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# Development of the Numerical Model for the Seismic Response of Transmission Towers considering with the Bolted Joint Slip

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## *Abstract*

Based on the experience of the 2011 off the Pacific coast of Tohoku Earthquake, it is required to evaluate the seismic response of transmission towers against large earthquake predicted in the future such as Nankai Trough Earthquake. The bolted joints of the towers have possibility to slip when subjected to large axial force due to large earthquakes. The slip at the joint yields the additional damping effect to seismic response of the towers under large earthquakes. This paper aims to provide the numerical model to evaluate the seismic response of the towers realistically taking the slip effect into consideration. At first, we carried out the cyclic loading experiment in order to clarify the hysteresis characteristic of slip. The result shows that the hysteresis behavior can be classified into four processes: (1) elastic behavior of the joint members and bolt, (2) both elastic behavior and slipping behavior at joint surface, (3) slipping behavior at joint surface and (4) the contact of the bolt with bolt-hole. We also developed the constitutive law of the slip at the joint and defined its three parameters: the cross-sectional area and Young's module of the elastic behavior, the magnitude of the shear load under slipping and the gap between bolt and bolt-hole. Secondary, the shaking table experiment using the partial tower model of the full scale tower was carried out in order to evaluate the local slip effect on the response of entire structure. The experiment result shows that the damping of the model increases by the slip of the joints and the axial force of braces and the acceleration response of the model decreased. In addition, we develop the numerical model taking the slip effect into consideration using the commercial finite element method code Abaqus. The element containing the bolted joint divides into two elements: one is truss element applied the constitutive law of the slip, another one is beam element whose axial stiffness is negligible small not to transfer axial force. Simulating the shaking table experiment using developed numerical model, the simulated result agrees with the result obtained by the shaking table experiment.

*Keywords: Transmission tower, Bolted joint slip, Seismic response, Damping, Numerical model*

## 1. Introduction

Based on the experience of the 2011 off the Pacific coast of Tohoku Earthquake, it is required to evaluate the seismic response of transmission towers against large earthquake predicted in the future such as Nankai Trough Earthquake. Although the bolted joints of the towers have possibility to slip when subjected to large axial force due to large earthquakes, the slip at the joints is not considered in the evaluation of the seismic response. Because the slip yields the additional damping effect to seismic response of the towers under large earthquakes [1, 2, 3], it is important to take the slip effect into consideration to evaluate realistic seismic response. This research aims to develop the evaluation method of seismic response of transmission towers considering the slip at the bolted joints during large earthquake. At first stage of the research, the numerical model to evaluate the seismic response of the towers realistically taking the slip effect into consideration is provided in this paper. In order to develop the numerical model, the hysteresis characteristic of the slip was clarified based on the cyclic loading experiment. Secondary, the shaking table experiment using the partial tower model of the full scale tower was carried out in order to evaluate the local slip effect on the response of entire structure. In addition, we developed the numerical model taking the slip effect into consideration using the commercial finite element method code Abaqus [4]. Simulating the shaking table experiment using developed numerical model, the simulated result agrees with the result obtained by the shaking table experiment.

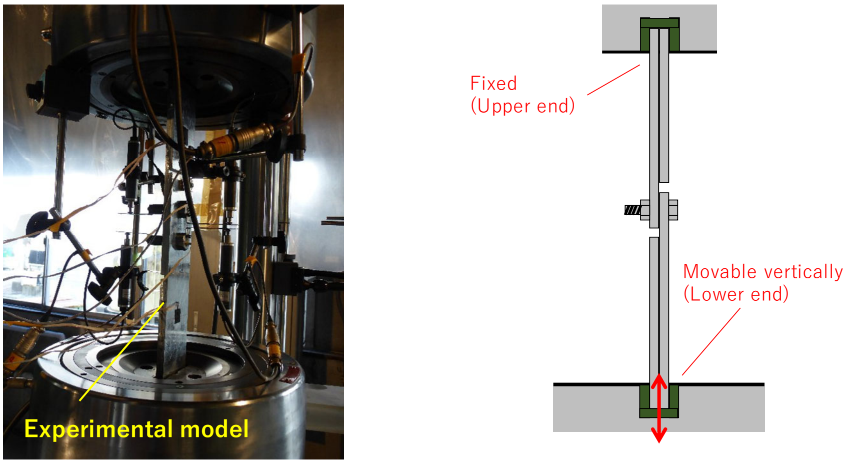
## 2. Experimental methods

### 2.1 Cyclic loading experiment

A static cyclic loading experiment of a displacement increasing type was performed using an experimental model simulating a bolted joint. Fig.1 shows the installation status of the experiment model. The test specimen was fixed to the upper and lower ends of the tester. In the experiment, tensile and compressive loads were cyclically applied to the experimental model by applying a forced displacement to the lower end in the vertical direction in Fig.1. In the experiment, we focused on the relationship between the displacement at the joint and the load acting on the member.

