Seismic performance of steel pipe pile with wings and a construction method for joining with an upper column

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Abstract:

We are working to develop a method for joining piles and columns such that foundation beams become unnecessary. In this method, an upper column is joined with a steel pipe pile with wings that can suppress the generation of waste soil. By a full-scale bending shear test, we found the following. First, using design criteria with a retaining lateral load-bearing joint (100% proof stress), the joint was not damaged, even when the member angle reached 1/25 rad. Second, no difference was seen in deformation performance even when the joint proof stress was set at 50%. Third, no difference was seen in deformation performance even when a gap with gradient 1/100 was generated on the contact surface between pile and column.

Key words: steel pipe pile with wings, joined pile and column, reduced environmental impact, labor-saving construction method, connection experiment

1. Introduction

Various external forces, such as self-weight, loading load, and seismic load act on structures. External forces acting on the structure are transmitted to the ground through the foundation by means of a design with sufficient strength and deformation performance for the external forces and by ensuring construction quality according to the design[1].

Foundations are classified into one of several types according to the method of transmitting the external force to the ground, but if the ground near the foundation is soft and the designed bearing capacity cannot be expected or the depth of the supporting layer that produces the designed bearing capacity is deep underground, a pile foundation is often used.

When a pile foundation is used, independent foundations transmit the external force acting on the superstructure to the supporting ground via the footings between the columns and the piles, but in the case of an independent foundation, nonuniformity of the ground and the column load become factors, and there is a possibility of different interlaminar displacement or twisting occurring on each column, such as in the case inconsistent settlement or lateral force. This makes it necessary to join the footings with a foundation beam.

However, not only does the foundation beam require a lot of time and labor, it also places a large burden on the global environment due to the large amount of surplus soil displaced by

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production.

To solve these problems, the authors have conduced various research aimed at developing a construction method (hereinafter, "the construction method") that joins a steel pipe pile with wings (the "pile"), which produces no surplus soil, to an upper column (the "column") and integrates the pile and column to eliminate the need for foundation beams.

This report details the results of a full-scale bending shear experiment and simulation results by the 3D finite element method (FEM), conducted for the purpose of ascertaining the earthquake resistance of connections.

2. Materials and Method

2.1. Connection design method

The connection of this construction method conforms to the design method of high-strength bolted-tube flange joints ("the design method") of the Architectural Institute of Japan "Recommendation for Design of Connections in Steel Structures."[2] From among the predictions of four collapse mechanisms (three collapse mechanisms derived from equilibrium conditions for an axially symmetric collapse mechanism given by yield line theory and a local collapse mechanism for when the number of bolts is small), the minimum connection bearing capacity is calculated for the design method. However, in the application of the design method, the shapes and dimensions of the joined parts are made the same.

2.2. Purpose of the experiment

In this research, a full-scale bending shear experiment was conducted on a connection, assuming a three-story steel-frame building. To ascertain the basic characteristics, no vertical force is introduced. The purpose of the experiment is fourfold:

1) to ascertain the failure mode of the connection when subjected to bending shear force;

2) to ascertain the difference when the connection bearing capacity is set to 100% and 50%;

3) to ascertain the hysteresis properties in the case where the joined members are different shapes; and

4) to ascertain the influence of the gap (gradient of 1/100 rad or less) of the joint surface, which may occur due to construction error.

The experimental standards were set for connection bearing capacity, column shape, and gap between joint surfaces. Here, 100% connection bearing capacity ("100% bearing capacity") is defined as the connection bearing capacity calculated by the design method when the full plastic moment of the column acts.

2.3. Test specimens

Figure 1 shows a drawing of a test specimen, and Table 1 shows a table of test cases. In total, six test specimens were produced. To join the piles and columns, disk-shaped steel plates were

welded to the pile head and column base and joined by high-strength bolts. Hereinafter, the plate at the pile head is called the top plate (TP), the column base plate is called the base plate (BP), and the upper surface of the TP is used as the reference surface of the test specimen.

