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Numerical model for predicting composite behavior of stud shear connectors

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Abstract

The objective of this research is to study the behavior of stud shear connectors numerically and compare the numerical prediction with the experimental results to validate the numerical method. In this regard a numerical model is developed for the prediction of static behavior of the stud shear connectors, which are commonly used in the composite structure construction. The accuracy of the numerical evaluation significantly depends on the proper modeling of shear force transmission from stud shank to surrounding concrete. To attain this effectively, one-dimensional nonlinear bearing springs are employed and the characteristics of these are estimated from the bearing test of concrete. The numerical method and model proposed are validated by comparing its findings such as strain at the base and at mid height of the stud shank and slip with the experimental results.

Keywords: stud shear connector, numerical analysis, nonlinear FEA, experiment, slip, base strain

1. Introduction

Shear connectors are usually used in the composite constructions for instance steel-concrete composite girder bridge, mixed rigid bridges and steel building construction to achieve composite action of the component members. Experimental study is the key resource, which is essential to investigate the complicated behavior of the composite structure or its component. Parallel to the experimental investigation, numerical prediction bears noble achievement to justify the behavior of the composite structure. The base of the stud shank is subject to large deformation and the static as well as the fatigue failure may occur at its base. Therefore, it is important to observe the strain behavior at the base of the stud shank by both the experimental and numerical tests.

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Moreover, base strain is a more appropriate measure to predict the shear force transmission through the stud shank.

To measure the base strain experimentally by employing generally used solid stud is rather impossible because of welding at the base and coating provided to protect the strain gauge. Pipe stud shear connector[1,2] is effectively used to measure the base strain experimentally. Numerical evaluation plays important role to validate the experimental results or vice versa. Incidentally, a numerical model is developed to evaluate the static responses of pipe stud shear connector. The numerical analysis can check any variation for instance geometry or material properties more easily, while experimental investigation is rather time consuming and expensive as well. Appropriate modeling of the composite system such as the shear connector, surrounding concrete and the interaction between them plays a significant role and the accuracy of the numerical analysis totally depend on how well these are modeled.

To this end, Civjan and Singh[3], Salari and Spacone[4] and Spacone and El-Tawil[5] are some of the researchers, who had investigated the shear behavior of the composite structure or its components. But the research on the behavior of the shear connector itself is quite limited. Moreover, the investigation on the base strain behavior of the stud shank either by the experiment or numerical method is almost absent, although many researchers reported some numerical results. On the other hand, Nakajima et al.[6] investigated the behavior of stud shear connectors under the pulsating and alternating load conditions numerically and compared those with the experimental results. No comparison of the strain behavior of the stud shank is available. Miah et al.[7] improved the accuracy of the strain and slip behavior of the stud shear connector based on the method proposed by Nakajima et al.[6]. The strain behavior at the base of the stud shear connector was investigated, but no comparison was made with the experimental results.

In this study, attention is paid towards the base strain behavior of the stud shear connector. Nonlinear finite element method along with Timoshenko beam theory is employed for the numerical analysis. The numerical results are compared with the experimental ones to validate the numerical formulation for the pulsating and alternating load conditions. The load condition with the compressive shear force cycles is defined as the pulsating load condition and the reversed cyclic shear force is defined as the alternating load condition.

2. Push-and pull-out test specimen

The push- and pull-out test specimen[1,2] shown in Fig. 1, is briefly introduced here and the results obtained from the test specimen are used afterward for the comparison. A pair of headed pipe studs with inside diameter 17.9mm, outside diameter 21.7mm and length 120mm was welded on the base steel plate (530mm×120mm×13mm). The size of the stud head and the welding are shown with the test specimen. Another steel plate (350mm×60mm×19mm) was welded to the base plate on the other side to increase the stiffness of the base plate and to provide sufficient resistance against plate bending. Two displacement transducers were installed to measure the slip between the concrete block and the base plate at the same level of the studs. One pair of strain gauges was installed on the inside face of the stud at the base level and another pair on the outside face at the mid height of each stud as shown in Fig. 1. The inside area of the pipe stud was then filled with cement mortar to minimize the local deformation of the pipe section during the tests.