Fig.2 shows the shape and dimensions of the experimental model. The experimental model consisted of members of the same shape, which were fixed with one or two bolts and nuts. The bolt used for the experimental model was M16. In addition, the thickness of the members was set to 6 mm in accordance with the manufacturing standards for angle steel towers for power transmission. The bolt hole diameter was also set to 17.5 mm (clearance 1.5 mm) based on the manufacturing standard of the angle steel tower for power transmission, and the bolt hole was provided at the center in the member width direction. The shape of the member was a flat plate, and the width of the flat plate was set to 80 mm due to the limitations of the testing machine. In addition, a flat plate with a thickness of 6 mm and a width of 80 mm was spot-welded to the fixed end of the member in order to make the load acting surface (center of the testing machine) coincide with the member joining surface. The material of the members and bolts was SS400, the members were coated with hot-dip galvanized with an adhesion amount of 550g/m$^2$ or more based on HDZ55 specified in JIS H 8641, and the bolts and nuts were also coated with hot-dip galvanized with an adhesion amount of 350 g/m$^2$ or more based on HDZ35 specified in JIS H 8641. In the model A, the upper and lower members were fixed with a single bolt through the bolt holes provided 50 mm from the end of the member. On the other hand, in the model B, the upper and lower members were fixed with two bolts through bolt holes provided at 50 mm and 100 mm (the distance between the centers of the bolt holes was 50 mm) from the end of the member.

Table 1 shows a list of experimental conditions. The experimental parameters were the number of bolts and the axial force applied to the bolts. In S1 and S2, the model A was used to grasp the basic characteristics of bolt joint slip. The axial force of the bolt was different between S1 and S2, and it was 12kN in S1 and 24kN in S2. In S3, the effect of the number of bolts was grasped using the model B in comparison with S1 and S2. The total bolt axial force was 36 kN, and the bolt axial force of each bolt was 18 kN.

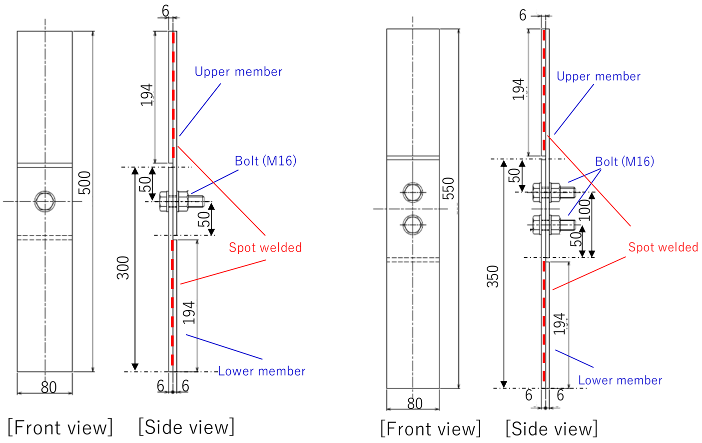


(a) Picture (b) Schematic

Fig.1 – Parameters for cyclic loading experiment

Table 1 – Parameters for cyclic loading experiment

| No. | Model | Number of bolts | Axial force |
|---|---|---|---|
| S1 | A | 1 | 12kN |
| S2 | A | 1 | 24kN |
| S3 | B | 2 | 36kN (= 18kN+18kN) |



(a) Model A (b) Model B

Fig.2 – Shape and dimension of experimental model

The loading method was a static cyclic loading of displacement increasing type, and loading was performed by displacement control. During loading, the upper member was fixed and a forced displacement was applied to the lower member. The cyclic displacement amplitude was increased from 0.2mm to 1.6mm in 0.2mm increments per cycle and returned to the initial position after giving -1.6mm. In the experiment, the axial force generated in the member and the displacement of the joint were measured. The axial force of the member was measured using a load cell built into the testing machine, and its polarity was defined as positive when a tensile force was applied to the member and zero when no load was applied. The displacement of the joint was measured using a pie-type displacement meter attached near the joint.

