some extent but the specimens do not failed due to the grip failure both in the GSA and UGSA. On the other hand, complete reversal loading cycles (from compression to tension) were repeated up to ±90kN peak load and then the tensile load was increased monotonically up to the failure of the specimens. The failure resulted from the crack in the concrete block of the specimens with the GSA only. The specimens with the UGSA neither failed by cracking in the concrete block nor stud failure. Only gripping failure achieved for the UGSA case under the alternating load condition.

In this paper, the load condition with the only compressive shear force cycles is defined as the pulsating load condition and the reversed cyclic shear force is defined as the alternating load condition. During application of load, the slip between the concrete block and the base plate at the different stud levels, strain at the base and the mid height of each stud shank were measured at each loading step. In the GSA, the slip was measured by the middle displacement transducers were fastened 20mm inside (at the mid point of 60mm wide stiffener) than the top and bottom ones (10mm from outside of the stiffener) to arrange all six displacement transducers. On the contrary, the slips at the different stud levels were measured by the displacement transducers fastened at 10mm from outside of the stiffener along the height of the stiffener in the UGSA.

In the fatigue test, a set of maximum and minimum load was selected in order to apply the required amplitude of the total shear force of 135, 150 and 165kN with the loading frequency of 3.0Hz. Constant minimum load was kept to be 2.5kN for the pulsating load condition and the magnitude of the maximum and minimum load were set to be equal in absolute sense for the alternating load condition. During the fatigue test, the magnitude of the load, slip and strain at the base of the stud shank were measured by the dynamic data acquisition system. 480 sets of data were recorded by this dynamic system with 5 ms sampling rate after each 5 to 600s interval according to the expected fatigue life of each specimen.

4. DISCUSSION ON STATIC TEST RESULTS

4.1 Shear force-slip relations

The typical shear force-slip relations obtained from the GSA and UGSA for the pulsating load condition are shown in **Fig. 4**. The ordinate indicates the shear force applied to the specimen and the abscissa indicates the average value of the slip at the top, middle and bottom stud levels between the concrete block and the base plate. In this relations, the solid lines stand for the relation at the top stud level, the dashed lines for the middle one and the dotted lines for the bottom one respectively. The slip was recorded by two displacement transducers fastened both sides of the stiffener as mentioned earlier, and the average value is used in the shear force-slip relation. In **Fig. 4**, it is observed that the slip is larger in the order of the top, bottom and middle stud levels. To minimize the effect of the local deformation at the base of the pipe section, the behavior is mainly focused within rather small load range. Consequently, the slip relations are considered here up to the shear force of 120kN.

In **Fig. 4-a** as well as in **Fig. 4-b**, the bottom slip is larger than the middle one. This is the reason why the bearing characteristics[10] of the surrounding concrete at the base of the stud shank is mostly influenced on the slip behavior. The other reason is due to the deformation of the

