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Evaluation of Bending Capacity of Pile Head RC Joints for Over-Track Buildings with Steel Pipe Pile Groups

K. Shimizu(1), S. Yamada(2), H. Kusaka(3), M. Kitahama(4), M. Wada(5), K. Nakazawa(6)

(1) *Assistant Senior Researcher, Railway Technical Research Institute, shimi@rtri.or.jp*
(2) *Senior Researcher, Railway Technical Research Institute, seiji@rtri.or.jp*
(3) *Senior Manager, Nippon Steel & Sumitomo Metal Corporation, kusaka.ey3.hiroki@jp.nssmc.com*
(4) *Senior Researcher, Nippon Steel & Sumitomo Metal Corporation, kitahama.7dm.masashi@jp.nssmc.com*
(5) *Senior Manager, Nippon Steel & Sumikin Engineering Co., wada.masatoshi.kx4@eng.nssmc.com*
(6) *Manager, Nippon Steel & Sumikin Engineering Co., nakazawa.kimihiro@eng.nssmc.com*

Abstract

For normal-scale buildings, the structural design against large earthquakes of foundation structures such as a pile head joint are not required legally because of unclear ground behavior under large earthquakes. In the future, however, structural design for pile head joints for over-track buildings, which is grouped in buildings such as public facilities, is required to ensure no damage under large earthquakes. The pile constructions of over-track buildings, which often result in large-diameter piles, have many restrictions, because they entail constructing cast-in-place concrete piles without footing beams. Then, the pile head joints should also have good workability.

In this report, we propose new over-track buildings with the group of small-diameter steel pipe piles with which a large-diameter pile is replaced. And we propose how to connect the steel column and the steel pile group with reinforced concrete footing, which is reinforced by U-shape bars around the pile. Cyclic bending shear load tests on the reinforced concrete joints between the steel pipe pile group and the column are conducted to obtain the mechanical properties of the pile head joint with the U-shape bars. Evaluation method of the bending capacity of pile head reinforced concrete joints for over-track buildings with steel pipe pile groups is proposed based on the strength evaluation of the steel square tubular column bases for corner column embedded in concrete footing.

Keywords: Over-Track Building; Steel Pile Group; Pile Head Joint; Bending Capacity

1. Introduction

For normal-scale buildings, structural design against large earthquakes of foundation structures such as a pile head joint are not required legally because of unclear ground behavior under large earthquakes.

In the future, however, structural design against large earthquakes is required in buildings such as public facilities expected to ensure the continuity of operation after large earthquakes. In the same breath, over-track low-rise buildings typified by the over-track station have the following characteristics.

a) This structure has high seismic performance as a railway structure.

b) The track story has a high floor height and a wide column span.

c) One column is jointed to one pile without footing beams.

d) The pile is often a cast-in-place reinforced concrete pile.

There is a structural design standard, "Standard for Structural Design of Over-Track Low-Rise Buildings" [1] (hereinafter called "SOLB") established in consideration of their characteristics. To ensure high earthquake resistance, this standard requires that pile head joints be not damaged under major earthquakes. The pile constructions of over-track buildings, which often result in large-diameter piles, have many restrictions due to their characteristics. In recent years, the pile diameter increases as the over-track buildings height increases. The pile construction is becoming more difficult. There is a way to replace a large-diameter pile with a pile group of small-diameter steel pipes as shown Fig. 1. Workability is increased by using the small-diameter steel pile group. However, the joint between a steel pipe pile group and a column is rotated by earthquake loading, because it does not have a footing beam. The joints should have high seismic performance for this rocking behavior which is different from normal structures behavior.

In this report, cyclic bending shear load tests on the reinforced concrete joints between the steel pipe pile group and the column are conducted to obtain the mechanical properties of the reinforced concrete joint. Evaluation method of bending capacity of pile head reinforced concrete joints for over-track buildings with steel pipe pile groups is proposed based on the strength evaluation of the steel square tubular column bases for corner column embedded in concrete footing.