## 2.2 Shaking table experiment

A shaking table experiment using a partial tower model was performed to understand the effect of the joint slip on the vibration characteristics of the entire structure. The experimental model was designed so that the joint became the actual size. Fig.3 shows the whole view of the experimental model and its installation status on the shaking table. The experimental model was the actual size of 11 and 12 panels of a standard 66 kV angle steel tower (tower height 28.6 m, root height 4.72 m, number of panels 17), and the bolt size was M16 which was the same as that used in the static cyclic loading experiment. In this paper, the lower panel was called "Panel 1" and the upper panel was called "Panel 2." The height of Panel 1 and Panel 2 was 1.5m and 1.4m respectively, and the bottom width was 2.15m and 1.89m respectively. The main leg member was a single member through panels 1 and 2, and its cross-sectional shape was L100 × 10 of equilateral angle iron. The cross-sectional shape of the brace member was L45 × 4 of equilateral angle iron, and the main leg and brace members were connected by one bolt, and the brace member was joined by one bolt via a ring filler. The experiment was performed on the condition that slip was generated only at the joint of panel 1, and no slip occurred at the joint of panel 2. For this reason, auxiliary members were added to panel 2, and the joints of each member were tightened using high-strength bolts at three times the design torque. In panel 1, the bolted joints on the plane perpendicular to the vibration direction (east and west faces shown in Fig. 3) were also tightened with high strength bolts at three times the design torque. In the experiment, the response of the experimental model at resonance was also targeted, so the resonance frequency of the experimental model had to be within the frequency band (20Hz or less) that could be reproduced on the shaking table. Therefore, a dummy weight (2ton) and a support member for fixing the dummy weight (1ton) were added to the upper part of panel 2 to reduce the resonance frequency. The support was joined by welding and treated as a rigid body. As shown in Fig.3, the direction was defined as south on the front and north on the back. The excitation direction was one direction in the east-west direction.