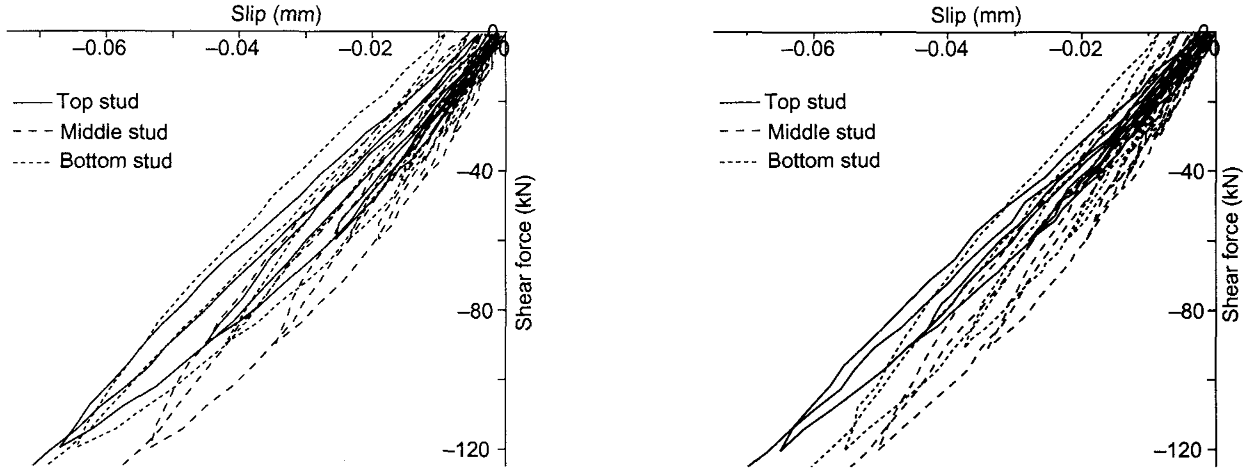

Fig. 4-a Grouped stud arrangement **Fig. 4-b** Ungrouped stud arrangement

Fig. 4 Shear force-slip relations under pulsating load condition

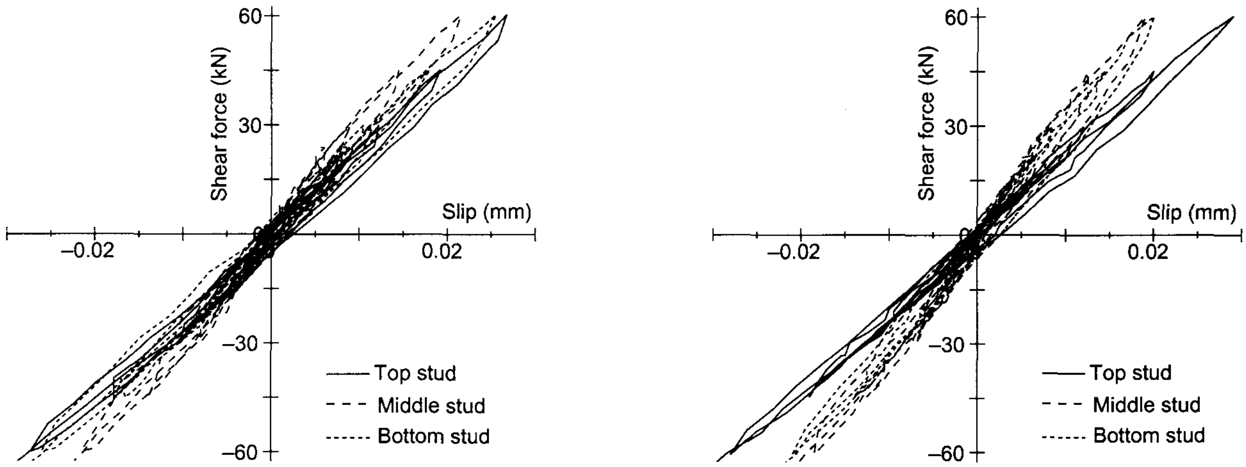

Fig. 5-a Grouped stud arrangement **Fig. 5-b** Ungrouped stud arrangement

Fig. 5 Shear force-slip relations under alternating load condition

concrete block itself. Since the targets (front view in **Fig. 2**) were fastened with the concrete block to support the tips of the displacement transducers, which were fastened with the stiffener, the slip also affects due to the deformation of the concrete block at the target locations during the test. Moreover, the deformation of the base steel plate as well as the unavoidable rotation of the base plate also significantly affects the slip behavior among the studs located at different levels. The typical relations for the GSA and UGSA between the shear force and slip under the alternating load condition are shown in **Figs. 5-a** and **5-b**. In these figures, the slip relations for compression sided loading as well as tension sided loading of the alternating load condition exactly follow the same phenomenon as the pulsating load condition in **Figs. 4-a** and **4-b**.

4.2 Strain behavior of stud shank

The strain behavior recorded at the base of the stud shank as shown in **Fig. 3** for the GSA and UGSA under the pulsating and alternating load conditions is discussed here. Since the static as well as the fatigue failure usually occurs at the base of the stud shank and the base is subjected to large strain response, only the base strain behavior are mentioned here and those are used later for the prediction of shear force distribution among the studs. The typical relations between the shear force and the direct strain at the base of the stud shank for the GSA and UGSA under the pulsating load condition are shown in **Fig. 6**. Both the top and bottom sided strains at the base of each stud shank are shown in this figure for easy understanding the bending strain behavior.

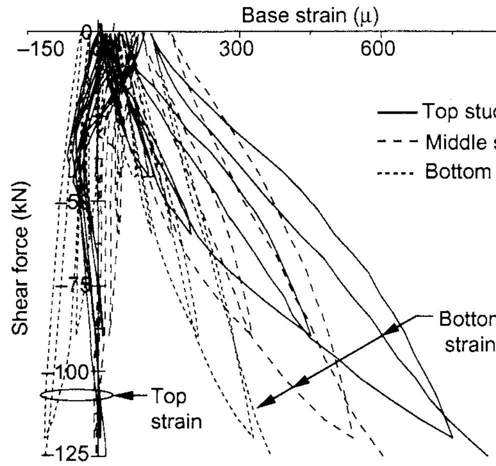

Fig. 6-a Grouped stud arrangement

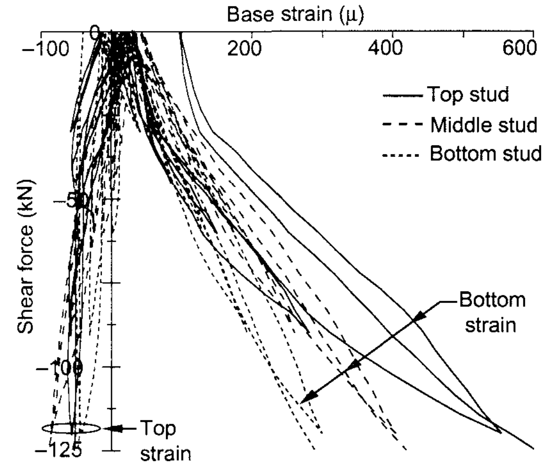

Fig. 6-b Ungrouped stud arrangement

Fig. 6 Shear force-direct strain relations at base under pulsating load condition