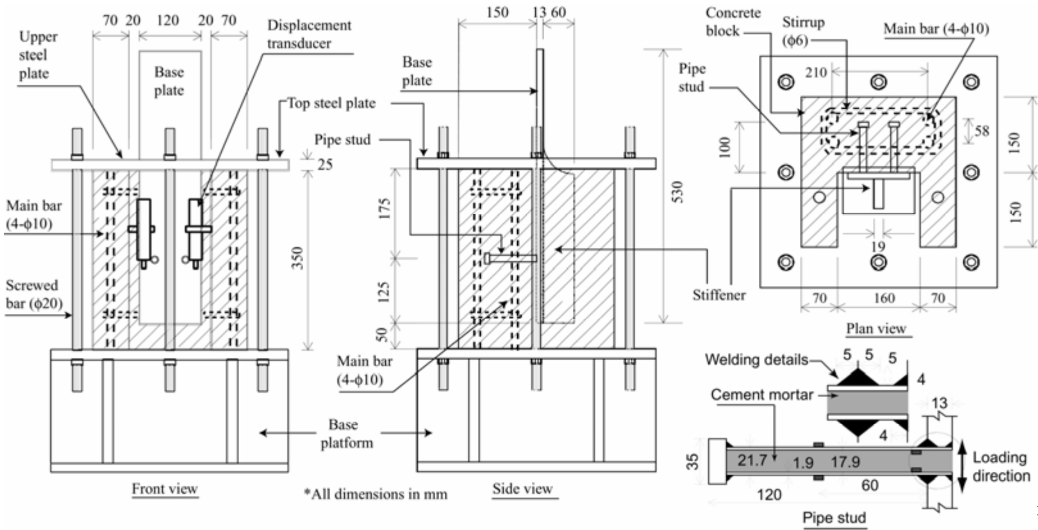
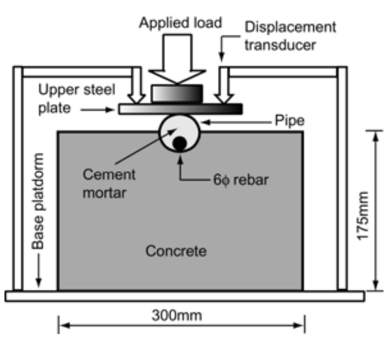


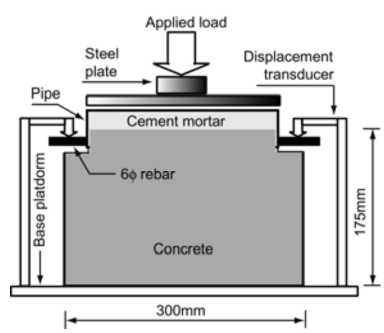
Fig. 1 Outline of test specimen

3. Bearing Test

The bearing test specimen is shown in Fig. 2 and was employed to conduct the bearing test to determine the bearing characteristics. The bearing test specimen was composed of the concrete block with the same height from the fixed end to the centerline of the stud shank of the push- and pull-out test specimen[1,2] shown in Fig. 1. A 6mm diameter rebar was welded at the inside bottom of the pipe to measure the relative displacement. The pipe was also filled with cement mortar after concreting. Two displacement transducers were placed on the top steel plate and another two were on the rebar as shown in Fig. 2 to measure the relative displacement. After a certain load level for instance 30kN, the rate of change of the rebar displacement apparently decreased. Consequently the stiffness increased with increased load levels. This was due to some set back in the experimental setup. However, for the numerical model, the initial stiffness value was used for the total loading range.