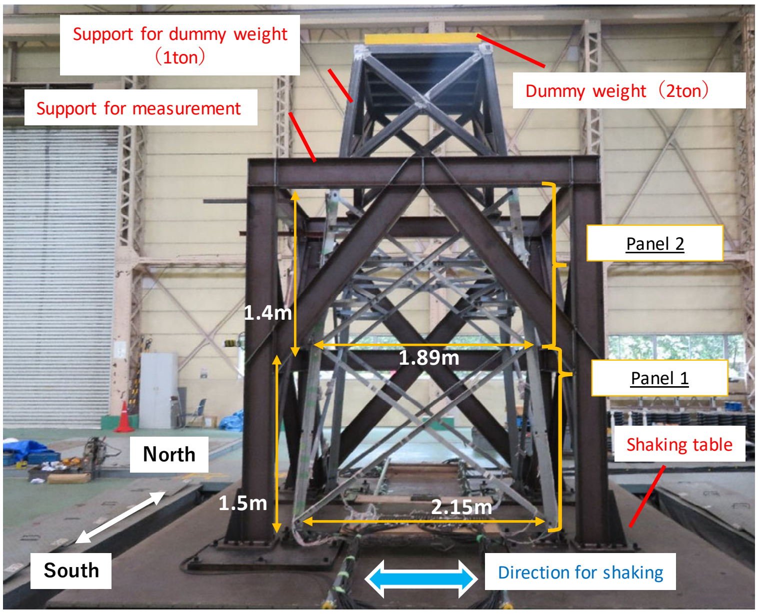


Fig.3 – Partial tower model in the shaking table experiment

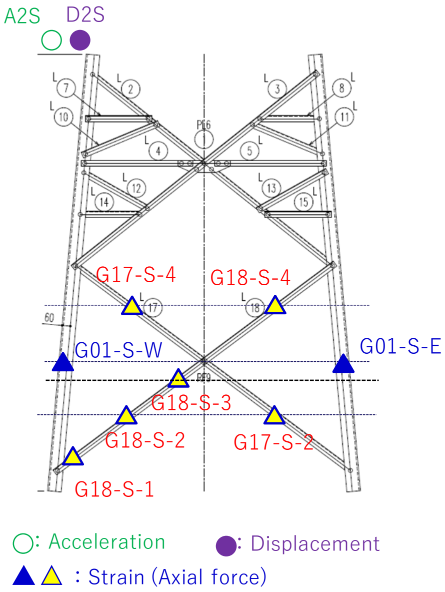
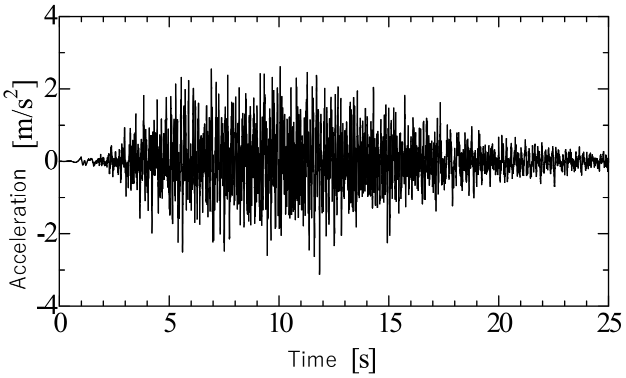


Fig.4 – Measurement position



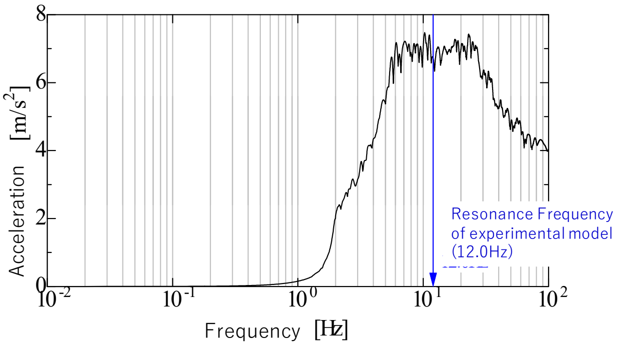


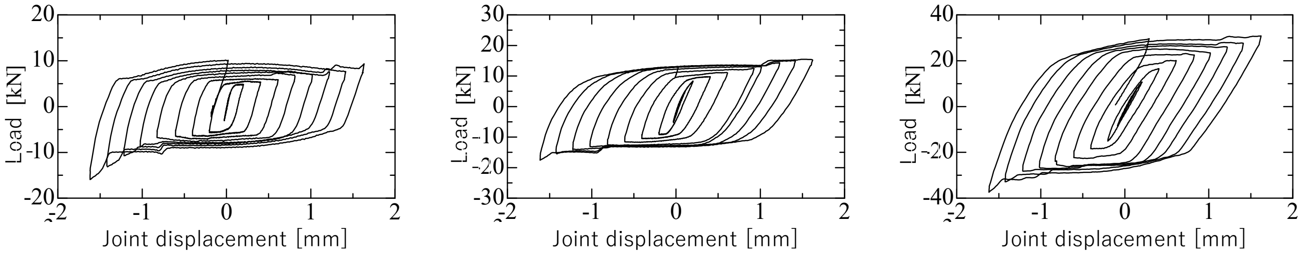
Fig.5 – Exitaion waveform

Fig.6 – Acceleration responce spectrum

In order to measure the response of the experimental model, the acceleration, displacement, and strain of the experimental model were measured. Fig.4 shows the measurement positions and measurement point names. Note that only the measurement points on the south side are illustrated in Fig.4, and the names of the measurement points on the north side are the names of the south side with "S" replaced by "N". The acceleration and displacement were measured at the upper end of panel 2, the acceleration was measured with an accelerometer, and the displacement was measured with panel 2 using a displacement meter installed on a measurement stand. On the other hand, the strain of the member was measured on panel 1. The position was the center between the member joints in the main leg member, and the center between the member joints and the vicinity of the joint in the brace member. The strain of the member was measured by attaching strain gauges to four points at each location and converted to axial strain in the member axial direction.