All piles had the same specifications and a height of 300 mm. To prevent damage from the piles, reinforcing ribs with a thickness of 16 mm were attached to the sides of the piles, but a clearance of 50 mm was provided between the upper surface of the reinforcing ribs and the lower surface of the TP so that rotation of the TP was not inhibited. The loading axis was 1000 mm above the reference surface. A loading surface was provided on the loading axis by which to attach a hydraulic jack via two plates passing through the cross section of the column.
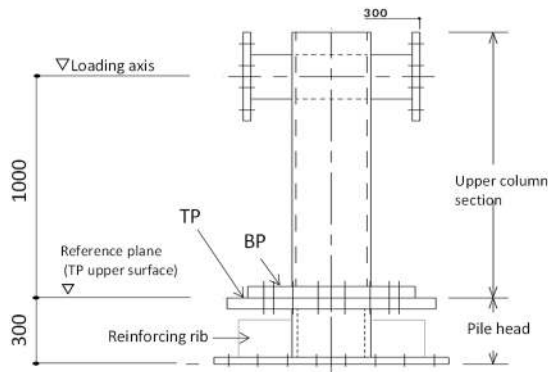

Fig1. Test Speciment

Table1. Test Cases

| Test body No. | Column | | Pile | | Junction bearing capacity | No. of joint bolts (F10T-M24) | Joint surface gradient (gap) |
	Form × plate thickness (material)	BP Plate thickness × outer diameter (SN490C)	Form × plate thickness (material)	TP Plate thickness × outer diameter (SN490C)			
1	φ267.4 × 12.7 (STK490)	50 × 570 φ		50 × 670 φ	100%	16	No gap
2		32 × 500 φ		32 × 640 φ	50%	8	No gap
3	□250 × 250 × 12 (BCR295)	50 × 570 φ	φ267.4 × 19.0 (STK490)	50 × 670 φ	100%	16	No gap
4		32 × 500 φ		32 × 640 φ	50%	8	No gap
5	φ267.4 × 12.7 (STK490)	50 × 570 φ		50 × 670 φ	100%	16	0 mm~6 mm
6		32 × 500 φ		32 × 640 φ	50%	8	0 mm~6 mm

2.4. Experimental method

Figure 2 shows a diagram of the loading apparatus and the positions of measurements. In the experiment, a reaction frame was constructed and a lateral force was applied by a 1000-kN hydraulic jack installed in the reaction frame[3]. Alternating static cyclic loading was carried out by a lateral displacement control at the position of the loading axis. Figure 3 shows a loading cycle diagram. Loading was repeated twice at each member angle to confirm the change in bearing capacity and stiffness at the same member angle. The lateral displacement and the rotation angle and lateral displacement of BP and TP (relative displacement) were measured at the position of the loading height. The displacement of the test specimen set base was also measured. This measurement was used for setting the boundary conditions (vertical, lateral, and rotational springs) of the 3D FEM analytical model. The bending moment generated in the column was measured by affixing uniaxial strain gauges to 5 cross sections on the loading core and the side of the pile at intervals of about 200 mm from the BP at positions that segmented the circumference of the column into four.
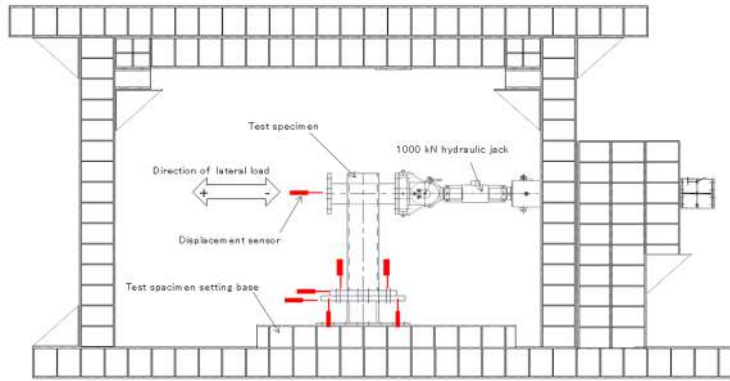
Page 143