(a) Front view



2(b) Side view

Fig. 2 Bearing test specimen

4. Analytical model

4.1 Outline of the numerical model

When the studs are employed in the steel-concrete composite structure, the applied shear force is usually transferred by the bearing force between the stud shank and the surrounding concrete across the transverse direction of the stud shank. Therefore, attention is focused on the proper modeling of the bearing force as shown in Fig. 3, which is the key resource for accurate numerical analysis to trace the mechanical behavior of the stud shear connectors.

Based on the geometry and loading symmetry, half of the specimen is modeled in this regard. The numerical model is shown in Fig. 4 including the base plate, stud and surrounding concrete. The 120mm length stud shank and 250mm length base plate are modeled as 24 and 26 beam-column elements respectively. The base plate is considered symmetrical with respect to the axis of stud shank. The effect of the stiffener is taken into account by the way of increasing the thickness of the base steel plate.

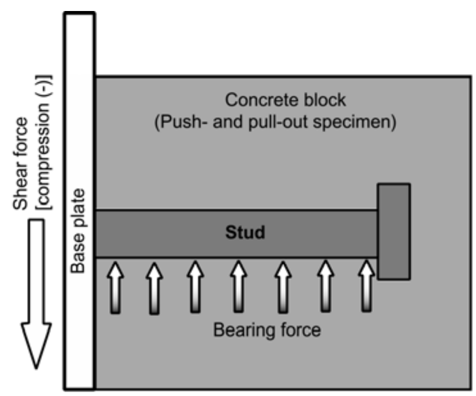


Fig. 3. Bearing force of concrete

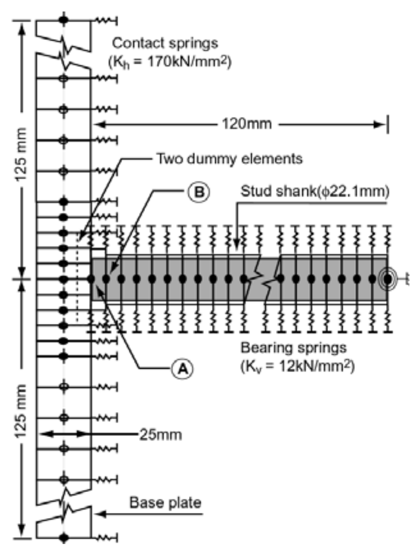
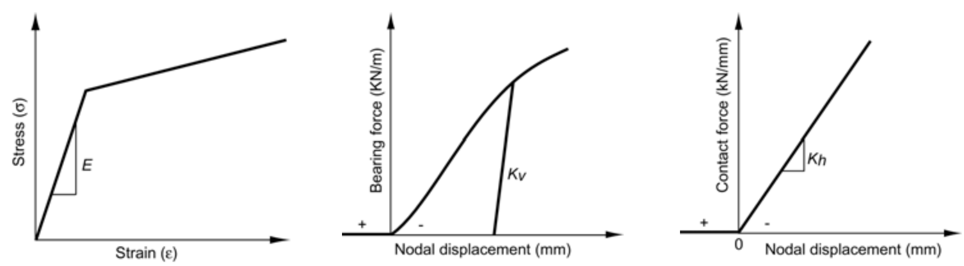


Fig. 4 Numerical model

4.2 *Stud and base plate*

Two-dimensional nonlinear finite element method along with Timoshenko beam model is employed for the numerical analysis of the stud and base steel plate. The base of the stud shank in the test specimen was little thicker than the diameter of stud itself due to welding. The length of the welding of 5mm with tapered section and average thickness of 2.5mm is considered in numerical analysis. The strength of the cement mortar inside of the pipe is considered in terms of increased flexural stiffness (EI) of the pipe itself. In this regard, the flexural rigidity of the pipe stud is increased by 13.5%.

The thickness of the base steel plate is assumed to be 25mm instead of 13mm in order to account for the effect of stiffener. The stud and the base plate are modeled as the beam-column element with geometrical and material nonlinearities. For geometrical nonlinearity, finite displacement and infinitesimal strain problem are taken into account since it is rational and realistic for general framed structures. The constitutive relation for the stud and base plate is shown in Fig. 5(a), which includes Von Mises yield criterion, associate flow rule and linear kinematic hardening.