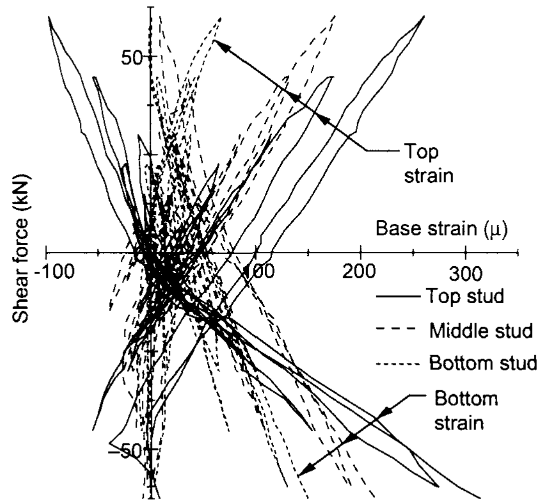

Fig. 7-a Grouped stud arrangement

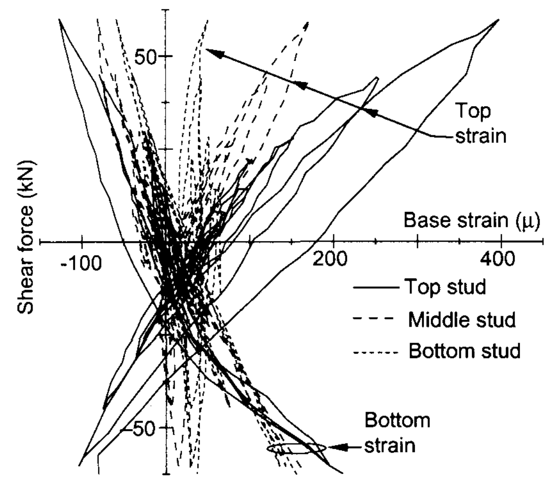

Fig. 7-b Ungrouped stud arrangement

Fig. 7 Shear force-direct strain relations at base under alternating load condition

According to **Figs. 6-a** and **6-b**, it is observed that the bottom strain is larger in the order of the top, middle and bottom stud levels for the both GSA and UGSA. At the base of the stud shank, the bottom strains (tension side) are larger than the top ones (compression side) in the sense of the absolute value for the pulsating load condition. In **Fig. 6**, the bottom sided strains marked by the solid, dashed and dotted lines at the top, middle and bottom stud levels are the average values recorded from two studs at each level as shown in **Fig. 3**. The top strain relations at the different stud levels are considered by same way.

Fig. 7 shows the typical shear force-direct strain relations at the base of the stud shank for the GSA and UGSA under the alternating load condition. In **Figs. 7-a** and **7-b**, the average strain is also larger in the order of the top, middle and bottom stud levels for the GSA and UGSA. All the strain relations in **Figs. 6** and **7** for the GSA and UGSA under the pulsating and alternating load conditions show similar behavior. The strain behavior follows a definite trend along the height of the specimen, which is quite different from the slip behavior. To observe the bending strain behavior among the stud levels for the GSA and UGSA, bending strain is estimated from the direct strain at the base of the stud shank considering elementary beam theory. The bending strain at any section is the half of difference between the top and bottom strains in **Fig. 3**, whereas the axial strain is the average of the top and bottom strains.

The typical bending strain relations at the base for the pulsating and alternating load conditions are shown in **Figs. 8** and **9**. The bending strain