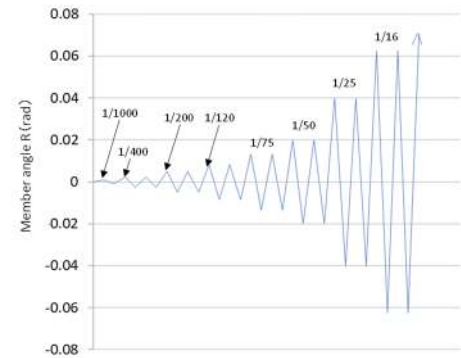Fig2. loading apparatus and the positions of measurements

Fig3. Loading cycle

2.5. Finite element method model

Analysis was performed on test cases 1, 2, 3, and 5. The analytical model was created from a composite model of solid elements and shell elements, and the mechanical properties in this construction method were examined by reproducing the experimental results via static loading (pushover). Table 2 shows each analysis condition[4].

Figure 4 shows the analysis model for No. 1 and No. 3. To simplify the connection, the analytical model considered the nodes on the TP upper surface and the BP lower surface to be shared and integrated. For No. 5, the washer used for creating the gap at the joint surface was modeled as a solid element, and a gap model for the connection was created by a method in which TP and BP are made to share a node in contact with the washer on the joint surface. For the boundary conditions, the node spring shown in Figure 4 (a) was input to the node positioned on the contact surface between the reaction beam and the test pile plate. The input load was input as a nodal load for the nodes (total number: 273) on the loading surface such that the maximum load of each test body was equal. The material properties were bilinear.

Table2. Analysis Condition

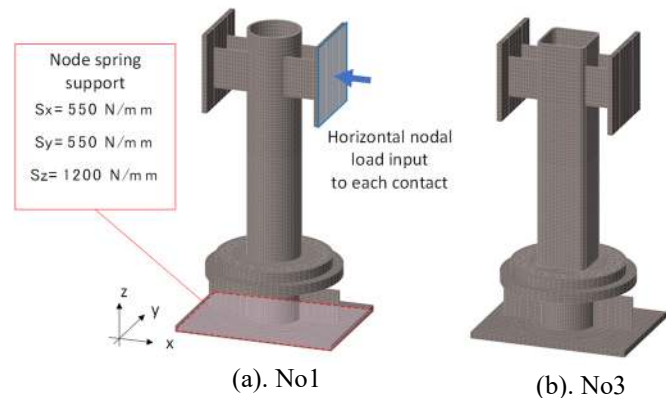| Analysis code	Midas iGen ver.860
Analysis content	Material nonlinear analysis
Elements used	Solid elements, plate elements
Yield conditions	Mises yield conditions
Hardening rule	Kinematic hardening rule
Loading method	Node load in lateral direction

