- Technical Paper -

PARAMETRIC STUDY ON SHEAR CAPACITY OF JOINT BETWEEN UFC SLAB AND STEEL GIRDER USING HEADED STUDS BY FEM ANALYSIS

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ABSTRACT
In a hybrid bridge, the joint of UFC bridge slab and steel girder using headed stud shear connector and non-shrinkage mortar has been developed. Nevertheless, in the real structures, in order to adjust the elevation of the slab, the thickness of the filled mortar is varied, whereas, the shear capacity needs to be ensured. This paper presents a 3D FEM model, which simulated accurately the experimental results. Furthermore, results of a parametric study on shear capacity of the headed stud connection with different mortar thickness and stud height using 3D FEM analysis are reported.
Keywords: shear capacity, headed stud, FEM analysis, slab joint, optimization, bridge

1. INTRODUCTION

In the recent years, deterioration of bridge slab of the aging bridges has become a concern in many countries. It is required to replace deteriorated slabs with the high durable ones. To address this problem, a bridge slab system using ultra high strength fiber reinforced concrete (UFC), which has light weight, high strength and high durability has been developed [1]. For bridge slab replacement, in order to shorten construction time, the UFC slabs are manufactured at a factory, then delivered and jointed with steel bridge girders at construction site. The connection between the UFC slab and the steel girders uses headed studs as shear connectors. The headed studs are welded on the flange of the steel girder. After the UFC slab is located, a non-shrinkage mortar is filled in the hole and the space between the slab and the girder as shown in Fig. 1. There has been a numerous existing research [2-6] focusing on the shear capacity of the connection between concrete slab and steel girder. Nevertheless, there is lack of study for the cases where the slab made of UFC. In this research, push-out tests were carried out to investigate the shear capacity and behavior of the connection between UFC slab and steel girder using headed studs. The detailed results of the experiments are described in the previous paper. Since the existing design method has been developed based on the data of the connection, which used the original concrete slab. Therefore, the applicability of the design method to the case where UFC slab used, was inappropriate.

On the other hand, some researchers conducted finite element analysis (FEM) to simulate push-out experiments of the headed stud shear connectors [7, 8]. However, in the existing papers, the FEM models were made for the cases a concrete slab was used. Moreover, the slab was a solid one and a filled mortar had not been considered. Therefore, this paper presents a FEM analysis model which simulated the joint between the UFC slab and steel girder using headed studs. The results of FEM analysis were verified with the experimental results.

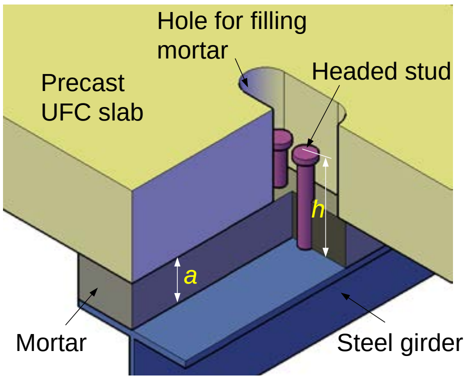

Fig.1 Joint between UFC slab and steel girder using headed studs

Furthermore, in the real situation, in order to adjust the slab elevation, thickness of the filled mortar needs to be varied and the shear capacity of the structure needs to be ensured. In this regard, the FEM analysis model was adopted to investigate the shear capacity of the connection with different thickness of mortar and stud heights. The results of parametric study on shear capacity of the headed stud connection having different mortar thicknesses and stud heights are also reported.