(a) Stud and base plate (b) Bearing springs (c) Contact springs

Fig. 5. Constitutive relation of different materials

The material properties such as Young's modulus (E) and Poisson's ratio (ν) are considered as 210kN/mm^2 and 0.3 respectively. Initial yield stress (σ_y) and the effective shear coefficient[8] (κ) are taken as 235N/mm^2 and 0.575 for the stud and 293N/mm^2 and 0.867 for the steel plate. The kinematic hardening parameter H is assumed as 1% of the Young's modulus E. Two stress components, one normal component in longitudinal direction and another shear component in the transverse direction are considered whereas the other components are assumed to be zero. A particular stress integrating algorithm with little modification of the return-mapping algorithm[9] is considered here for the simulation of the above plastic constitutive relation with two stress components.

4.3 *Bearing spring*

For the accurate numerical analysis, it is of course important to take into account the proper bearing characteristics between the stud shank and the surrounding concrete. The bearing force to relative displacement relation obtained from the bearing test is shown in Fig. 6. The ordinate shows the bearing force applied per unit length of the pipe (Fig. 4) and the abscissa shows the relative displacement between the rebar and base platform shown in Fig. 2. A fourth order polynomial curve given by the following equation (Eq. 1) is assumed to fit the envelope curve of the mechanical characteristics of the bearing springs shown in Fig. 5(b) for nonlinear hardening.

$$P = a_1\delta + a_2\delta^2 + a_3\delta^3 + a_4\delta^4 \qquad (1)$$

where, P is the bearing force and δ is the relative displacement at any load level.

The coefficients a_1, a_2, a_3, and a_4 are determined from best fit curve and are taken as 1.43, 6.30, -8.96 and 3.45 respectively. The spring constant (K_v) per unit length along the stud shank was estimated to be $12kN/mm^2$ based on the unloading stiffness of the bearing force-relative displacement relation. The bearing force for an element is distributed equally to two nodes that belong to the element. So, the spring constants of the base and tip springs are proportionately evaluated as per contributing length. The bearing springs are considered to be active only in compression and arranged between the stud shank and the virtual fixed end. One-dimensional return-mapping algorithm[9] is employed to compute plastic effect of the bearing springs.

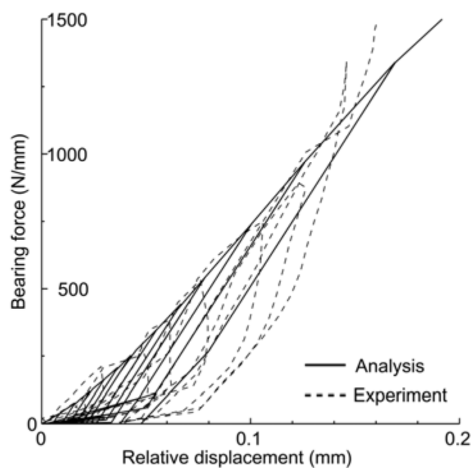


Fig. 6. Bearing force-relative displacement relation

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4.4 Contact spring

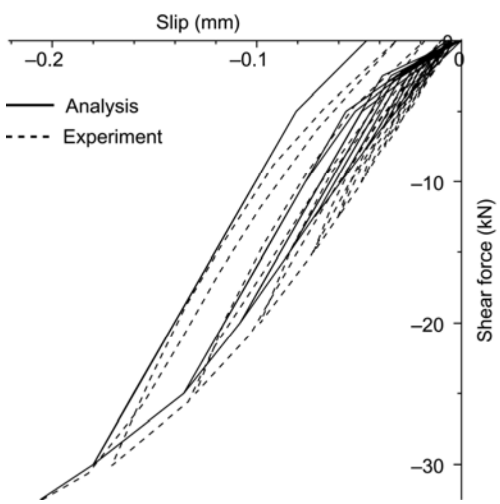
The natural bond between the concrete block and base steel plate was omitted by providing craft tape and grease before placing concrete in test specimen. In numerical analysis the contact surface between the concrete block and base plate is modeled as a type of penalty[10] springs provided horizontally as shown in Fig. 4. The spring constant (K_h) of the contact springs is estimated by trial and error and its magnitude is considered sufficiently large and taken as $170kN/mm^2$. It is assumed that the spring works only in compression and constitutive relation of the contact spring is shown in Fig. 5(c).