Table 2 – Parameters for shaking table experiment

| No. | Slipping at joint | Acceleration amplitude [m/s$^2$] |
|---|---|---|
| D1 | Noshing | 0.5,1.0,2.0,5.0,7.5,10.0 |
| D2 | Slip during excitation | 0.5,1.0,2.0,5.0,7.5,10.0,11.5,15.0 |



(a) S1

(b) S2

(c) S3

Fig.7 – Relationships between the joint displacement and the load obtained in the experiment

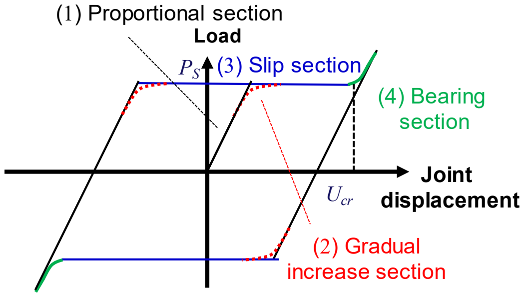


Fig.8– Schematic diagram

Table 3– Sip load, slip coefficient, and bolt axial force

| No. | Slip load | Slip coefficient | Bolt axial force |
|---|---|---|---|
| S1 | 4.63 kN | 0.44 | 10.65 kN |
| S2 | 8.66 kN | 0.41 | 21.41 kN |
| S3 | 14.89 kN | 0.44 | 33.71 kN |

An artificial seismic wave was used as the excitation waveform. Fig.5 shows the time history waveform of the artificial seismic wave, and Fig.6 shows the acceleration response spectrum (5% attenuation). Fig.6 also shows the resonance frequency of the experimental model. Fig.6 shows that the artificial seismic wave has the predominant resonance frequency component of the experimental model.

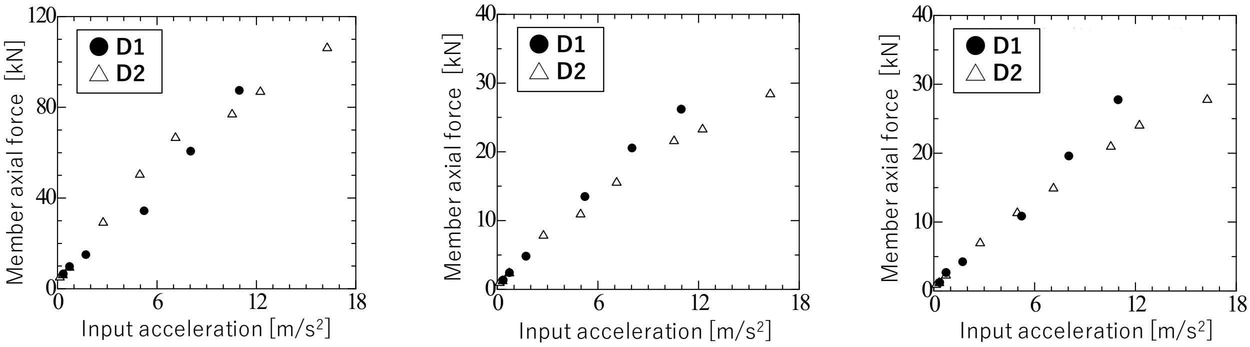
As shown in Table 2, bolt tightening torque and acceleration amplitude of artificial seismic wave were used as parameters in the shaking table experiment. In D1, the tightening torque was set to three times the specified value in order to prevent the joint from slipping during excitation. The acceleration amplitude was set to 0.5 to 10.0 m/s$^2$. On the other hand, in D2, the tightening torque was such that the joint would slip during the excitation, and the acceleration amplitude was 0.5 to 15.0 m/s$^2$.

