Strain Behavior of Shear Connectors in Composite Structures

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ABSTRACT

To observe the deformation characteristics of the shear connector employed in steel-concrete composite structure, numerical analysis serves better than that of the experimental investigation. In experiment, installing strain gauges all through the length of the shear connector in infinitesimal interval is rather difficult. On the other hand, in numerical analysis, strain response can easily be computed at each nodal point with infinitesimal interval by developing a suitable numerical model. The accuracy of the numerical computation typically relies on the proper modeling of shear force transmission from the shank of the shear connector to the surrounding concrete. To achieve this requirement, one-dimensional nonlinear bearing springs are employed and the characteristics of those are estimated from the bearing test of concrete

1. INTRODUCTION

The structural system referred to as the steel-concrete hybrid structure is frequently adopted in the developed and developing countries for the construction of buildings and bridges, even in the regions of high seismic risk. Steel-concrete hybrid structure is composed of the composite structure and the mixed structure. Hybrid steel and concrete elements can take many forms. Examples include the steel girder with concrete slab, concrete pier with steel girder, steel framing of a building with the concrete floor slabs, the encasement of a steel element with concrete, or the filling of a steel hollow section with concrete. These hybrid elements rely on the transfer of shear force between the two materials in order to realize the benefits of hybrid action. Benefits can include an increase in strength and stiffness as well as the restraint of buckling instabilities in the steel or confinement of the concrete.

Hybrid action can be achieved through mechanical connection between the steel and concrete members or elements. Typically, mechanical shear connection is accomplished with headed studs. Shear transfer between the steel and concrete through the stud shank allows the two materials to work as a single element. The effectiveness of this shear transfer is determined by the strength of the stud, the integrity and strength of the stud welding, the resistance to crushing or cracking of the concrete surrounding the stud shank and the slip of the two materials (steel and concrete).

The number of bridges is increasing rapidly in the developed as well as in the developing countries all over the world to fulfill the traffic demand. In this regard, considering the high-speed traffic movement and long span bridge, composite bridge is one of the key solutions to meet the traffic requirement. For the composite bridges, appropriate shear connectors need to connect the steel and concrete members for allowing the composite action to develop. The headed studs are commonly used as the shear connectors in all type of the steel-concrete composite and mixed structures belonging to the hybrid structures.

To investigate the complicated behavior of the hybrid structures or its components, the experimental investigation is the key resource. Besides the experimental investigation, numerical evaluation also plays a significant role to examine the mechanical properties of hybrid structures. To conduct experiment with varying geometric properties is a time consuming matter, whereas numerical analysis can easily check the effect of any variation. The advantage and necessity of the numerical evaluation are the followings. While the base of the stud shank is subjected to the most severe deformation, it is not easy to measure the strain at the base of studs experimentally, due to the welding at the base and necessity of the protection of the strain gauges. Moreover, the bearing characteristics between the stud shank and the surrounding concrete can be easily estimated through the numerical analysis rather than experiment.

Many research works were carried out on the behavior of stud shear connectors both experimentally and numerically all over the world from different angle of views. Lloyd and Wright [1], Oehlers [2, 3], and Nakajima et al. [4] are some of the researchers, who worked on shear connector experimentally. On the other hand, Gattesco [5], Civjan and Singh [6], Nakajima et al. [4] and Spacone [7] investigated the behavior of stud shear connector numerically.

Although, a variety of research works carried out from different perspective, but the investigation on the strain behavior as well as the deformation characteristics of the stud shear connector itself is relatively limited. For instance, Nakajima et al. [4, 8] investigated the slip behavior as well as the strain behavior at the mid height of stud shear connectors in composite structures using push- and pull-out test specimens. Employing the pipe stud shear