2. SIMULATION OF EXPERIMENT BY 3D FEM MODEL

2.1 Layout of push-out experiment

Details and dimensions of push-out experiment is

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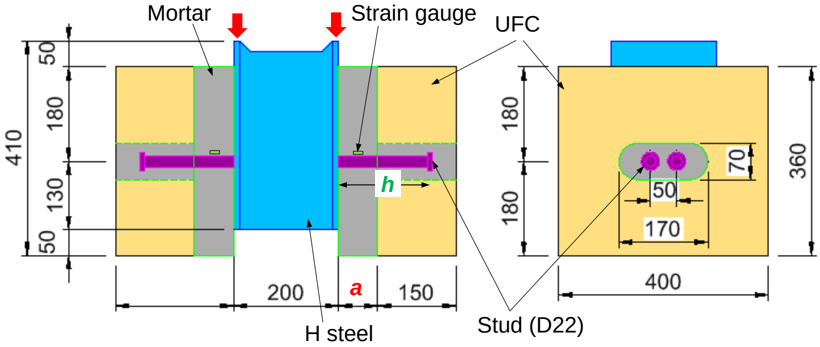


Fig.2 Layout of experiment

Table 1 Material properties and experimental results

Mortar			UFC	Stud			Ultimate shear load per stud		V^{cal}/V^{exp}
Thickness (a)	Comp. strength	Tensile strength	Comp. strength	Height (h)	Yield strength (f_y)	Ultimate strength (f_u)	Exp. result (V^{exp})	Calculated result (V^{cal})	
mm	N/mm^2	N/mm^2	N/mm^2	mm	N/mm^2	N/mm^2	kN	kN	
50	68.5	5.2	179.4	150	346	457	149.3	173.7	1.16

Comp. strength: compressive strength; Exp. Result: Experimental result;

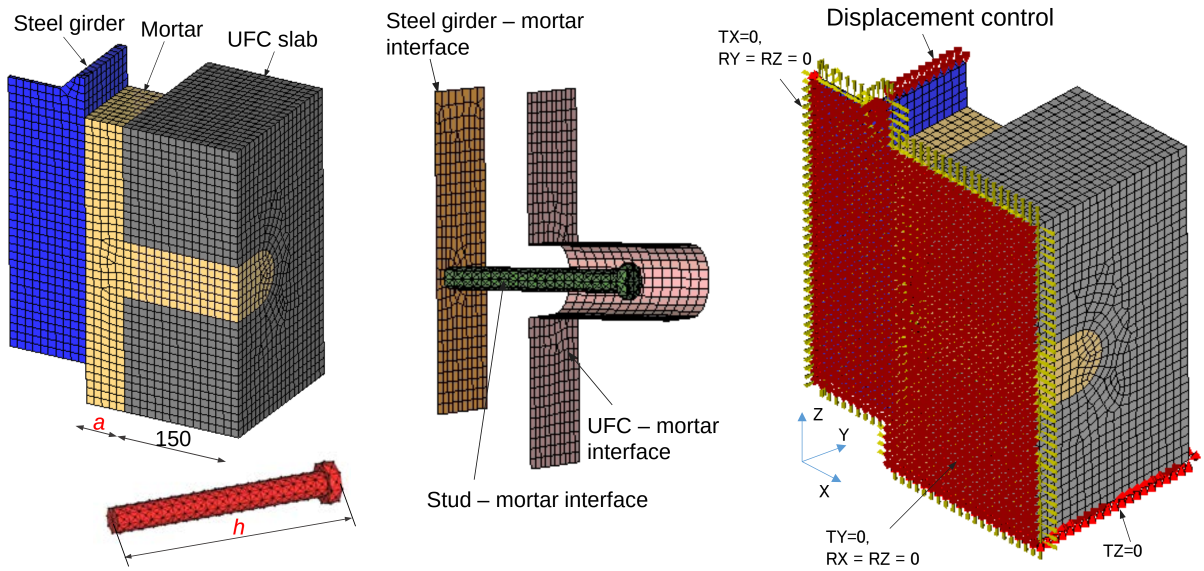


Fig.3 3D model, interface elements and boundary condition

shown in Fig. 2. The experiment consisted of UFC slab, H steel girder, two studs with diameter of 22 mm were welded on each side of H steel girder. The thickness of UFC slab was constant of 150 mm, while the height of stud h = 150 (mm) and thickness of the filled mortar a = 50 (mm). A non-shrinkage high strength mortar was filled in the space between UFC slab and the steel girder through a hole in the UFC slab. The material properties, experimental result are summarized in Table 1. The load was applied on top of H steel as shown in the figure.