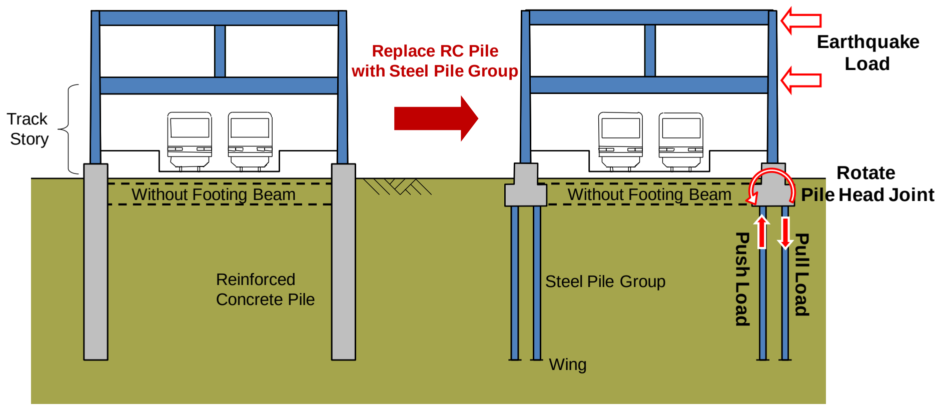

Fig. 1 – Over-track buildings with steel pipe pile groups

2. Load of the pile head by frame analysis

Three dimension frame static increment analysis is conducted to obtain the loads of pile head joints of over-track buildings with steel pile groups with which reinforced concrete piles are replaced. The three dimension frame models are shown Fig. 2 and Fig. 3. The original model (Fig. 2) is a model of a general over-track building of two-story steel structure; the floor area is 420 m^2, the structural height is 10m, the reinforced concrete pile diameter is 1.2m and the pile is anchored by engineering bedrock at a depth of 11m from the ground line. The other details are given in an example design of SOLB [1].

This model is replaced with a new model in which one column is connected to two steel pipe piles; the pile diameter (D_p) is 318.5mm, the thickness (t_p) is 10.3mm, the tip wing diameter (D_w) is 637mm, the ratio of the tip wing diameter to the pile diameter is 2 (D_w=2.0D_p) and each pile distance (L) is 2.0D_w. In addition, the joints between the one column and two piles are configured so as to have enough stiffness and strength not to yield before the other members yield. The horizontal ground stiffness and strength are based on “Recommendation for Design of Building Foundations” [2] (hereinafter called “RBF”). The vertical ground resistance of the small diameter screw pile is based on [3]. The ground characteristics are configured in consideration of ground’s non-linear properties.

The distribution of internal force at the maximum capacity, which is a capacity corresponding to an angle of 1/75rad. according to the SOLB [1], of the track story that is obtained from the frame analysis is shown in Fig. 3. Due to the overturning moment, the axial force of the left side column on the track story turns from compression to tension by the dead load. The shear force of the joints is 80 to 120kN, the tensile force is 152 to 181kN and the compressive force is 144 to 1185kN.

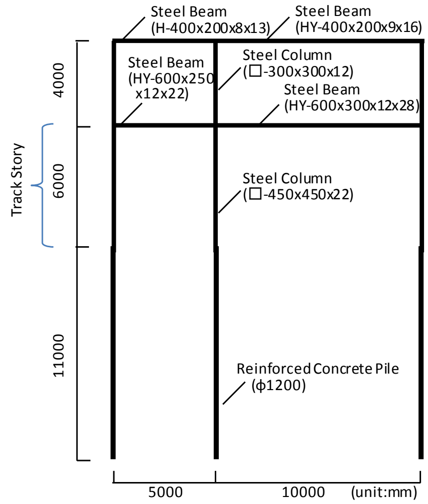

Fig. 2 – Three dimension frame model of SOLB [1]