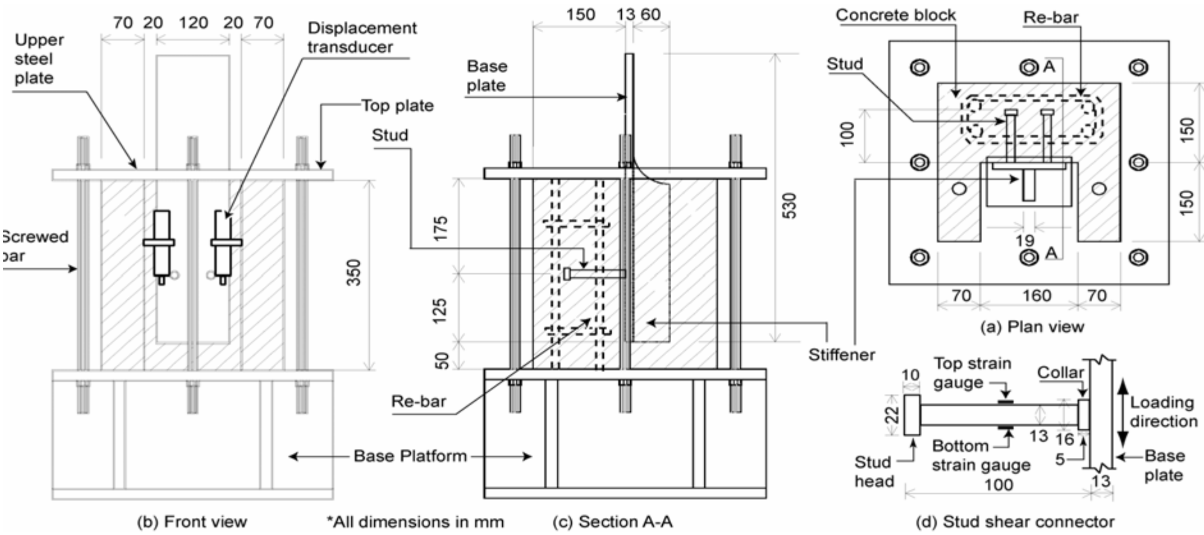


Fig. 1: Specimen details

connector, Nakajima et al. [9] and Miah et al. [10, 11] investigated the strain behavior at the base and mid height of the shear connector in push- and pull-out test specimens. Miah et al. [12, 13] investigated the behavior of shear connector numerically and compared the numerical results with the experimental ones. In this context, the author investigated the deformation characteristics of the developed numerical model [12] of the stud shear connector under the pulsating and alternating shear forces. The shear force with only compressive shear force cycles or only tensile shear force cycles is defined as the pulsating shear force and the reversed cyclic shear force that includes both tension and compression cycles is defined as the alternating shear force.

2. TEST SPECIMEN

The test specimen shown in Fig. 1 is briefly introduced here. A pair of headed studs with diameter 13mm and length 100mm was welded on the base steel plate. The average size of the stud head and the collar are shown with the test specimen. A stiffener was welded to the base plate for increasing the stiffness of the base plate as well as to provide sufficient resistance against plate bending. To resist rotation during the application of load at the top of the base plate, the concrete section (hatched part) was selected as a U-shaped one conveniently. The objective of selecting the shape and size of the specimens was to realize easy application of various types of shear forces in the static and fatigue tests. Four 10mm diameter longitudinal deformed bars and two 6mm diameter stirrups of 200mm spacing (Fig. 1) were provided to overcome the premature cracks in the concrete block.

One pair of strain gauges was installed at the mid height of each stud (Fig. 1). To measure relative displacement between the concrete block and the base plate, a pair of displacement transducers (CDP type) was fastened at same level. Before applying the load, the concrete block was inserted between the steel base platform and the upper steel plate, and that was fixed by eight screwed bars of diameter 16mm. All the eight screwed bars were subjected to almost equal tensile force that was ensured by the torque wrench. The pulsating and alternating shear forces were applied to the specimen by clamping the top of the base steel plate at the head of the loading actuator.

3. MODELING AND ANALYSIS TECHNIQUE OF SHEAR CONNECTOR

The shear force applied to the composite system is transmitted through as the bearing forces between the stud and the surrounding concrete in the transverse direction of stud shank. To observe the behavior of the stud shear connectors, it is of course essential to develop appropriate model of the shear force transmission. Consequently, attention is drawn to model the bearing force between the stud shank and concrete block for the numerical analysis. Half of the specimen is modeled based on geometric and loading symmetry.