5. Comparison of numerical and experimental responses

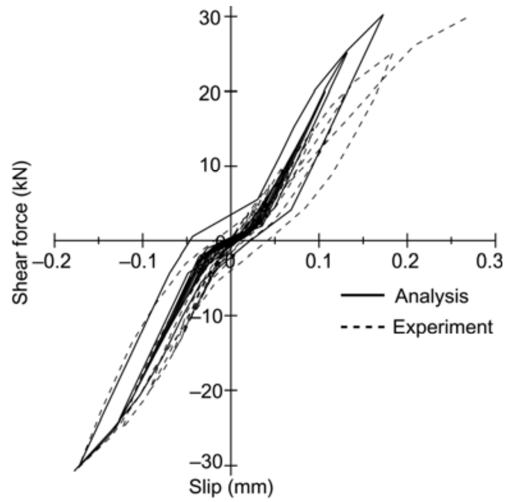
The numerical evaluations of the stud shear connectors obtained from two-dimensional nonlinear finite element method are discussed and compared with the experimental results for the pulsating and alternating load conditions.

5.1 Shear force-Slip relation

The relation between the shear force and slip obtained from the numerical analysis for the pipe stud is shown in Fig. 7(a) under the pulsating load condition along with the experimental value obtained from push- and pull-out test[1,2]. The same relations obtained from the alternating load condition are shown in Fig. 7(b). The solid lines stand for the result obtained from numerical analysis and the dashed lines stand for the experimental results. The ordinate indicates the shear force applied per single stud and the abscissa indicates the slip between the concrete block and the base plate. The slip is estimated by the vertical displacement at the base node A (Fig. 4) of the numerical model. According to Fig. 7(a), it is observed that the numerical results agree well with the experimental ones under the pulsating load condition. On the other hand, in Fig. 7(b), the agreement between the numerical and experimental results for compression sided loading are found to be good under the alternating load condition, but for tension side loading the estimation by the numerical analysis is somewhat less than the experimental data.