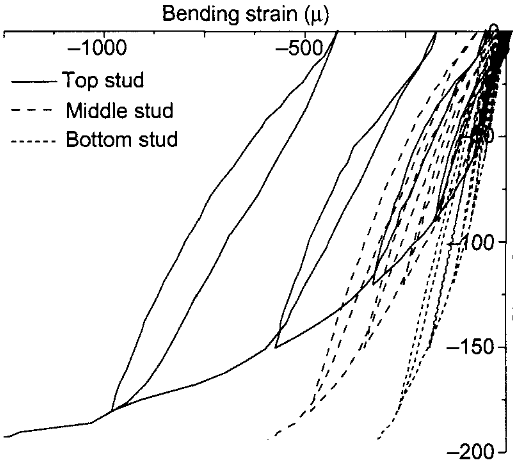

Fig. 8-a Grouped stud arrangement

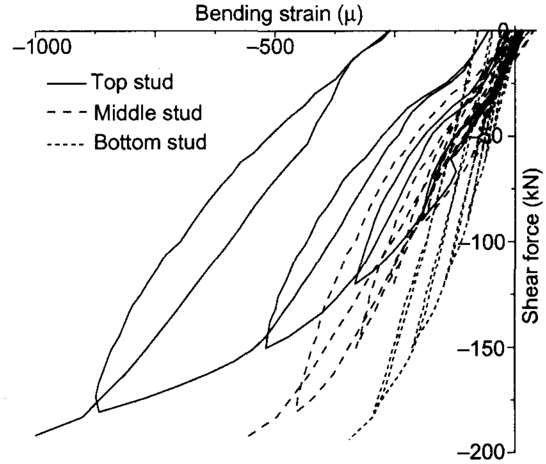

Fig. 8-b Ungrouped stud arrangement

Fig. 8 Shear force-bending strain relations at base under pulsating load condition

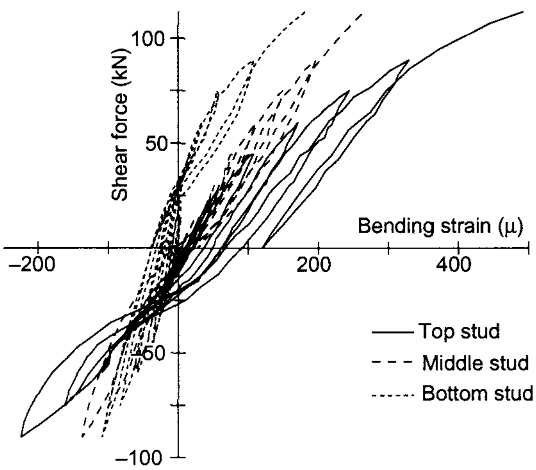

Fig. 9-a Grouped stud arrangement

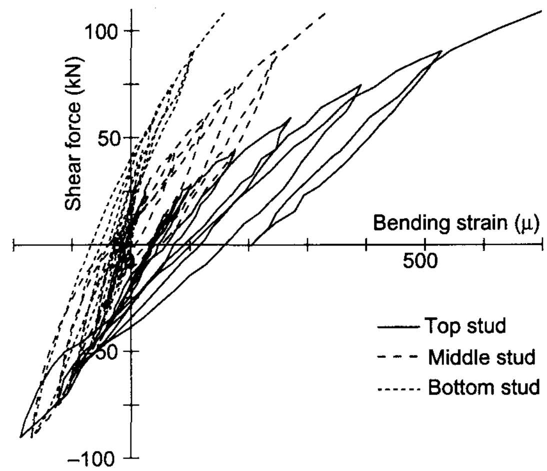

Fig. 9-b Ungrouped stud arrangement

Fig. 9 Shear force-bending strain relations at base under alternating load condition

is also larger in the order of the top, middle and bottom studs for the GSA and UGSA. For the prediction of the shear force transmission through the base of the stud shank, shear force-bending strain relations[5),6)] at the base of the stud shank were utilized because of well correlation among the plotted data. The experimental study was carried out on push- and pull-out test specimen with a pair of pipe studs. In this study, bending strain relations also showed better correlation among the several strain relations and used later for the shear force transmission by each stud.

4.3 Shear force amplitude-slip amplitude relation

The relation between the amplitude of the shear force and corresponding slip amplitude are constructed from shear force-slip relations to predict the shear force distribution among the studs. The relations between the shear force amplitude and the slip amplitude for the GSA and UGSA under the pulsating and alternating load conditions are shown in **Fig. 10**. The ordinate stands for the shear force amplitude applied to the specimen and the abscissa stands for the slip amplitude. The amplitude of the shear force is defined as the difference between the maximum and minimum peak values within the range of 120kN shear force amplitude and the corresponding strain amplitude is considered for the GSA and UGSA. By this way a number of sets of shear force amplitudes and the corresponding slip amplitudes for the pulsating and alternating load conditions are estimated from the experimental records. The average value of the three similar tests results is considered for the GSA and UGSA in amplitude relations.