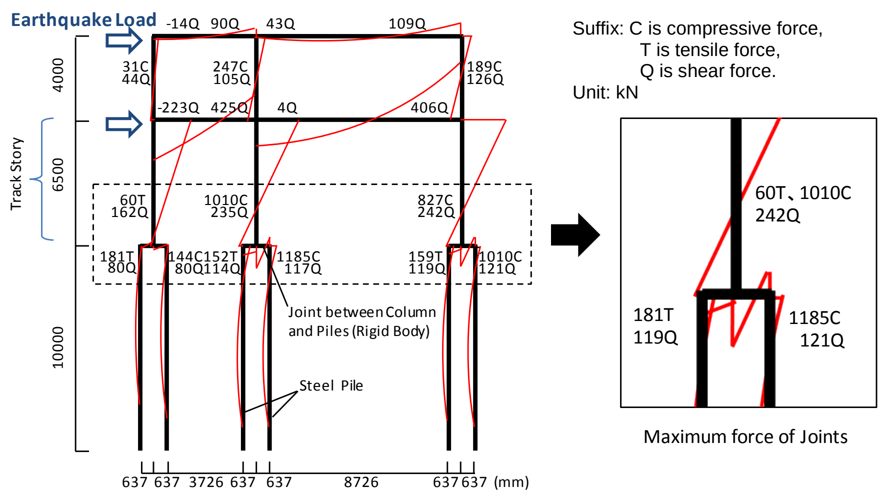

Fig. 3 – Distribution of the moment(red lines), shear and axial force at horizontal load capacity

3. Bending shear test of the pile head joint

Structural design for pile head joints is required to ensure no damage under the load of pile head joints as shown above. And pile head joints should have good workability. We have decided to connect the steel column base joint and steel pile group head joint with reinforced concrete footings. When the embedment length is $1.0D_p$ or greater, it is described in RBF [2] that fixable condition of the pile head joint is the fixation. However, we propose that the pile embedment length is $1.5D_p$ in order to ensure high load resistance. And it is proposed that the reinforcing bars of U-shape should be put around the pile in order to reinforcing bars to resist the bearing by the same way as the corner embedment type steel column-footing reinforcing bar as is shown in the upper steel structures design method, “Recommendation for Design of Connections in Steel Structures” [4] (hereinafter called “RCSS”). The reinforcing bar is arranged so as to surround the pile. Therefore, it is considered to be effective against crack opening in the tangential direction of the pile. In this study, tests of the pile head joint with the reinforced bar are conducted.

3.1 Outline of the tests

The dimension of the specimens is shown in Fig. 4. The number of specimens is three in total. The specimen JP-1 is a type of specimen which is designed based on the RCSS [4] in such a way that the pile is yielded before the yielding of the other members. The specimen JP-2 is a specimen fabricated by decreasing the number of U-shape reinforcing bars by half form that of the specimen JP-1. The amount of reinforcement of the specimen JP-3 is the same as the specimen JP-1, but the U-shape reinforcement is concentrated in the vertical direction. Except for the reinforcement, the material specifications and the dimensions of specimens are the same for all of the test specimen. The diameters of main bars and stirrups of the footings are 16mm (D16). The diameter and thickness of steel piles are 267.4mm and 9.3mm respectively. The pile embedment length is 401mm ($1.5D_p$), and the length from footing edge to the pile face is 267.4mm ($1.0D_p$). Inside of the pile head are arranged the inside bar of 6-D10 and the two ribbands according to “Design Standard for Railway Structures and Commentary (Foundation Structures)” [5]. The reduction ratio of the specimen is 0.84. The steel pile is filled with concrete so as not to cause the yielding and buckling earlier than the pile head joint.