(a). No1

(b). No3

Fig4. Analysis Model
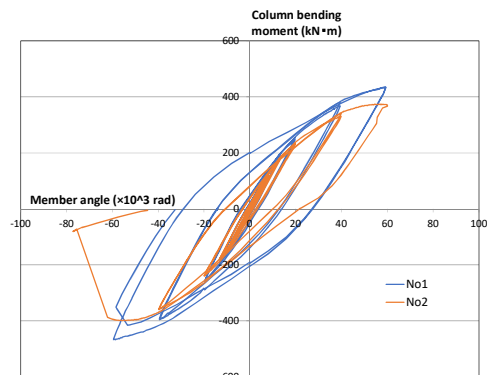
3. Results

3.1. Experimental results

3.1.1 Difference in design connection bearing capacity

Table 3 lists the experimental results. It is seen that when the connection bearing capacity is reduced to 50% ("50% bearing capacity"), a decrease of about 15% occurs in bearing capacity at the maximum bending moment of the column base. It was presumed that the influence on deformation performance as a whole is small. The failure modes were clearly different at 100% and 50% bearing capacity: at 100%, the experiment ended with weld fracture of the reinforcing rib of the pile head; at 50%, the high-strength bolt bearing the tensile force inside the connection fractured in the end.
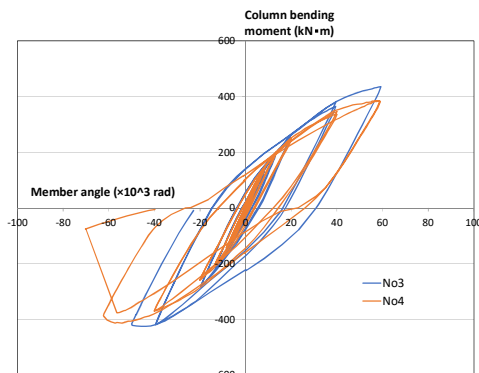
Figures 5(a)–(c) show the hysteresis loops of the column bending moment–member angle compared under the same experimental standards. The figures show that the initial stiffness is almost the same under all standards, and although the hysteresis properties also showed a slight reduction in bearing capacity before the member angle reaches 30×10^{-3} rad (=1/33 rad), it seems that the influence due to the difference in connection bearing capacity is small.
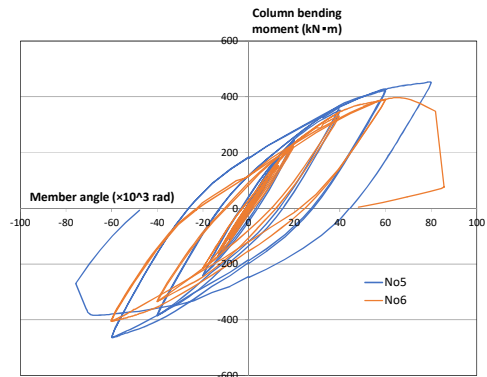
Table3. Experimental Results

| Test body No. | Direction of load | At max. column bending moment | | Failure mode | Rate of decrease of bending moment | Rate of decrease of member angle |
		Bending moment (kN·m)	Member angle (rad)			
1	+	435.0	0.060 / 1/16.8	weld zone of reinforcing rib		
	−	-466.9	-0.058 / -1/17.1			
2	+	374.1	0.056 / 1/17.7	high-strength bolt	0.86	0.95
	−	-398.5	-0.054 / -1/18.5		0.85	0.92
3	+	435.0	0.059 / 1/16.9	weld zone of reinforcing rib		
	−	-424.5	-0.046 / -1/21.8			
4	+	385.1	0.057 / 1/17.6	high-strength bolt	0.89	0.96
	−	-413.0	-0.054 / -1/18.4		0.97	1.18
5	+	453.4	0.080 / 1/12.5	weld zone of reinforcing rib		
	−	-463.9	-0.059 / -1/16.9			
6	+	397.0	0.065 / 1/15.4	high-strength bolt	0.88	0.81
	−	-405.0	-0.060 / -1/16.7		0.87	1.01

(a) No. 1 vs No. 2

(b) No. 3 vs No. 4

(c) No. 5 vs No. 6

Fig5(a)-(c). column bending moment–member angle

3.1.2. Difference due to joining of irregularly shaped members

Figure 6 compares the hysteresis loops of the column bending moment–member angle of No. 1 and No. 3. From Figure 6, there was no difference in the initial stiffness and the hysteresis properties, and very similar historical properties were seen. Also, since the decrease in bearing capacity does not occur with the column bending moment at the same member angle, and the loop areas are also almost equivalent, the energy absorption performance is assumed to be equal. Therefore, for irregular members in this study, although they are outside the applicable range for the design method, it may be possible to calculate the connection bearing capacity in compliance with the design method.