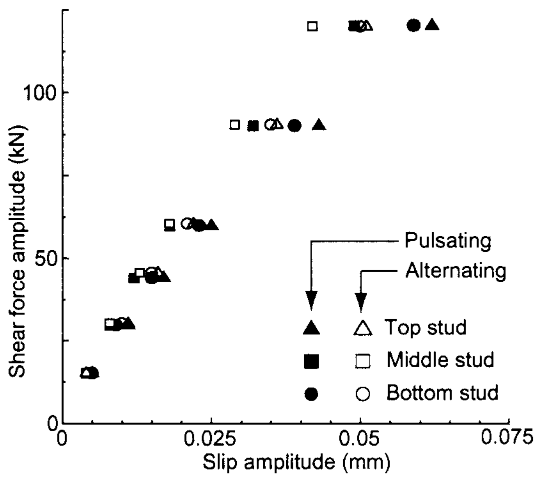

Fig. 10-a Grouped stud arrangement

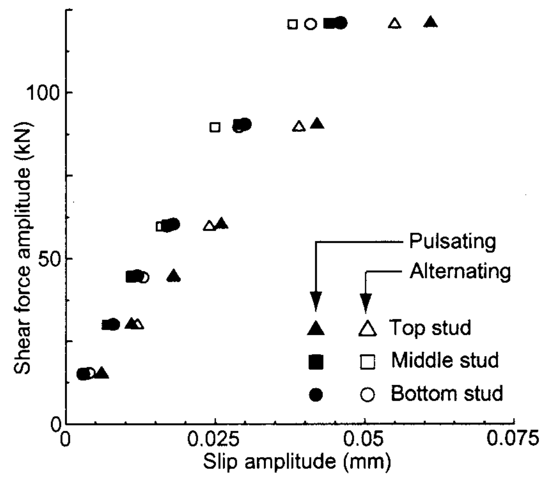

Fig. 10-b Ungrouped stud arrangement

Fig. 10 Shear force amplitude-slip amplitude relations

Although the pipe studs were employed in this research, the local deformation may be overcome within the 120kN shear force amplitude. Moreover, the shear force distribution among the studs does not change significantly within the shear force amplitude of 120kN. In **Fig. 10**, the solid circle, square and triangle are for the pulsating load condition while the open circle, square and triangle are for the alternating load condition. The slip amplitude is larger in the order of top, bottom and middle studs for the GSA and UGSA.

4.4 Shear force amplitude-strain amplitude relation

The strain amplitude is estimated from the strain relation and only bending strain relations are considered here because of better correlation among the plotted data. The relations between the shear force amplitude and the bending strain amplitude at the base of the stud shank for the GSA and UGSA under the pulsating and alternating load conditions are shown in **Fig. 11**. In the GSA and UGSA, the strain amplitude at the top, middle and bottom studs under the pulsating load condition is greater than the ones under the alternating load condition for a particular shear force amplitude. This is the reason why the difference between the axial force at the peak and zero shear forces under pulsating load condition is larger than the one at maximum and minimum peak loads under the alternating load condition[5].

4.5 Shear force distribution

To estimate the percentage of total shear force carried by individual stud at the different levels, the slip amplitude relations in **Fig. 10** and bending strain amplitude relations at the base in **Fig. 11** are considered here. The shear force distribution among the top, middle and bottom stud levels for the GSA and UGSA are shown in **Fig. 12** based on the slip and bending strain consideration. For a particular shear force amplitude of 90kN in **Fig. 10**, secant lines are drawn up to the corresponding slip amplitude at each stud level and the distribution is calculated considering the slip amplitudes. By this way the shear force distribution at each shear force amplitude is estimated for the GSA and UGSA under the pulsating and alternating load conditions. It is observed that the distributions at all the shear force amplitude levels are almost same and the typical one is shown in **Fig. 12-a**.

In the slip consideration as shown in **Fig. 12-a**, the percentages of the total shear force carried by top and bottom studs in the GSA under the both load conditions are almost same and greater than the middle one. On the contrary, in the UGSA, top, middle and bottom studs carry about 42%, 28% and 30% of the total shear force. The relations associated with the slip behavior shown in **Figs. 4, 5** and **10** show different tendency from the strain behavior. This is due to the reasons with some uncertainties of the recorded slip data as explained earlier. Therefore, the trend of this distribution may not be accepted as a typical distribution for the shear force transferred.

In **Fig. 12-b**, the percentage of the total shear force carried by the studs in different levels is larger in the order of top, middle and bottom