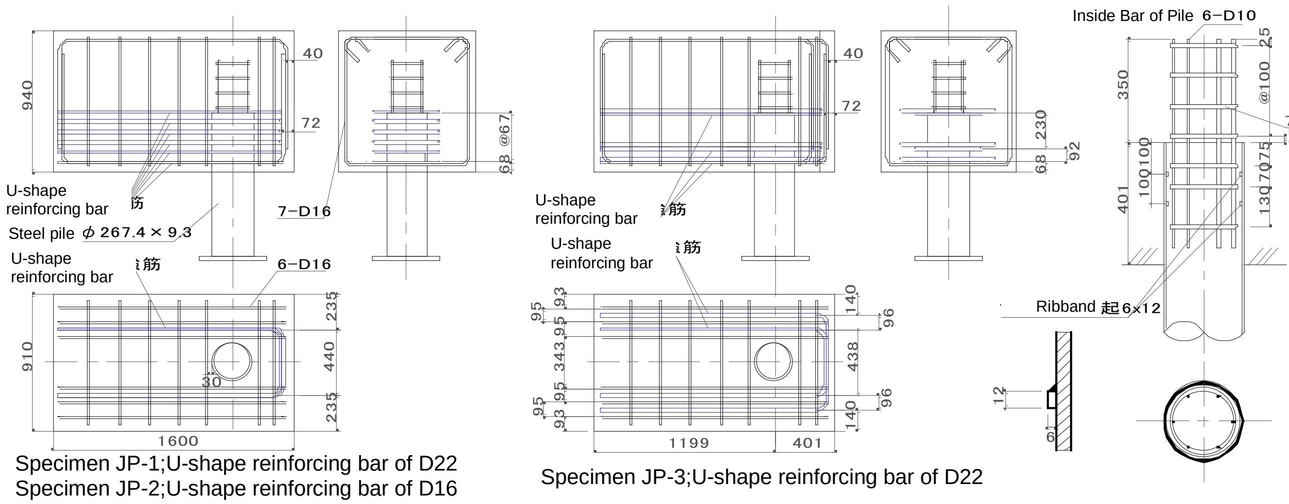

Fig. 4 – Dimension of the specimens (unit: mm)

The bending shear test method is shown in Fig. 5. The test specimen is turned upside down; the pile is set above the reinforced concrete footing. The horizontal loading is positive and negative cyclic loading: outward (+) and inward (-) direction. The vertical loads are set to +150kN of pull force when the horizontal load is applied in the outward direction, and -1000kN of push force when the horizontal load is applied in the inward direction. The axial force is kept constant in each horizontal load direction. The footing with the pile head joint is fixed at the column surface position; the distance from the pile center to the column surface is 535mm. This is because it is necessary not to restrain the behavior of the footing as a beam as much as possible.

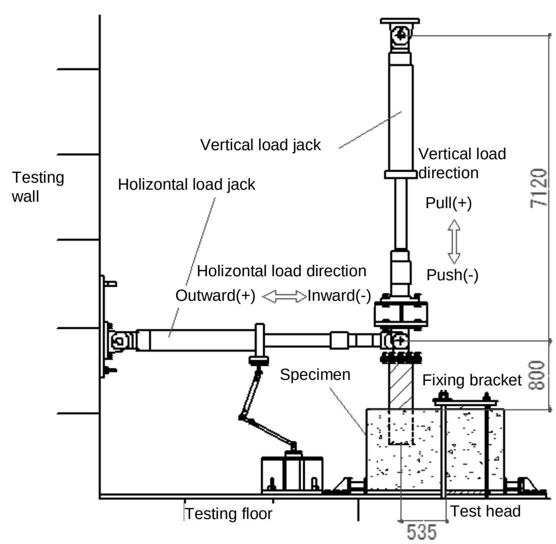

Fig. 5 – Arrangement of the bending shear test (unit: mm)

3.2 Material properties

Material test results of concrete and steel products are shown in Table 1 and Table 2. The material test of concrete, has been carried out immediately prior to the bending shear test, there is no significant difference in concrete strength among test specimens. Compressive strength of concrete is about 35 to 37MPa, and yield strength of the reinforcing bar is about 450MPa.