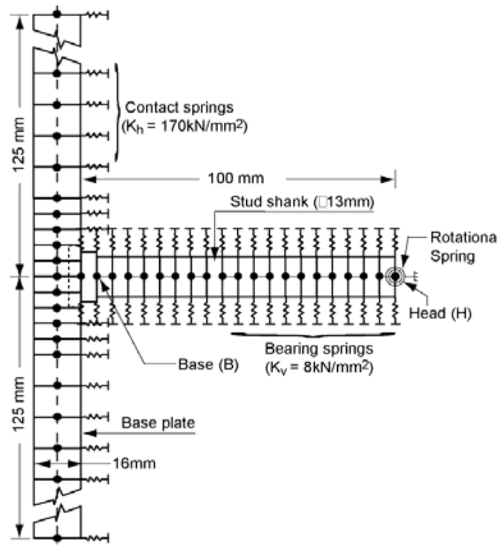
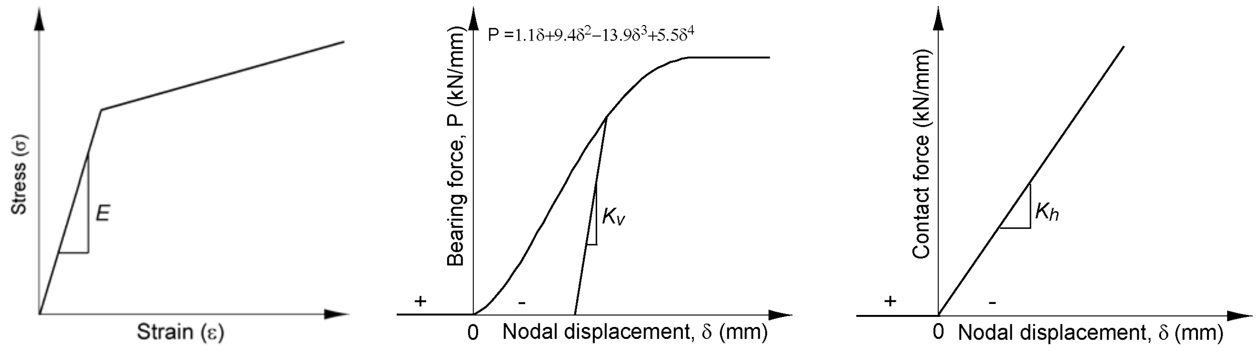


Fig. 2: Numerical Model

The numerical model of the stud shank with the base steel plate, bearing and contact springs (Fig. 2) are employed for the numerical analysis. The stud shank of size 100mm×ϕ13mm is modeled as 20 beam-column elements and the base plate of size 250mm×60mm×13mm is modeled as 26 beam-column elements. The base plate is assumed to be little thicker (16mm) than the actual one (13mm) to include the effect of stiffener. The base plate is considered as symmetrical with respect to the axis of stud shank.



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

Fig. 3: Constitutive relation of different materials

Two-dimensional nonlinear finite element analysis in conjunction with Timoshenko beam theory is employed for modeling the stud and the base steel plate. The welding/collar at the base of the stud shank as shown in Fig. 1 is modeled as an element of diameter 16mm and length 5mm on average. The stud and the base plate are modeled as the beam-column element with geometrical and material nonlinearities. For the constitutive relation of the steel material shown in Fig. 3(a), von Mises yield criterion, associate flow rule and linear kinematic hardening are taken into account.

The kinematic hardening parameter H is assumed as 1% of the Young's modulus E. The Young's modulus E and the Poisson's ratio ν are respectively assumed as 210kN/mm^2 and 0.3 for the stud and the base plate. The initial yield stress σ_y for the stud and the base plate was used 360N/mm^2 and 300N/mm^2 according to the test result and mill sheets. The effective shear coefficient (κ) is assumed as 0.89 and 0.85 for the stud and base plate sections. Two stress components, one normal component in longitudinal direction and the other shear component in the cross section plane are considered and all other components are assumed to be zero. To simulate above plastic constitutive relation with two stress components, a particular stress integrating algorithm by modification of return-mapping algorithm [14, 15] is employed.