## 3. Experimental Results

### 3.1 Cyclic loading experiment

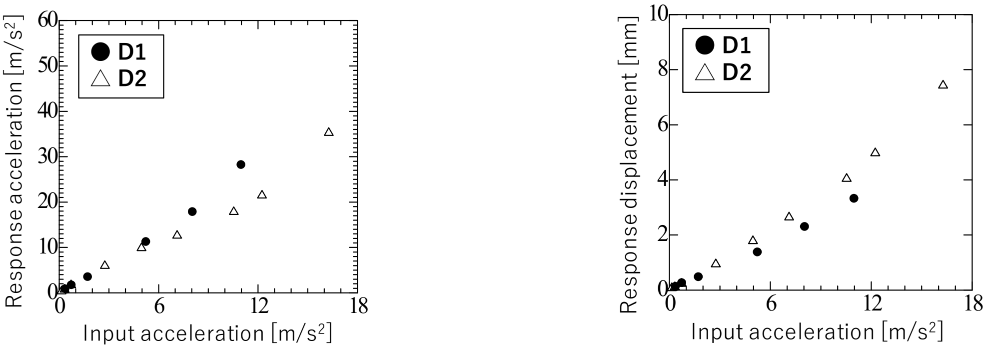
Fig.7 shows the relationship between the joint displacement and the load obtained in the experiment. Focusing on S1, the load immediately after loading was roughly proportional to the displacement of the joint. After the load increased gradually, when the load reached a certain load value (4.63 kN), the load did not increase and only the displacement increased. When the loading direction was reversed, the load decreased, the load changed gradually, and then transitioned to the section where only the displacement changed again. Also, in this section, the absolute value of the load slightly changed and increased every cycle. Eventually, the load suddenly increased as seen at displacements of +1.6mm and -1.2mm. These trends were similar for S2 and S3. Fig.8 shows a schematic diagram of the relationship between the joint displacement and the load based on the experimental results. In this paper, the section in which the load is proportional to the displacement of the joint immediately after loading is referred to as the "proportional section", the section in which the load increases gradually is referred to as the "gradual increase section", and the section in which the load reaches the peak and only the displacement increases is referred to as the "slip section". In particular, the load at which slipping starts to occur for the first time is called "slip load", and the ratio of the load to the bolt axial force is called "slip coefficient". The sudden increase in the load is caused by the contact of the bolt body with the bolt hole wall. Therefore, this section is called the "bearing section".

Next, we focus on the slip load and the slip coefficient. Table 3 shows the slip load, slip coefficient, and bolt axial force used in calculating the slip coefficient in S1, S2, and S3. The bolt axial force was measured by a strain gauge embedded in the bolt. According to Table 3, the slip load was almost proportional to the bolt axial force. It indicates that the slip coefficient is the almost same regardless of the bolt axial force and the number of bolts.



(a) G01-S-W (b) G17-S-4 (c) G18-S-2

Fig.9 – Relationships between input acceleration and member axial force by experimental results



(a) acceleration (b) displacement

Fig.10 – Relationships between input acceleration and response of experimental model by experimental results

## 3.2 Shaking table experiment

Fig.9 shows the relationship between input acceleration and member axial force. Here, the input acceleration indicates half amplitude value, which is calculated as one half of the difference between the maximum value and the minimum value, of the acceleration measured on the shaking table. Also, the member axial force is the half amplitude value of the axial force measured for each member. In addition, the results for G01-S-W for the main leg member and G17-S-4 and G18-S-2 for the brace member are shown. In D1, the axial force of any member was almost proportional to the input acceleration. On the other hand, in D2, the axial force of the member was approximately proportional to the input acceleration up to the input acceleration of 7 m/s$^2$, but after 7 m/s$^2$, the rate of change of the axial force of the member with respect to the input acceleration decreased. Considering the occurrence of joint slippage in D2, it is indicated that the occurrence of joint slippage reduces the axial force of the member.

Fig.10(a) shows the relationship between input acceleration and response acceleration, and Fig.10(b) shows the relationship between input acceleration and response displacement. The response acceleration and response displacement are also shown as half amplitude values. In D1, both the response acceleration and the response displacement were almost proportional to the input acceleration. On the other hand, in D2, the response acceleration and the response displacement were both proportional to the input acceleration up to the input acceleration of about 5 m/s$^2$, but the change rate of the response acceleration and the response displacement with respect to the input acceleration changed with the input acceleration exceeding it. Specifically, in response acceleration, the rate of change once decreased at an input acceleration of 5 m/s$^2$ and increased at an input acceleration of 11 m/s$^2$. In response displacement, the rate of change increases after input acceleration of 5 m/s$^2$. It is indicated that these are due to the slip at the joint.