Table 1 – Material test results of the concrete

Specimen	Compressive strength (MPa)	Strain at compressive strength (μ)	1/3 Secant modulus (GPa)	Split tensile Strength (MPa)
JP-1	37.6	2093	29.85	2.77
JP-2	35.0	1780	31.01	2.96
JP-3	37.7	2084	28.34	2.92

Table 2 – Material test results of the steel products

Steel product	Dimension (mm)	Yield strength (MPa)	Tensile strength (MPa)	Elastic modulus (GPa)
U-shape reinforcing bar (Specimen JP-1 and 3)	D22	450	648	180.6
U-shape reinforcing bar (specimen JP-2), Main bar and stirrup	D16	465	642	189.8
Inside bar of steel pile	D10	441	610	169.2
Steel pipe pile	t=9.3	512	573	201.6

3.3 Bending shear test results

3.3.1 Crack patterns

Crack patterns after the end of the loading are shown in Fig. 6. First of all, cracks on the surface of the pile occurred. Next, by the loading in outward direction, cracks occurred in the orthogonal direction to the horizontal loading. Finally, cracks in the 45-degree direction to the horizontal loading are opened, with the result that the horizontal load became the maximum value. Compression failure of concrete caused by the bearing of the pile occurred when the horizontal loading in the inward direction is maximum value. Buckling of the steel pipe pile is observed at the time.

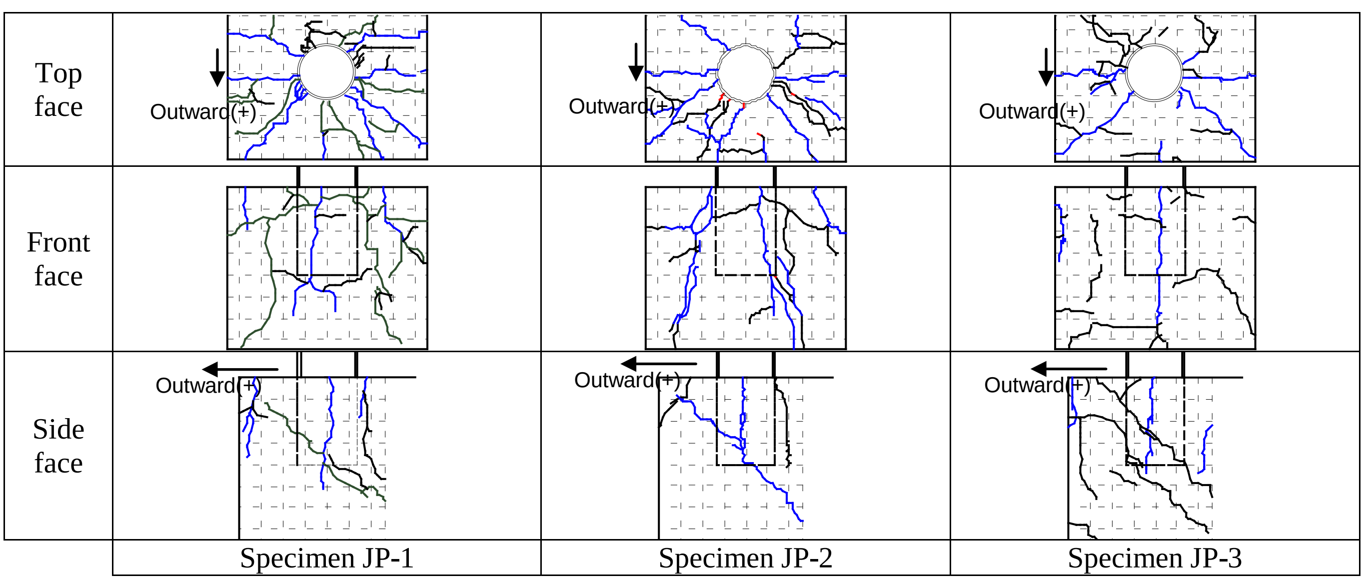

Fig. 6 – Crack patterns after loading
(blue line at the time of outward loading, black line at the time of inward loading)