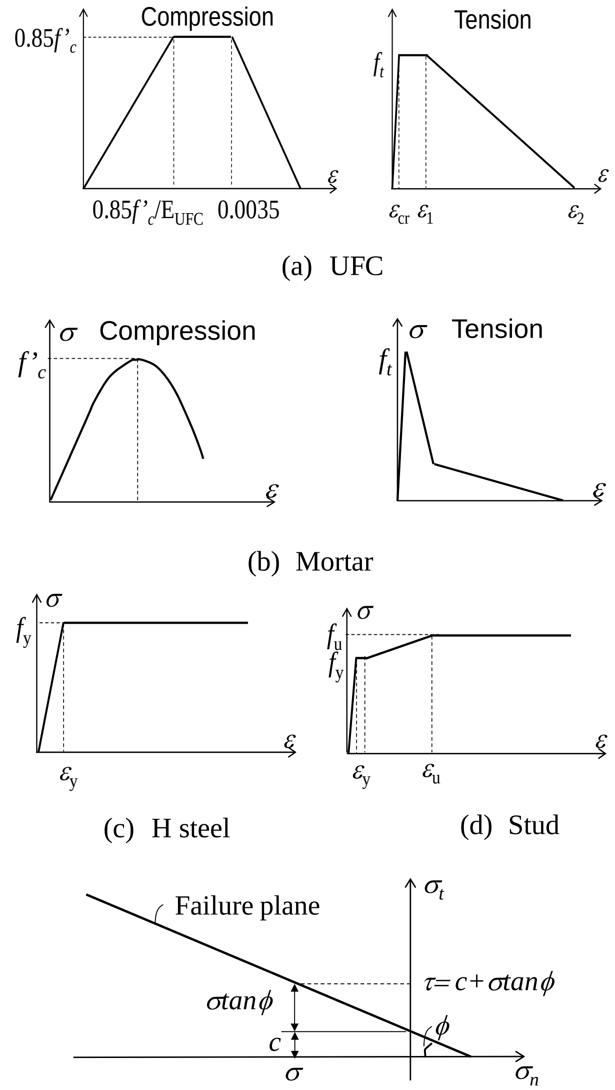
Since there has been no design method for the headed stud connection of UFC slab and steel girder, the equations proposed by JSCE in Design Specifications for Hybrid Structures [9] were adopted to predict the shear capacity of the connection. The ultimate shear capacity of a headed stud connector is determined by the smaller value of the calculations using Eqs. (1) and (2). While Eq. (1) is an empirical equation, which was developed based on the experimental data of the connection between concrete slab and steel girder using headed studs, Eq. (2) represents assumption of a failure of stud:

$$V_{sc} = 31A_{ss}\sqrt{(h/d)f'_c} + 10000 \qquad (1)$$

$$V_{ss} = A_{ss}f_{su} \qquad (2)$$

where,

A_{ss} is cross sectional area of stud (mm^2);
h is height of stud (mm);
d is diameter of stud (mm);
f'_c is compressive strength of concrete (N/mm^2);



(a) UFC

(b) Mortar

(c) H steel (d) Stud

(e) Coulomb friction model for interface

Fig.4 Stress-strain curves for materials

f_{su} is tensile strength of stud (N/mm^2).

To calculate the ultimate shear capacity of the experiment, the compressive strength of the mortar was used as f'_c in Eq. (1). The calculated results are given in Table 1. From the table, it can be seen that the calculation based on Design Specifications for Hybrid Structures overestimated the experimental results of 16%.

2.2 FEM analysis

(1) FEM analysis model

As the design equations were unable to predict the ultimate shear capacity of the connection, three dimensional FEM nonlinear analysis was also carried out in order to investigate the shear capacity and behavior of the experiment. The specimen was modeled and analyzed using DIANA ver. 10.2 program. Since the specimen is symmetrical, one fourth of the specimen was modeled for FEM analysis as shown in Fig. 3. The UFC slab, mortar, steel girder and stud were modeled by solid elements. The surface interface elements were used to model the interface behavior between steel girder and mortar, mortar and stud, mortar and UFC slab surfaces.