3.1.3. Influence of gaps occurring on joint surfaces

Figure 7 compares the hysteresis loops of the column bending moment–member angle of No. 1 and No. 5. From Figure 7, there is no difference in initial stiffness, and a slight decrease in bearing capacity is observed after exceeding 30×10^{-3} rad. However, since similar hysteresis properties are shown overall, the influence on the connection bearing capacity is small, even in the case where a slope with a gradient of within 1/100 occurs in the joint surface, and it may be possible to calculate the connection bearing capacity in compliance with the design method.
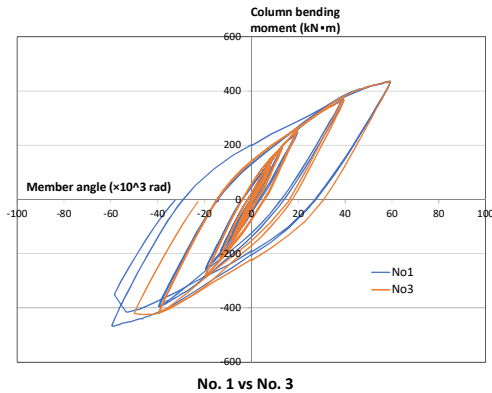

Fig6. column bending moment–member angle
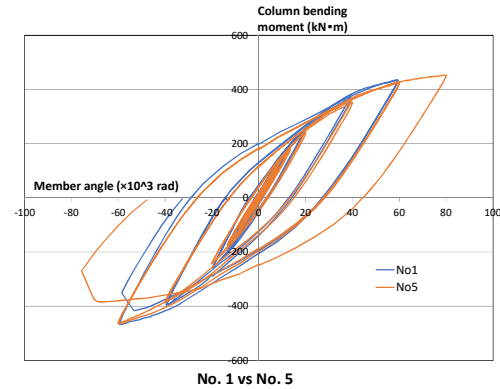
(irrgulaly shaped member)

Fig7. column bending moment–member angle

(gap occurringon joint surfaces)

3.2. Analysis results

3.2.1 Hysteresis characteristics