3.3.2 Shear load and translational angle curves

Relationships between the shear load and the translational angle are shown in Fig. 7. The translational angles are calculated by dividing the horizontal relative-displacement of the pile by the height of the pile from the top face of the reinforced concrete footing. Initial stiffness in case of pile head fixed condition and the full plastic strength of the pile when the axial load is zero are also shown in Fig. 7. When the load is being applied in the outward direction, that is, tensile loading, all specimens showed curves lower than the calculated initial stiffness. Inside bars yield at first, and the maximum strength is higher than the calculated full plastic strength of the pile. The stiffness of specimen SP-2 is lower than any other specimens after the inside bars yielding, and specimen SP-2 shows lower maximum strength than any other specimens after the tensile yielding of the pile. As for the specimens SP-1 and SP-3, low stiffness like the specimen SP-2 is not observed after inside bars yielding. But the load reached the maximum value after the pile yielding by tensile force. The yielding of U-shape bars by tensile force is observed only in the specimen SP-2. Therefore, it can be seen that there is a difference according to the number of reinforcing bars in the pile head joint. In the specimens SP-1 and SP-3, it can be seen that the difference according to the reinforcing bar arrangement is small. When the load is being applied in the inward direction, that is, compressive loading, all specimens show the same behavior with respect to the translational angle and horizontal load curves, and the same maximum strength. The maximum strength is higher than the calculated full plastic strength of the pile regardless of the loading direction.

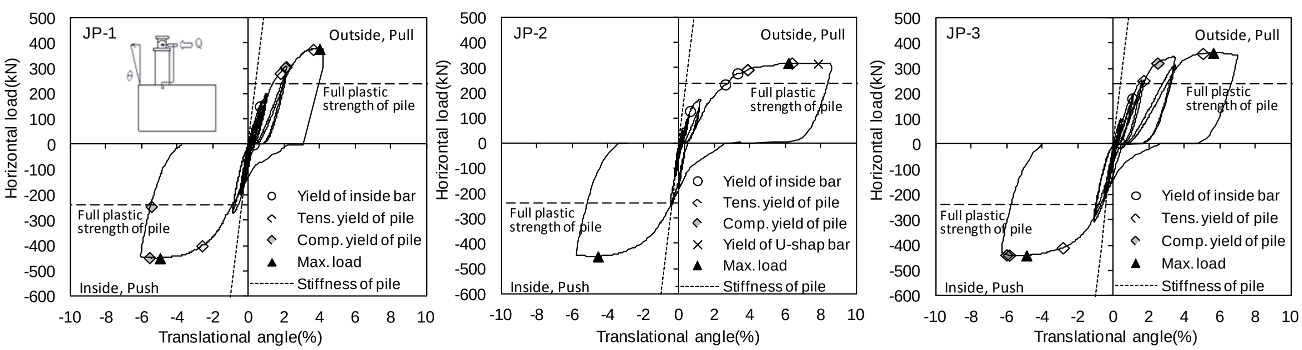

Fig. 7 – Horizontal load and translational angle curves

3.3.3 Distribution of strain

The strain distributions of reinforced concrete footings and U-shape reinforcing bars on the pile section plane are shown in Fig. 8. As for the strain distribution in the outward loading direction, the strains away from the pile are large. But as for the strain distribution in the direction at a right angle to the outward loading direction, the strains close to the pile are large. The reinforcing bars of the reinforced concrete footing are at the same strain level as the U-shape bars. Making a comparison between the specimens, the specimens SP-1 and SP-3 show a substantially equivalent behavior, therefore it can be seen that the difference according to the reinforcing bar arrangement is small. Because of the large strain of specimen SP-2 compared to the other specimens, it can be seen that there is difference according to of the number of reinforcing bars in the pile head joint.