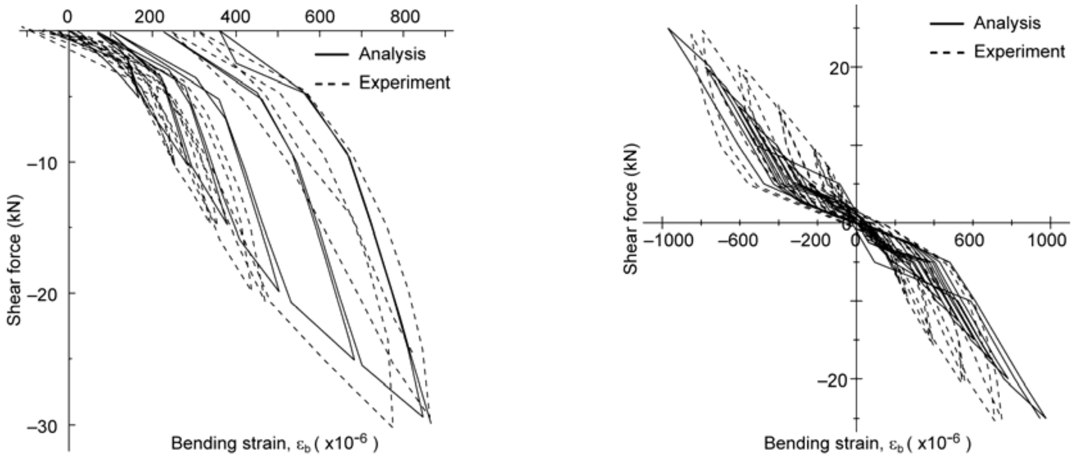
The bearing characteristics of the bearing springs employed in the numerical model was obtained from bearing test [12] of the shear connector. The constitutive relation of the bearing springs is shown in Fig. 3(b). The spring constant (K_v) per unit length was computed to be 8kN/mm^2, which was estimated based on the unloading path as the pulsating load was applied. The bearing force for an element is distributed equally to two nodes, which belong to the element. So, the spring constant of the base and tip springs is assumed to be half of the others. The bearing springs are assumed to be active only in compression and arranged between the stud shank and virtual fixed ends. One-dimensional return-mapping algorithm [14] is employed to compute plastic effect of the bearing springs. The contact surface between the base plate and the concrete block is modeled as a type of penalty [16] spring provided horizontally as shown in Fig. 2. Using trial and error method, the spring constant (K_h) of the contact springs is estimated, which was approximately 170kN/mm^2. The spring works only in compression and the constitutive relation is shown in Fig. 3(c). A rotational spring is incorporated into the stud head so as to take into account the rotational restriction at the stud head. The stud head is also restrained horizontally.

4. STRAIN BEHAVIOR OF STUD SHANK

Since the main objective of the study is to observe the deformation characteristics of the stud shank numerically, it is obviously important to show the performance of the numerical model and analysis procedure employed here. Comparison between numerical and experimental results can judge the degree of accuracy of the numerical model and analysis. This is the reason why test specimen is briefly discussed in Section 2 along with Fig. 1. Mid height strain behavior was recorded during the static test under the pulsating and alternating shear forces. Because of welding at the base, strain gauges could not be attached at the base of the stud shank, only mid height bending strain response is compared with the numerical result in Fig. 4. The bending strain is calculated from direct strains (ε_1, ε_2) using elementary beam theory.

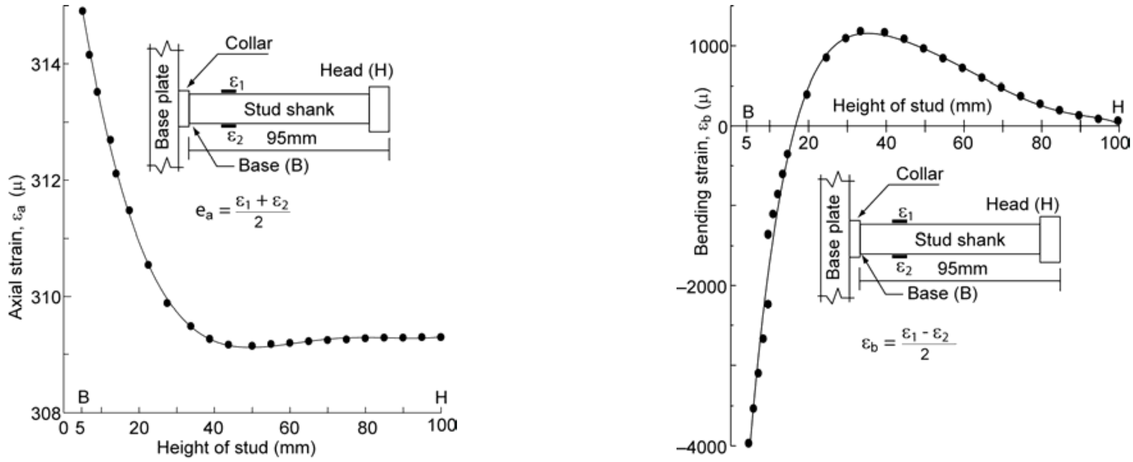
The solid lines (Fig. 4) stand for the results of the numerical analysis and the dashed lines for the experimental ones. According to the figure, numerical results agree with the experimental ones for both types of shear forces. Considering the mid height strain behavior, since the numerical results agree with the experimental ones, it can be expected that the strain at each nodal point along the height of the shear connector obtained from the numerical analysis agree with the experimental responses under the pulsating and alternating shear forces.

the stud shank is subjected to large strain responses as shown in Fig. 5. The base strain plays important role for the design of stud shear connector as well as the prediction of the shear force transmission through the stud shank.