Figure 8(a)–(d) shows the simulation results. For Nos. 1, 3, and 5, the results confirm that the maximum load and maximum member angle are roughly consistent with the experimental results. Moreover, from the hysteresis properties, it was found that the bending properties at the time of the experiment can be reproduced for Nos. 1 and 3 by using the connection model that shares the node of the joint surface. In No. 2 (see Fig. 8(b)), the experimental result and the analysis result diverge markedly when the column base moment exceeds 200 kN・m. This is presumed to be because separation occurred between the TP and BP in the experiment, and deformation increased due to the reduction of the burden shear force on the joint surface. In addition, the experimental result and the analysis result were confirmed to be consistent for No. 5, taking into account construction error[5].
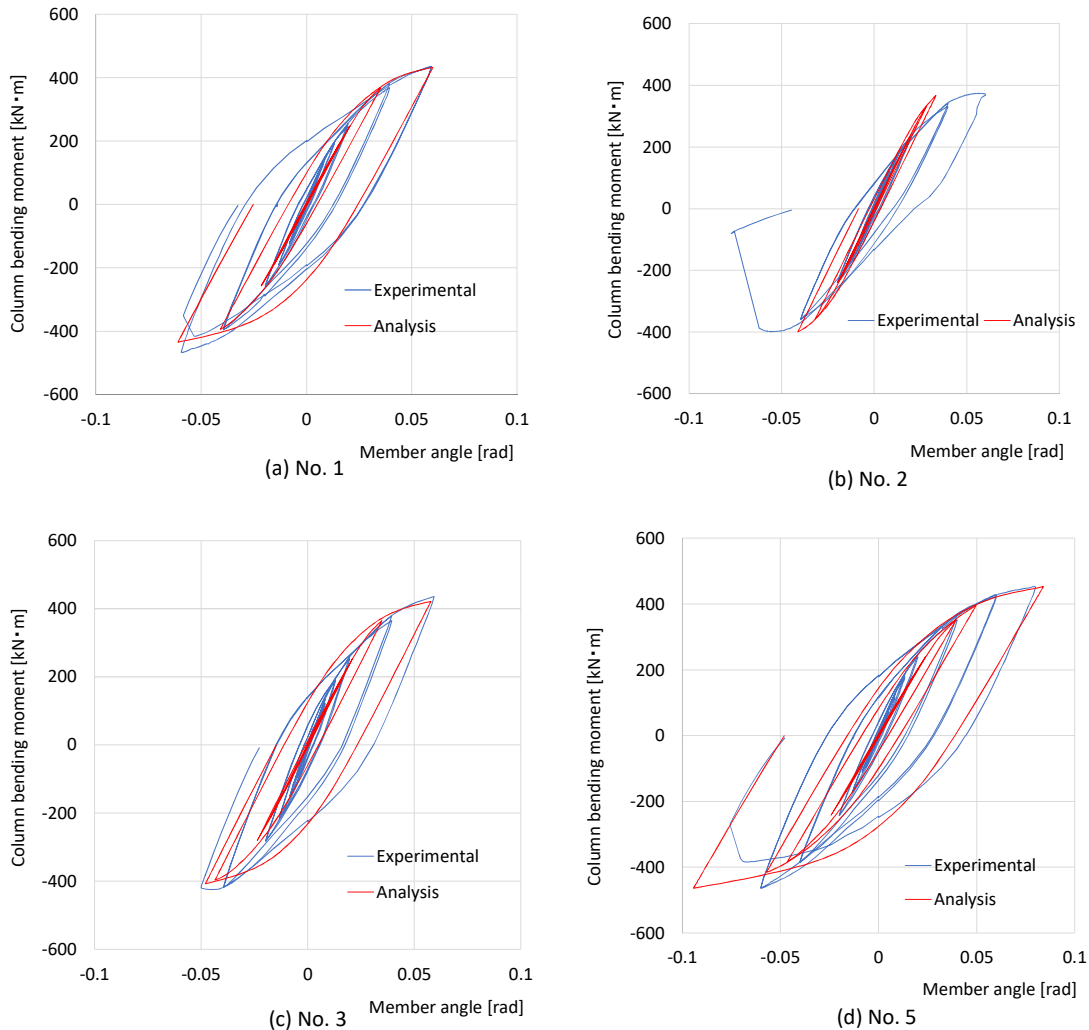