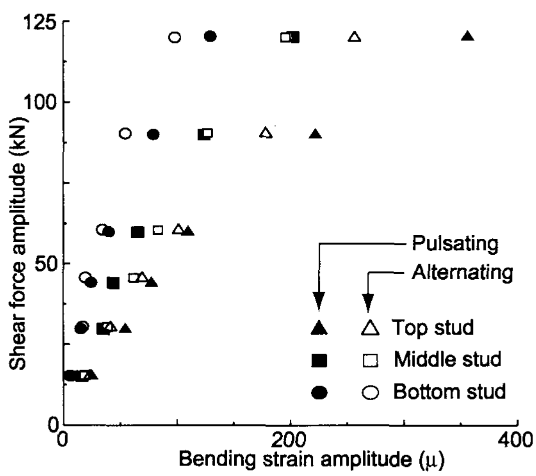

Fig. 11-a Grouped stud arrangement

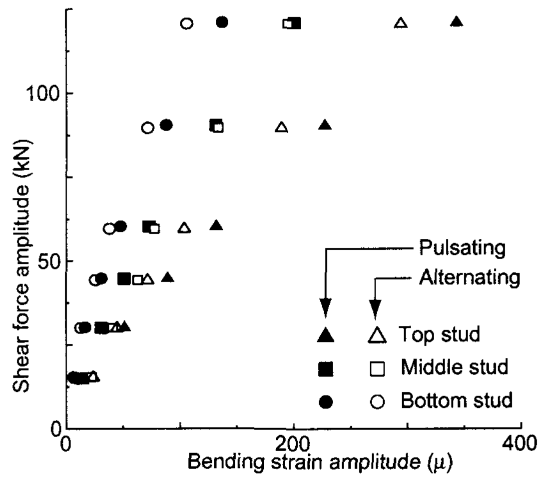

Fig. 11-b Ungrouped stud arrangement

Fig. 11 Shear force amplitude-bending strain amplitude relations at base

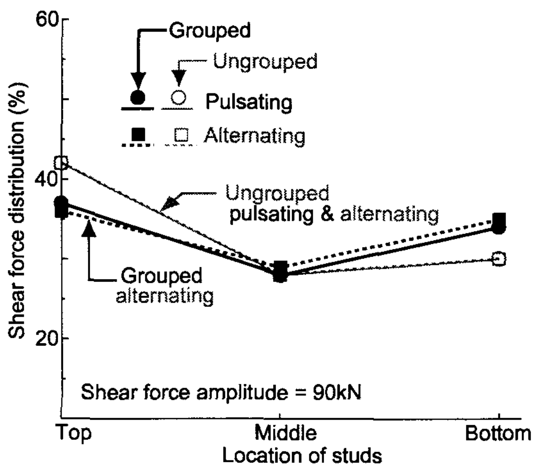

Fig. 12-a Based on slip consideration

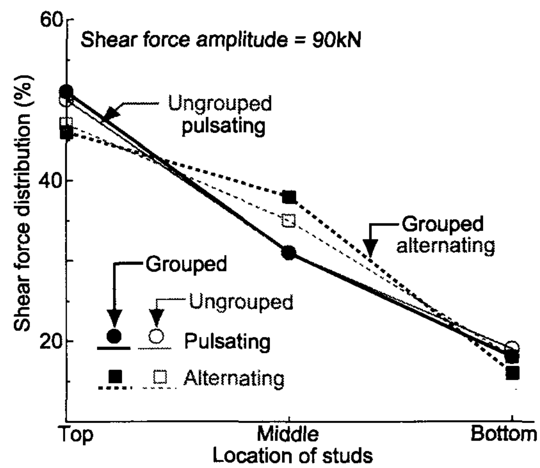

Fig. 12-b Based on bending strain consideration

Fig. 12 Shear force distribution among the studs

studs, which means that the distribution follows a definite trend along the height of the specimen and this fact is clearly visible. The same procedure as the slip consideration is adopted for estimating the shear force distribution based on the bending strain consideration. In this regard, the distribution based on the bending strain consideration is more reliable because the strain is so sensitive to detect any response near the base of the stud shank and it can be accepted as a typical one.

The shear force distribution in **Fig. 12-b** under the pulsating load condition for the GSA and UGSA is almost same. This indicates that the effect of stud arrangement is not so significant for the shear force transferred. On the other hand, under the alternating load condition, the shear force distributions for the GSA and UGSA are also almost same. The variation of the shear force distribution between the pulsating and alternating load conditions for the GSA and UGSA is about less than or equal to 5%. The percentages of the total shear force carried by the top, middle and bottom stud levels are about 50%, 30% and 20% for the GSA and UGSA under the pulsating load condition, whereas 47%, 35% and 18% of the total shear force are carried by the ones under the alternating load condition. The difference of the distributions under the pulsating and alternating load conditions is insignificant. However, it can be concluded that the shear force distribution at the top, middle and bottom stud levels is about 50%, 30% and 20% irrespective of the applied shear force types as well as the stud arrangements. This distribution will also be applicable for the conventional solid studs specimen,