(a) Pulsating shear force (b) Alternating shear force

Fig. 4: Shear force-bending strain relations at mid height

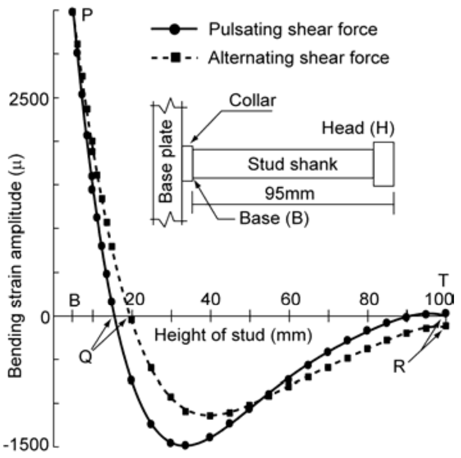


(a) Axial strain (b) Bending strain

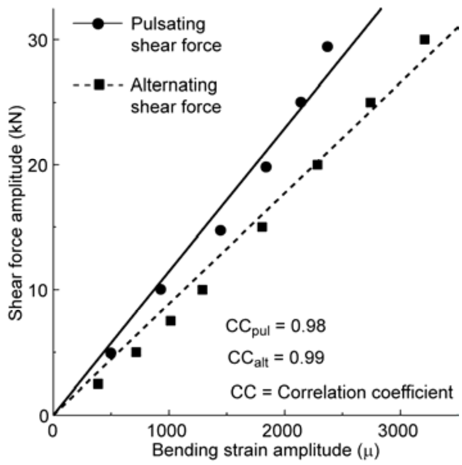
Fig. 5: Strain behavior along mid height of the stud shank

The studs are generally subjected to axial strain and bending strain. The variations of the axial strain as well as the bending strain along the height of the stud shank are shown in Figs. 5(a) and 5(b) for a shear force of 25kN. The ordinate is either the axial strain or the bending strain and the abscissa is the height of the stud from the base, **B** to the stud head, **H**. The height of stud shank is considered here 95mm and collar height is 5mm. The strain variation is shown for 95mm only without 5mm collar. The axial strain occurs maximum at base and gradually decrease towards the stud head but not zero at the stud head. Whereas the bending strain also occurs maximum at the base and change its direction as well as curvature after a certain height from the base, which is zero at the stud head. The bending strain relation in Fig. 5(b) shows that the stud is subjected to double curvatures. In a word it can be said that, the base of

From the bending strains, bending strain amplitudes are estimated along the height of the stud shank and shown in Fig. 6(a) for the pulsating and alternating shear forces. The amplitude of the bending strain is taken as the difference between the maximum and minimum peak values. The two curves, one for pulsating shear force and another for alternating shear force cross each other at the mid height of the stud shank (50mm from the base). The bending strain amplitude in Fig. 6(a) is also very large at the base of the stud shank and it is about 3.5 times larger than that at the mid height in absolute sense. The trace of the bending strain amplitude in Fig. 6(a) along the height of the stud shank is marked by ″PQR″, in which the curvature at ″PR″ portion near the base is opposite from the one at ″RQ″ portion. Therefore, in Figs. 5(b) and 6(a), it is clear that the stud shank is subjected to the double curvatures.



(a) Along stud height



(a) At base

Fig. 6: Bending strain amplitude relation

At the base, the shear force amplitude-bending strain amplitude relations are investigated as shown in Fig. 6(b), to observe the difference between the pulsating and alternating shear forces. The amplitude of the shear force is also taken as the difference between the maximum and minimum peak values of the shear force. Regression lines are plotted in Fig. 6(b) to observe the correlation among the plotted data in which and the correlation coefficients are mentioned. For particular shear force amplitude of 25kN, the bending strain amplitude for the alternating shear force is about 20% larger than the pulsating shear force. This means that the fatigue life of the shear connector under the alternating shear force will be shorter compared the pulsating shear force. Moreover, for the bending strain amplitude of 2000μ, the shear force amplitude under the pulsating shear force is larger, which pointed out that the stud capacity will be larger.

5. CONCLUSIONS

The following conclusion may be drawn based on the observation carried out during this study:

i) The numerical model of the shear connector along with the surrounding concrete and analysis method are developed. The numerical results compared with the experimental responses to validate the numerical method.

ii) The numerical results agree with the experimental ones at mid height.

iii) The base strain responses, which cannot be measured by the experiment, can be evaluated easily by the numerical analysis

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