(a) Pulsating load condition



(b) Alternating load condition

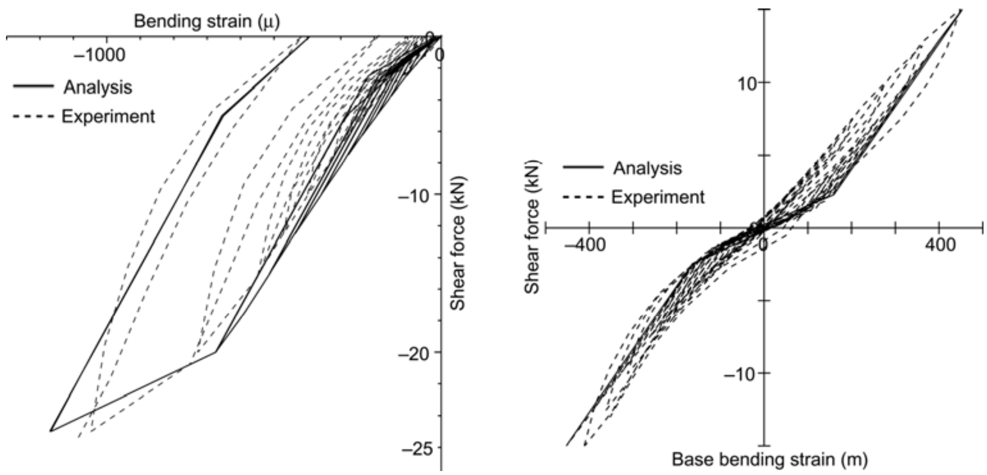
Fig. 7. Shear force-slip relations

5.2 *Bearing force-relative displacement relation*

The relation between the bearing force and the relative displacement obtained from the numerical analysis is shown in Fig. 6 by the solid line and the dashed line shows the one obtained from bearing test. Absolute values are considered for both the bearing force as ordinate and relative displacement as abscissa. In the numerical model, the relative displacement is estimated by the vertical displacement at the node B (Fig. 4). The numerical result agrees reasonably well with experimental one.

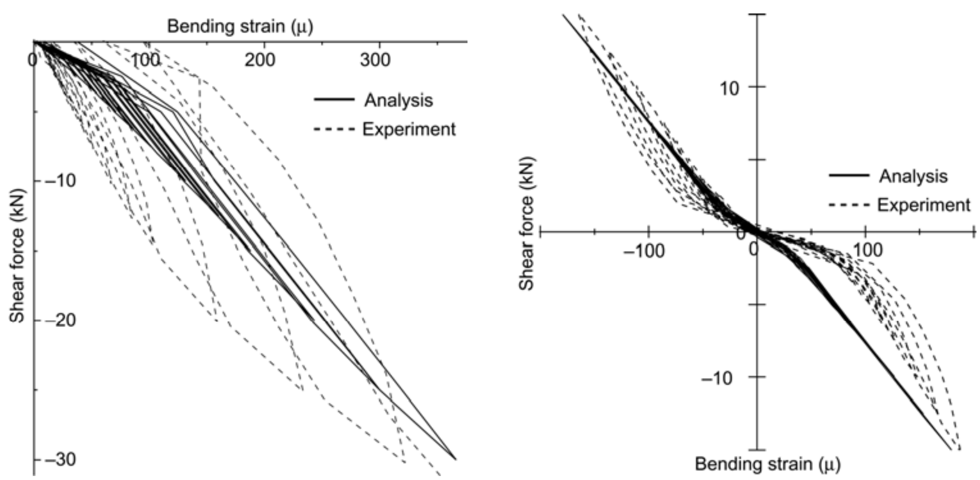
5.3 *Strain behavior of stud shank*

In the numerical analysis, the strain can be estimated at any point along the height of the stud shank. From experimental records, strains are available at the base and mid height of the stud shank. The strain behavior determined from numerical analysis is compared with the experimental ones at the base and mid height of the stud shank for the pulsating and alternating load conditions.



(a) Pulsating load condition (b) Alternating load condition

Fig. 8. Shear force-bending strain relations at base



(a) Pulsating load condition (b) Alternating load condition

Fig. 9. Shear force-bending strain relations at mid height

Only the bending strains at the base and mid height levels obtained from the experimental investigation are compared with the numerical predictions. The bending strains at the base and mid height are estimated from the elementary beam theory and the corresponding relations are shown in Figs. 8 and 9 along with the experimental data. The bending strain relations obtained from the numerical analysis agrees well with the experimental responses. The agreement between the numerical and experimental results for the pulsating load condition is better than the one for the alternating load condition. In the pulsating load condition, the correlation between the numerical and experimental strain behavior at the base of the stud shank is better than those at the mid height level. The shear force-slip relations and shear force-bending strain relations play important role for the structural design and show good correlation with each other. In reality, pipe stud shear connectors are non-existent in the field of composite construction while base strains are almost impossible to measure experimentally for solid studs. However, it can be observed that the numerical results of pipe stud shear connectors predict the experimental response with fair degree of accuracy. Hence, numerical results of pipe stud and solid stud shear connector can be compared with each other to arrive at some practical solution. From numerical solution of both type of studs, shear force amplitude to bending strain amplitude relation are constructed in Fig.10 to investigate the shear force transmission for the pipe stud as well as solid stud (13mm).