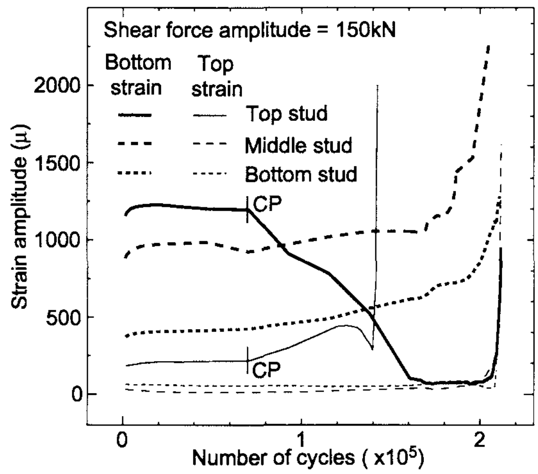

Fig. 13-a Grouped stud arrangement

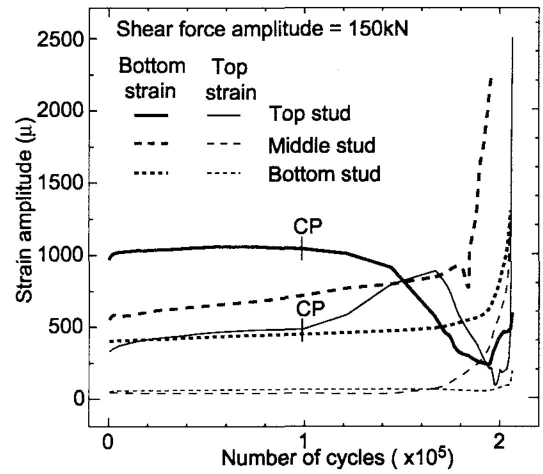

Fig. 13-b Ungrouped stud arrangement

Fig. 13 Direct strain amplitude-number of cycles relations under pulsating load condition

Table 1 Fatigue life (cycles) of studs in grouped and ungrouped arrangements

	Pulsating load condition		Alternating load condition	
Shear force amplitude	GSA	UGSA	GSA	UGSA
165kN	110460	78600	148530	143750
150kN	211080	205390	737150	174500
135kN	274260	460730	1071990	443280

because the pipe stud[5),6)] experimental results almost similar with the solid stud one.

5. DISCUSSION ON FATIGUE TEST RESULTS

5.1 Strain amplitude-number of cycles relation

The typical relations between number of cycles up to the fatigue failure and the strain amplitude at the base of the top, middle and bottom studs for the GSA and UGSA under the pulsating load condition are shown in **Fig. 13**. The strain amplitude was obtained from the difference between the maximum and minimum strains in a couple of cycles at each time interval. From **Fig. 13**, it is observed that the bottom sided strains at the base is larger than the top sided ones under the pulsating compression loading. Moreover, the bottom sided strain in **Fig. 3** is larger in the order of top, middle and bottom stud levels. This tendency agrees well with the one under the static test shown in **Fig. 6**. According to **Fig. 13-a**, the bottom strain of the top stud suddenly decreases after a certain number of fatigue cycles, where the fatigue cracks were developed near the bottom strain gauge and reduced the shear force transmission. On the other hand, top strain gauge receives more response due to the fatigue crack developed near the bottom strain gauge and finally fails. Similar fact is also observed in **Fig. 13-b**.

The typical relations between the strain amplitude and number of cycles at the base of the studs for the GSA and UGSA under the alternating load condition are shown in **Fig. 14**. In this figure, the difference between the top and bottom strains in the top stud level is rather larger, which is similar with the one under the pulsating shear force. According to the **Figs. 13** and **14**, it is clear that the strain gauges installed at the top stud failed earlier due to larger percentage of the shear force transmission as shown in **Fig. 12**. Furthermore, the strain gauge at the base of the stud can be used to monitor the fatigue failure of the pipe stud carefully.

5.2 Shear force amplitude-number of cycles relation

The shear force amplitude-number of cycles (S-N) relations for all the specimens are shown in

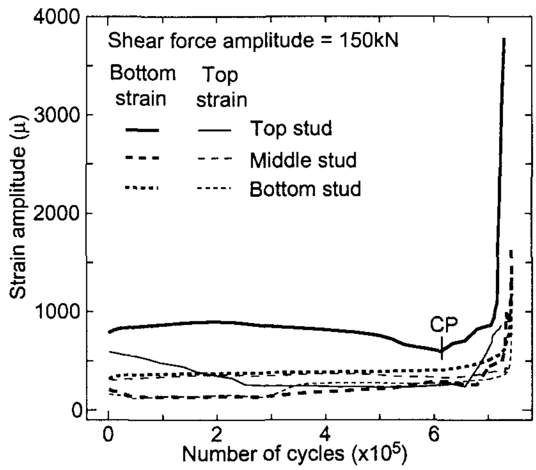

Fig. 14-a Grouped stud arrangement

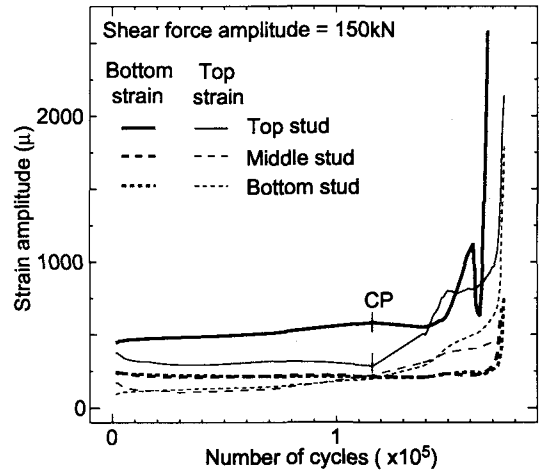

Fig. 14-b Ungrouped stud arrangement

Fig. 14 Direct strain amplitude-number of cycles relations under alternating load condition