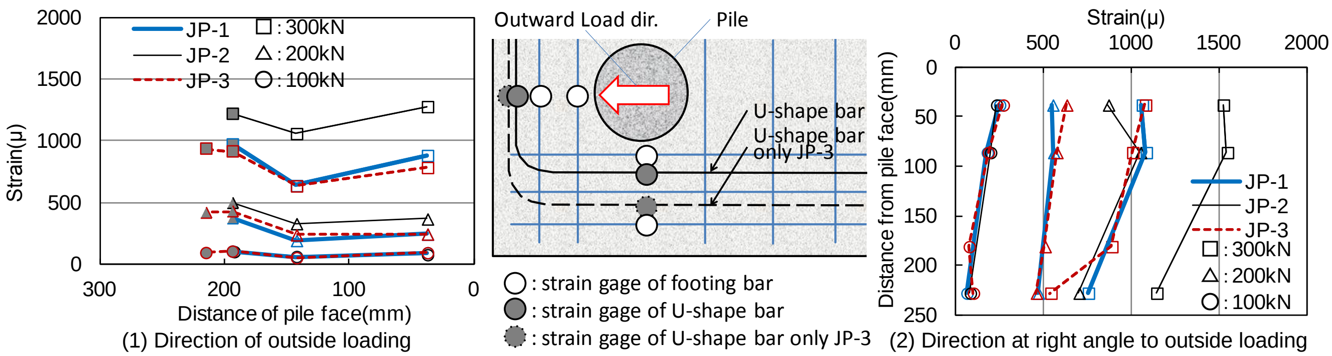

Fig. 8 – Strain distribution on the pile section plane

The U-shape reinforcing bar strain distributions in the pile axial direction in the specimen SP-1 are shown in Fig. 9. As for the strain distributions of both the front and side faces of the specimen when the load is being applied in the outward direction, the strain becomes greater with increasing proximity to the top face. This indicates that the U-shape bars are resistant to the bearing by the pile. As for the strain distributions of the front face when the load is being applied in the inward direction, the strains are smaller with decreasing proximity to the top face. As for the strain distributions of the side face when the load is being applied in the inward direction, the strain becomes greater with increasing distance from the top face.

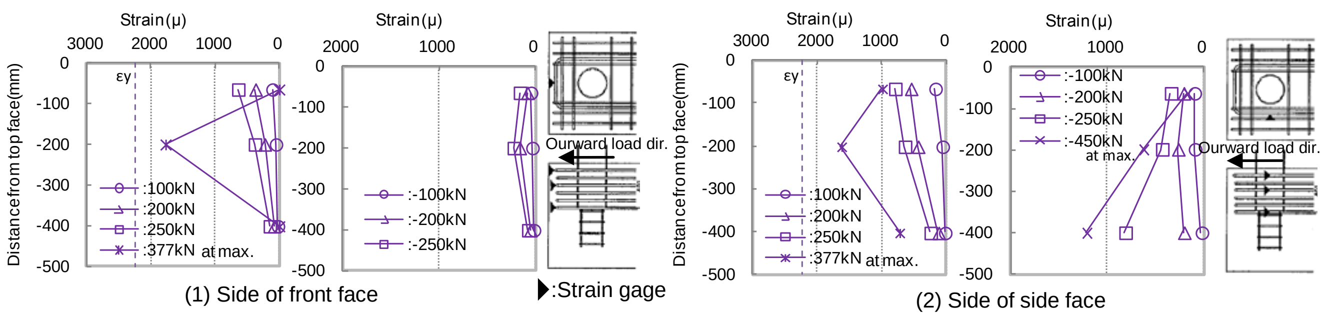

Fig. 9 – Examples of U-shape bar strain distributions in the pile axial direction