The total strain fixed smeared crack model was adopted for modeling cracks of the UFC slab and mortar. Fig. 4(a, b) shows the nonlinear behaviors of UFC and mortar in compression and tension. The UFC material was modeled in accordance with JSCE design guidelines [10]. For the mortar, Feenstra stress-strain relationship (parabolic curve) [11] was used to model behavior in compression. In tension, after tensile stress reaches the tensile strength of the material, tension softening was considered. The actual strengths resulting from material compression and tension tests were adopted in the models.

For H steel girder, the stress-strain relationship was modeled by a bi-linear curve as shown in Fig. 4(c). The experimental value of yield strength of 300 N/mm^2 was adopted in the model. The stud was modeled by multi-linear stress-strain relationship [7, 8] in which the yield and tensile strengths obtained from tensile tests were used (Fig. 4(d)).

The interface between different materials was modeled using Coulomb friction model, in which the behavior between two parts with different materials was governed by friction behavior as shown in Fig. 4(e). The failure criteria of the interface is shown as below:

$$\tau = c + \sigma \tan\phi \qquad (3)$$

where,

τ is shear stress at interface; c is cohesion; σ is compressive stress at interface; $\tan\phi = \mu$ is friction coefficient.

As the Coulomb friction model was adopted and modeled successfully the behavior of studs in the push-out experiments in the existing studies [7,8], the cohesive force $c = 0$ and friction coefficient μ was set as 0.3, which was similar to those in the existing papers.

To simulate the symmetry of the model in X and Y directions, restraints of displacement and rotation on symmetrical surfaces were applied. For the support condition, displacement of all nodes on the lower surfaces of the UFC slab and the filled mortar were restrained in Z direction.

(2) Verification of experimental results

The results obtained by 3D FEM analysis were compared with those obtained from the loading test. The ultimate shear capacity per a stud obtained by FEM analysis was 145.92 kN, which was equal to 98% of the experimental value. Fig. 5 shows the relationship between shear load per stud and the relative vertical displacement, in which the experimental result, the result from FEM analysis and the calculation based on Design Specifications for Hybrid Structures [8] are compared. In the figure, the relative vertical displacement indicates the difference in vertical displacement between the steel girder and the mortar at a level of center line of the stud.

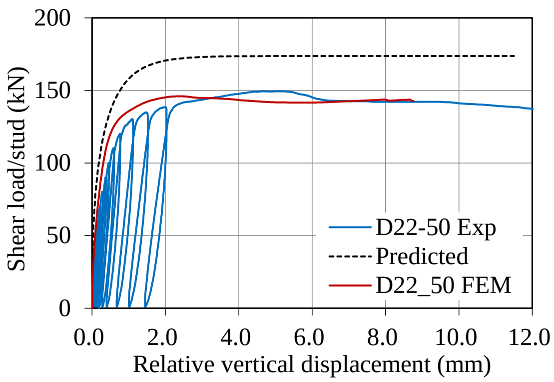


Fig.5 Shear load – relative vertical displacement between girder and mortar

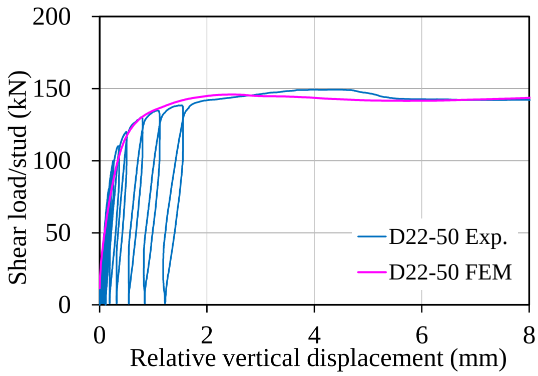


Fig.6 Shear load – relative vertical displacement between girder and UFC slab

The FEM analysis model simulated well the shear behavior of the headed stud connection, whereas, the calculations based on existing design equations of JSCE overestimated both the shear capacity and stiffness of headed stud connection.