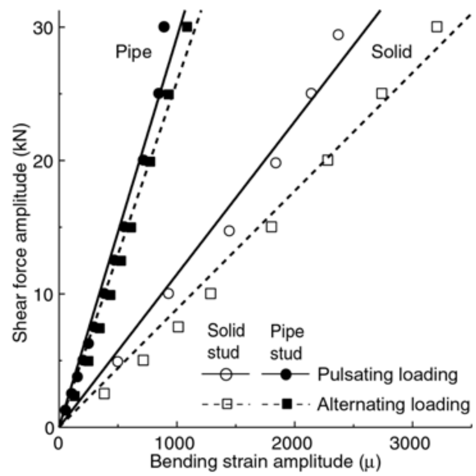


Fig. 10. Shear force amplitude-bending strain amplitude relation

Regression lines are plotted to observe the correlation among the plotted data. For shear force amplitude of 25kN, the bending strain amplitudes of the pipe studs under the alternating load condition are found to be about 10% larger than that under the pulsating load condition. This difference is over 30% for solid studs. On the other hand, the bending strain amplitudes of the solid studs are 2.5 times higher than the pipe stud shear connectors under the pulsating load and 3.0 times larger under alternating load conditions.

6. Conclusions

To evaluate the mechanical behavior like the strain and slip behavior of the stud shear connector, a numerical method has been proposed. One-dimensional bearing springs with nonlinear hardening and beam-column element with geometrical and material nonlinearity are included in this formulation. The assessment from this numerical approach agrees with the experimental results within a certain degree of accuracy ranging from 75% to 95%. Hence, the reliability of this formulation is reasonably established for predicting the behavior of the stud shear connectors.

References

1. Miah, Md. K., Nakajima, A., Saiki, I., Kadogaki, T. and Ooe, H.: Experimental study on Strain Behavior of Pipe Stud Shear Connector Subjected to Various Load Conditions, Proc. of The 5th Symposium on Research and Application of Composite Constructions, pp.231-238, 2003.

2. Nakajima, A., Miah, Md. K., Kadogaki, T., A., Saiki and Ooe, H.: Experimental evaluation of strain behavior of stud shear connector through shear transmission, Proc. of 5th Japanese-German Joint Symposium on Steel and Composite Bridge, pp.481-492, 2003.
3. Civjan, S. A. and Singh, P.: Behavior of shear studs subjected to fully reversed cyclic loading, Journal of Structural Engineering, ASCE, Vol. 129, No. 11, pp.1466-1474, 2003.
4. Salari, M.R. and Spacone, E.: Analysis of steel-concrete composite frames with bond slip, Journal of Structural Engineering, ASCE, Vol. 127, No. 11, pp.1243-1250, 2001.
5. Spacone, E. and El-Tawil, S.: Nonlinear Analysis of steel-concrete composite Structure: State of the Art, Journal of Structural Engineering, ASC}, Vol. 130, No. 2, pp.159-168, 2004.
6. Nakajima, A., Saiki, I., Kokai, M., Doi, K., Takabayashi, Y. and Ooe, H.: Cyclic shear force-slip behavior of studs under alternating and pulsating load condition, Engineering Structures, Elsevier Science Ltd.}, Vol.25, pp.537-545, 2003.
7. Miah, Md. K., Saiki, I. and Nakajima, A.: Numerical evaluation of static behavior of stud shear connectors, JSCE Journal of Applied Mechanics, Vol.7, pp.571-578, 2004.
8. Hutchinson, J.R.: Shear coefficients for Timoshenko Beam Theory, ASME Journal of Applied Mechanics, Vol.68, pp.87-92, 2001.
9. Simo, J.C. and Hughes, T.J.R.: Computational Inelasticity, Springer, 1998.
10. Wriggers, P.: Computational Contact Mechanics, John Wiley Inc., 2002