4. Evaluation of bending capacity

The reinforcing bars around the steel pipe pile are found to be resistant to the bearing by the pile, and this resistivity is foward to be distributed in the pile axial direction. The evaluation method of the pile head bending capacity is proposed based on the strength evaluation of the steel square tubular column bases for corner column embedded in concrete footing [4]. This bending capacity is expressed as follows. This method is built up based on the resistance moment derived from the maximum bearing resistivity of the footing concrete and the maximum tensile force of the column-footing reinforcing bars such as U-Shape reinforcing bars. The bending capacity of pile head joint is calculated by replaced the column with the pile as follow.

$$Q_{u1} = F_{cu} \cdot B_c \cdot \left\{ \frac{T_y}{F_{cu} \cdot B_c} - l - d + \sqrt{(l+d)^2 - \frac{2T_y \cdot (l + {}_t d_1)}{F_{cu} \cdot B_c}} \right\} \tag{1}$$

$$Q_{u2} = -(F_{cu} \cdot B_c \cdot l + T_y) + F_{cu} \cdot B_c \cdot \sqrt{l^2 + \frac{2T_y \cdot (l + d - {}_t d_2)}{F_{cu} \cdot B_c}} \tag{2}$$

where,

Q_{u1} = shear force at bending capacity in the outward direction

Q_{u2} = shear force at bending capacity in the inward direction

F_{cu} = compressive strength of concrete
B_c = width of the steel pipe pile
T_y = yield strength of the U-shape reinforcing bar
l = distance between the reinforced concrete footing top face and the point of contraflexure
d = embedment length of the pile
${}_t d_1$ = distance between the position where the tension of U-shape reinforcing bar is being applied and reinforced concrete footing top face
${}_t d_2$ = distance between the position where the tension of U-shape reinforcing bar is being applied and embedment end

The experimental values of maximum force and the calculated bending capacities are shown in Table 3. A calculated value-1 is a value that is calculated in consideration of only the effect of the U-shape reinforcing bars. The calculated values of all specimens are lower than the experimental values. Consequently, bending capacity calculated in consideration of not only effect of the U-shape reinforcing bars but also the main bars of reinfoced concrete footing is shown under the title of calculatad value-2, in Table 3. As shown in Table 3, when the load is being applied in the outward direction (tensile loading), the experimental values are in good agreemant with calculatad values-2.

Table 3 – Comparison between calculated bending capacities and experimental ones

Specimen	JP-1		JP-2		JP-3	
Load direction	Outside(+) and pull(+)	Inside(-) and push(-)	Outside(+) and pull(+)	Inside(-) and push(-)	Outside(+) and pull(+)	Inside(-) and push(-)
Experimental value(kN)	377	450*	319	451*	362	441*
Calculated value-1**(kN)	236	241	133	160	302	266
Ex. value/ Cal. value-1	1.60	1.87	2.40	2.82	1.20	1.67
Calculated value-2***(kN)	338	Same as cal. value-1	249	Same as cal. value-1	391	Same as cal. value-1
Ex. value/ Cal. value-2	1.12		1.28		0.926	

*: Maximum strength of joint is not lower than experimental maximum force, becouse of steel pile with local buckling.
**: Based on the method of Architectural Institute of Japan for connections in steel structures [4].
***: Added up reinforced concrete footing reinforcing bars to avobe AIJ method.

5. Conclusions

Structural design for pile head joints for over-track buildings, which are grouped in one of buildings such as public facilities, is required to ensure no damage under large earthquakes. And pile head joints should have also good workability. In this report, we proposed how to connect the steel column and the steel pile group with reinforced concrete footings. The cyclic bending shear load tests on the reinforced concrete joints between the steel pipe pile group and the column are conducted to obtain the mechanical properties of the reinforced concrete joint. Evaluation method of the bending capacity of pile head reinforced concrete joints for over-track buildings with steel pipe pile groups is proposed based on the experimental test results. The values obtained from the experimental tests show good agreemant with values obtained from the caluculations.

6. References

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