Fig. 6 plots the results of experiment and FEM analysis in which the relative vertical displacements between steel girder and UFC slab are compared. Similarly, the relative vertical displacement in the figure indicates the difference in vertical displacement between the steel girder and the UFC slab at a level of center line of the stud. The results implied that FEM analysis model could simulate accurately shear capacity, stiffness and the relative displacement of the experiment.

It should be noted that the ultimate shear capacity of the connection calculated based on JSCE Design Specifications determined the ultimate shear capacity with an assumption of a failure of the stud. That means the stud reached its tensile strength at the ultimate shear load. However, in the experiment, the failure of stud was not observed at the ultimate shear capacity. Furthermore, after the ultimate shear capacity was reached at the relative displacement of about 5 mm, the applied load decreased slightly and then remained at level of about 142 kN (Figs. 5 and 6). The relative displacement increased without further increase in the load carrying capacity. With this behavior, it can be said that the ultimate shear capacity of the connection was not

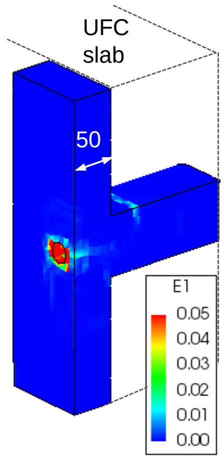


Fig.7 Principal tensile strains in mortar

Table 2 FEM analysis cases and results

Cases	Name	*a* (mm)	*h* (mm)	Ultimate shear capacity[2)] (kN/stud)
1	D22-50-150[1)]	50	150	145.92
2	D22-50-125	50	125	146.75
3	D22-50-110	50	110	145.74
4	D22-100-200[3)]	100	200	151.50[3)]
5	D22-100-175	100	175	151.08
6	D22-100-160	100	160	150.34

[1)]: FEM analysis results was described in section 2.2
[2)]: FEM analysis results
[3)]: Experimental results were reported in the reference paper [12]

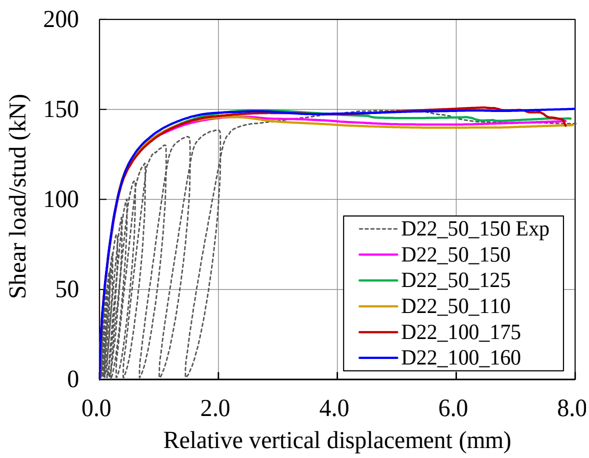


Fig.8 Shear load – relative vertical displacement between girder and mortar

governed by the failure of the stud in the experiment.

Fig. 7 shows a FEM analysis result of the distribution of principal strains in the mortar at the relative vertical displacement between steel girder and