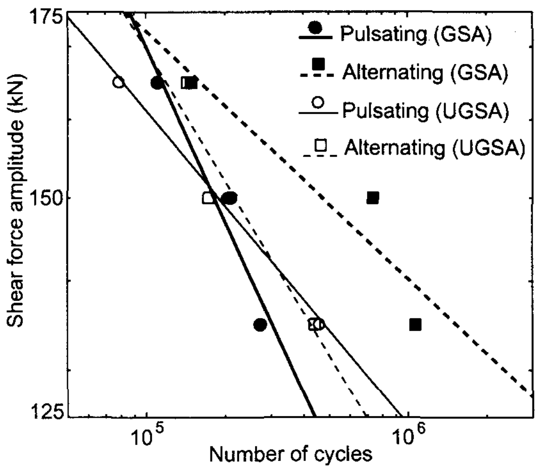

Fig. 15-a S-N curves for fatigue test

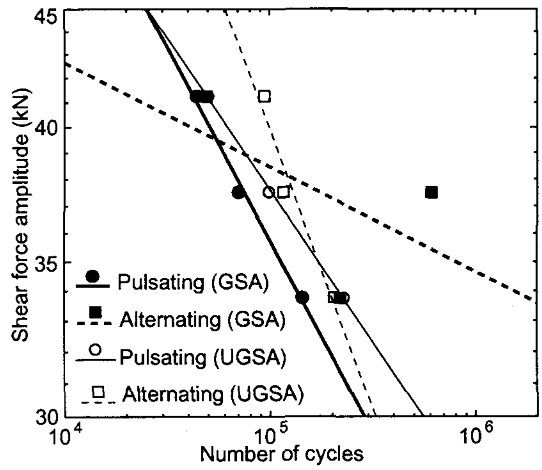

Fig. 15-b S-N curves for single stud

Fig. 15 Shear force amplitude-number of cycles (S-N) relations

Fig. 15-a. The ordinate is the amplitude of the shear force and the abscissa is the number of the cycles of the shear force up to the fatigue failure of the specimen. The regression lines are plotted to observe the correlation among the plotted data. From **Figs. 13** and **14**, it can be seen that the larger strain amplitude at the base of the top stud under the pulsating load condition is larger than the one under the alternating load condition. Then, the fatigue life under the alternating load condition is expected to be longer than the one under the pulsating load condition at the same shear force amplitude. From **Table 1**, it is clear that this fact is not always exists within small number of data as well as for the large scattering among the plotted data.

Finally, the S-N relations for the single stud in the GSA and UGSA are investigated in **Fig. 15-b** based on the commencement of first fatigue crack at the base of the top stud. In **Figs. 13** and **14**, the commencement of the first fatigue crack after a certain number of shear force cycles is marked by "CP", which means the critical point. In this regard, the shear force carried by one stud at the top level is taken as the ordinate. Because the larger percentage of the total shear force is carried the stud at the top level. The abscissa is the number of fatigue cycles is estimated from the strain amplitude-number of cycles relations of all the tests for the top stud only. In the fatigue tests under the pulsating and alternating load conditions, the studs at the top level of the specimens failed first in the GSA and UGSA. In this study with few numbers of the test data as shown in **Fig. 15-b**, it is rather difficult to draw conclusion. Therefore it needs to continue the research work with large number of specimens.

6. CONCLUSIONS

The following conclusions may be drawn based on the observations through the experimental study carried out in this research on the GSA and UGSA:

1) To predict the shear force distribution the strain response at the base is more appropriate than the mid height one and the slip response. In this regard, pipe stud shear connectors are employed instead of generally used solid ones in the GSA and UGSA. Bending strain amplitude relations obtained from the bending strain relations at the base are used to predict the shear force distribution among the studs.
2) The percentage of the total shear force carried by the top, middle and bottom studs are not equal in the GSA as well as in the UGSA. The top, middle and bottom studs in the GSA and UGSA under the pulsating load condition as well as under the alternating load condition carry about 50%, 30% and 20% of the total shear force.
3) The top stud fails first during the fatigue tests and this fact supports that the top stud transfers larger percentage of shear force.
4) The strain gauge at the base of the stud shank in different levels can carefully monitor the fatigue failure.
5) The S-N relations for the single stud in the GSA and UGSA are investigated based on the commencement of the first fatigue crack at the base of the top stud. These relations may be useful to estimate the shear force carried by each stud in other arrangements.

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