Fig8(a)-(d). simulation results

3.2.2 Stress distribution properties

Figures 9(a) and (b) show overall distribution maps of the Mises stress at the maximum load, and Figures 9(c)–(f) show the stress distribution on the BP lower surface and the TP upper surface. As shown in Figures 9(a) and (b), the stress concentrates in the vicinity of the connection, particularly the column base and pile head. The stress also concentrates on the welded portion of the reinforcing rib, which was the failure point of Nos. 1 and 3 during the experiment. This result confirms the consistency of the analysis results.

(a) Test body No. 1

(b) Test body No. 3

(c) No. 1, BP upper surface

(d) No. 3, BP upper surface

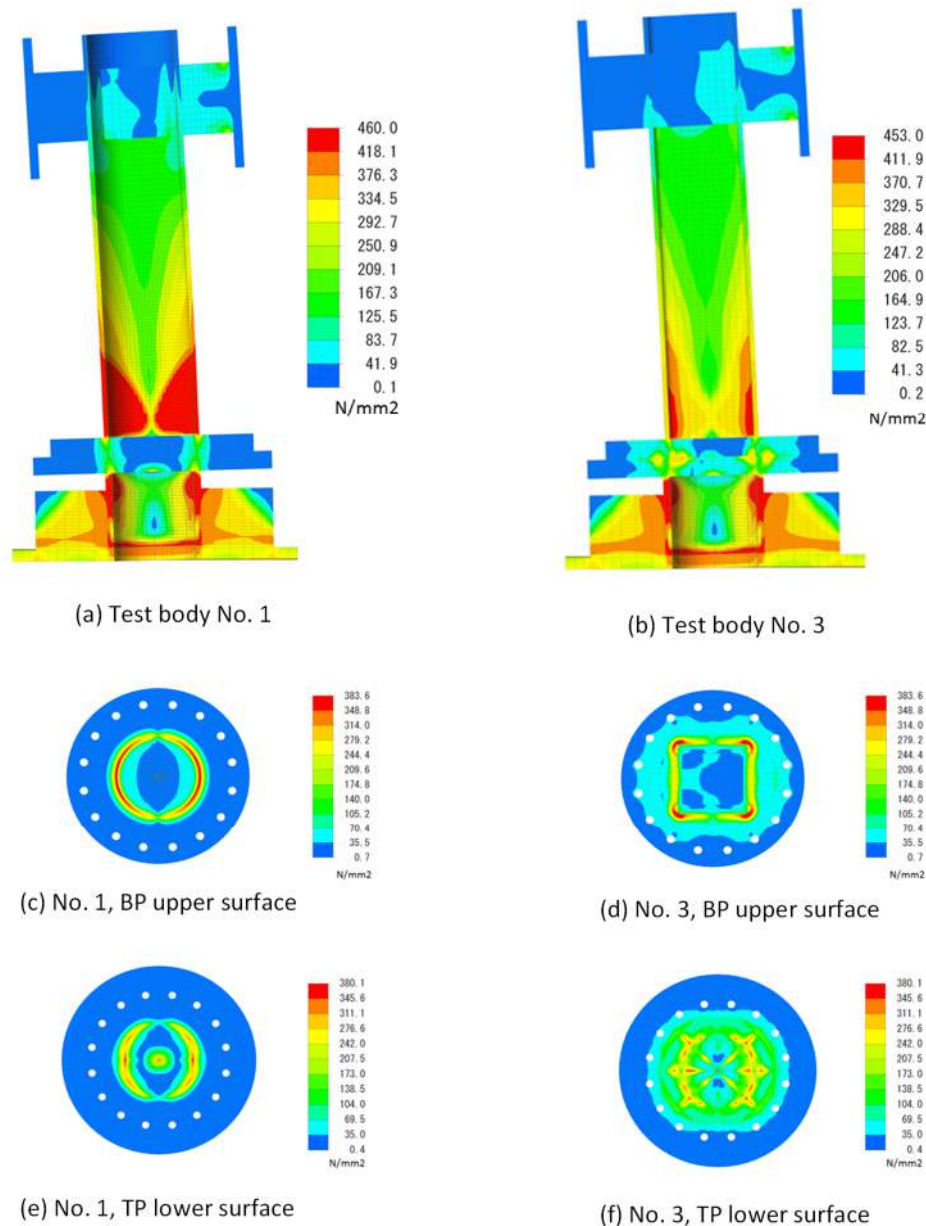(e) No. 1, TP lower surface

(f) No. 3, TP lower surface

Fig9(a)-(f). the Mises stress at the maximum load

Also, since the stress generated in the plate part is smaller than that of the column base and the pile head, the column base or the pile head is inferred to fail before the connection if loading is continued after destruction of the reinforcing rib in Nos. 1 and 3. From Figs. 9(c) and (e), it can be clearly confirmed that the bending stress of the column base is transmitted to the pile in No. 1. However, in No. 3, the stress is dispersed in the plate. Differences in the stress transmission mechanism were observed due to the difference in cross-sectional form of the columns and piles[6][7].

4. Discussion

Areas for future consideration are indicated below:

1) Cases where axial and horizontal forces simultaneously act on the column, particularly the fracture process when a tensile force acts on the column and TP and BP could become separated.

2) The decay mechanism of the whole building when the foundation is treated as a lateral spring[8].

3) A model of the connection that considers the contact conditions of the TP and BP, which will be useful for future analysis.

Conclusions

In this research, we reported the results of a full-scale bending shear experiment on the connection of a construction method that integrates a steel pipe pile with wings and the upper column, and simulation results given by 3D FEM. The findings of the present study are as follows.

1) When the design connection strength was set to 50%, the column bending moment that it could bear was reduced by about 15%.

2) There is no difference in hysteresis properties among methods, even when the combination of piles and columns had different cross-sectional forms, and so connection strength can be calculated according to a common design method.

3) A gap in the joint surface with a slope not steeper than a 1/100 gradient has no influence.

4) From the results of FEM analysis, it was found that the majority of bending stress in the column base is directly transmitted to the pile part with a circular steel pipe column. In

Page 149

contrast, for a square steel pipe column, the stress is transmitted over a wide range in the vicinity of the bolt hole.

Acknowledgements

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