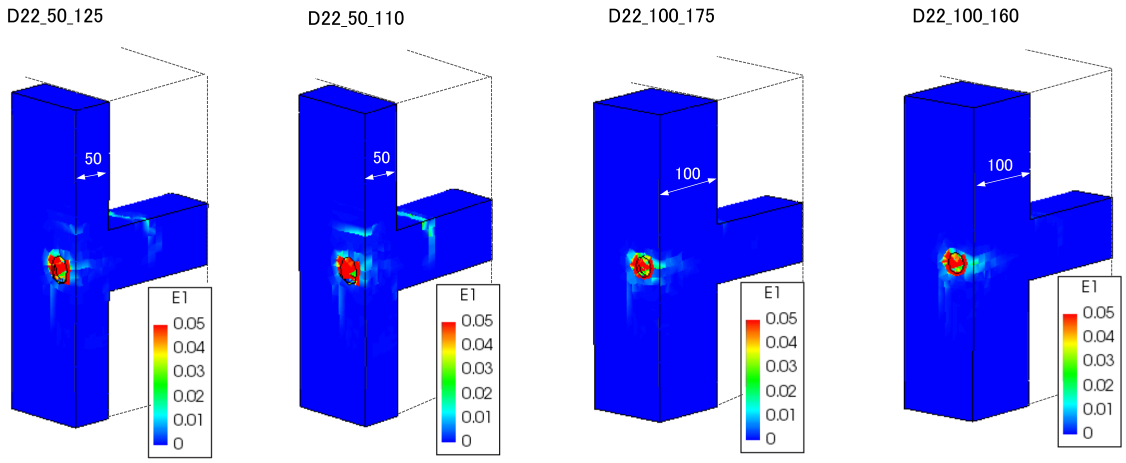


Fig.9 Principal tensile strains in mortar - analysis results of cases 2, 3, 5, 6

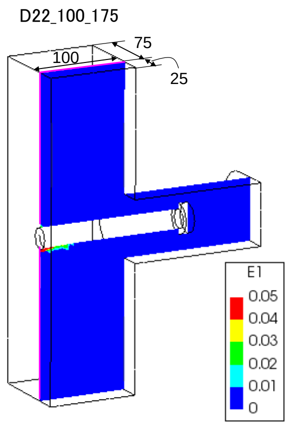


Fig.10 Principal tensile strains in mortar – section view

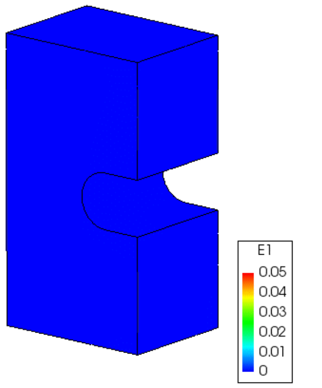


Fig.11 Principal tensile strains in UFC slab (cases 5)

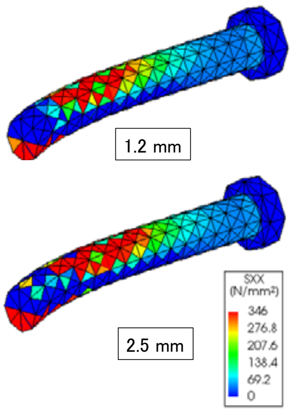


Fig.12 Tensile stress in stud (cases 5)

the mortar of 2.5 mm. It can be seen from the figure that there was high strain in mortar portion localized around the stud nearby the surface of the steel girder. It is supposed that the mortar gradually crushed in the vicinity of the stud in this region leading to a slight reduction in the load carrying capacity. Then, no further load could be carried.

3. PARAMETRIC STUDY ON SHEAR CAPACITY OF JOINT BETWEEN UFC SLAB AND STEEL GIRDER

3.1 Analysis cases

In the real construction, in order to adjust the top level of the bridge slab, the thickness of mortar layer (a) (as shown in Fig. 1) needs to be varied. Furthermore, to reduce the construction cost, the stud height also needs to be optimized. In this section, 3D FEM analysis was conducted to investigate the shear capacity of the headed stud connection between UFC slab and the steel girders with different mortar thickness (a) and stud height (h). The list of analysis cases and parameters is given in Table 2. The name of the case indicates diameter of the stud – thickness of mortar – height of the stud.

In the table, the first case shows the parameters of the analysis model, which is described in the section 2.2. In cases 2 and 3, the thickness of mortar was as the same as that of case 1 (a = 50 mm), whereas, the height of the stud was reduced from 150 mm in case 1 to 125 mm in case 2 and 110 mm in case 3.

The thickness of mortar increased to 100 mm for cases 4 to 6. Case 4 shows the experimental results, which was reported in the previous paper [12]. The result of this case was given for comparison. The stud height in cases 5 and 6 was reduced compared to that of the case 4. The height of the stud was 175 mm and 160 mm in cases 5 and 6, respectively. In these cases, the stud height were determined to ensure that the stud embedded in the UFC slab a minimum length greater than 50 mm. Except the above parameters, the stud diameter and the material properties were taken as the same as those used in case 1 for analysis.

3.2 FEM analysis results

The ultimate shear capacity of all the analysis cases are shown in Table 2. As can be seen in the table, for the joints with different thickness of mortar and different height of the stud, the change in the ultimate shear capacity could be negligible. In the other words, the changes in the ultimate shear capacity of the connection according to those changes in the mortar thickness and the stud height were almost unnoticeable.

Fig. 8 illustrates the relationship between shear load and the relative vertical displacement between the steel girder and the mortar of the analysis cases in comparison to the experimental data. The dash line indicates the experimental result of the specimen, which was described in section 2 and the solid lines indicate the results obtained by FEM analysis of each case. All the analysis cases showed a similar behavior to the experiment. Thus, the effects of the increase of the mortar thickness and decrease of the stud height on the shear performance of the connection were very slight.

In Fig. 9, the distribution of principal tensile strains of the mortar at the relative displacement of 2.5 mm are presented. In all the cases, the high strains occurred in the mortar portion around the stud where it jointed with the steel girder. Similar to the behavior discussed in the section 2.2, it is supposed that the localized failure of mortar governed the ultimate shear capacity of the connection. Section views of the principal tensile strain in mortar at the section crossing the center line of the stud in cases 5 are shown in Fig. 10 and the principal strain in UFC slab is shown in Fig. 11. Clearly, the principal strain was considerably high only in the vicinity around the stud where it connected with the steel girder. In the other portion and UFC slab, the principal tensile strain remained small. Therefore, the increase in the mortar thickness did not affect ultimate shear capacity and the shear performance of the connection.

The deformation and tensile of the stud of case 5 at the relative displacement of 1.2mm and 2.5mm is shown in Fig. 12. The stud deformed downward where it connected with the steel girder. Before the ultimate load at 1.2mm of displacement, the stress reached the stud yielding strength partially (red color), especially in the lower part of the stud. Even though a portion of the stud yielded at the relative displacement of 1.2 mm, the load carrying capacity still increased. It indicated a part of the shear force was carried by the other mechanisms.

Based on the FEM analysis results, the shear capacity and the performance of the connection when the mortar thickness increases to 100 mm can be ensured. Furthermore, the stud height can be optimized from 150 mm to 110 mm for the mortar thickness of 50 mm, and 200 mm to 160 mm for the mortar thickness of 100 mm without a significant influence on the structural performance of the connection.

4. CONCLUSIONS

This paper has presented a 3D FEM analysis model applicable for the joint between the UFC slab and the steel girder using headed stud as shear connector. The conclusions are as following:

(1) The 3D FEM model predicted well the ultimate shear capacity of the joint between UFC slab and steel girder as well as the relationship between shear load – relative vertical displacement between the girder and the filled mortar. Since the existing design method overestimated the experimental results, the FEM model can be considered as a tool for predicting the ultimate shear capacity and performance of the joint between UFC slab and steel girder.

(2) The parametric study of the connection with increase in the thickness of mortar and optimization of the stud height has been conducted using 3D FEM analysis. Based on the analysis results, due to the localized failure of the mortar around the stud, in the case of the mortar thickness is increased, there is no significant influence on the ultimate shear capacity and the performance of the connection.

(3) Moreover, with a given thickness of mortar, the optimized height of the stud can be determined by 3D FEM analysis model. For instance, the stud height can be reduced from 150 mm to 110 mm for the mortar thickness of 50 mm, and 200 mm to 160 mm for the mortar thickness of 100 mm.

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