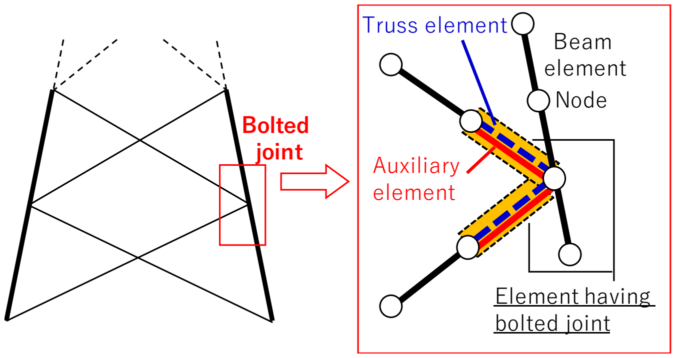


Fig.11 – Modeling of bolt joint sliding elements

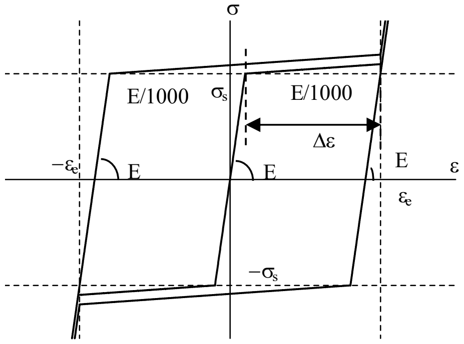


Fig.12 – Material constitutive law

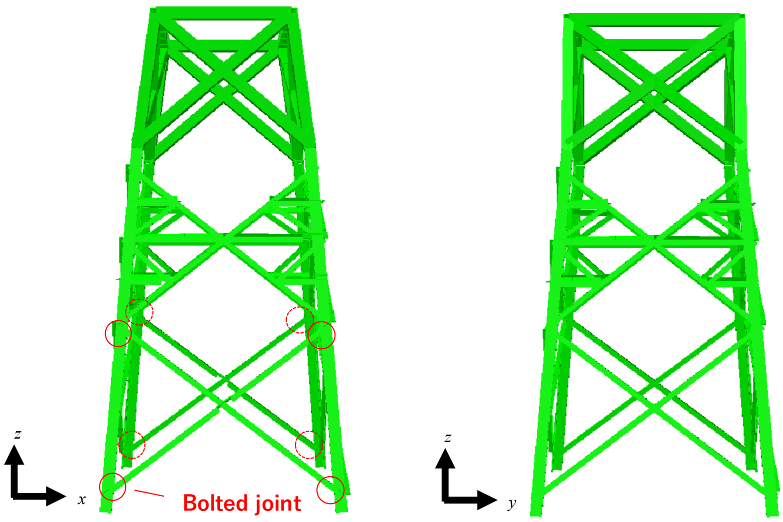
## 4. Construction of numerical analysis model and its verification

A numerical analysis model capable of considering the bolt joint slip was constructed, and its validity was verified by comparison with the results obtained by the shaking table experiment. The commercial finite element method analysis code Abaqus was used.

### 4.1 Numerical analysis model

We limited the direction in which the joint slip occurred to the axial direction of the member and modeled the joint slip. Therefore, as shown in Fig.11, a beam element having a bolted joint was divided into (1) a truss element that transmits only axial force and (2) a beam element that transmits shear, bending, and torsional moments (referred to as the auxiliary element). Next, the constitutive law of the joint slip identified based on the results obtained by the static cyclic load experiment was given to the material constitutive law of the truss element as shown in Fig.12. The initial stiffness was the Young's modulus $E$ of the member, and the stress was proportional to the strain below the sliding stress $\sigma_s$ corresponding to the sliding load of the joint. This indicates that the joint behaves as an elastic beam before slippage occurs. When the stress exceeded the sliding stress, the stiffness decreased and the strain increased by $\Delta\varepsilon$ corresponding to the bolt clearance. This section represents slip. When the strain further increased and reached $\varepsilon_e$, the stiffness returned to the initial stiffness. This indicates that the bolt is in contact with the bolt hole, that is, the bearing state. After the bolt contacted the bolt hole, it behaved as an elastic beam again. The stiffness at the time of unloading became the initial stiffness. When the stress exceeds the sliding stress again, the stiffness decreased, and slip occurred until it reached $\varepsilon_e$. The above behavior was the same for both tension and compression.

At the time of analysis, three parameters were given: slip load, slope of slip section, and bolt clearance. Slip load and bolt clearance were set based on the conditions of the target joint. For the slope of the slip section, the stiffness was set to 1/1000 of the initial stiffness. On the other hand, the auxiliary element was modeled by a beam element having a generalized section. It was necessary to set the Young's modulus to 0 in order not to transmit the axial force, but when the Young's modulus was set to 0, the convergence calculation became impossible. Therefore, the Young's modulus was set to 1/1000 of the initial stiffness of the truss members. The shear stiffness, bending stiffness, and torsional stiffness of the auxiliary element were the same as those of the member before divided.



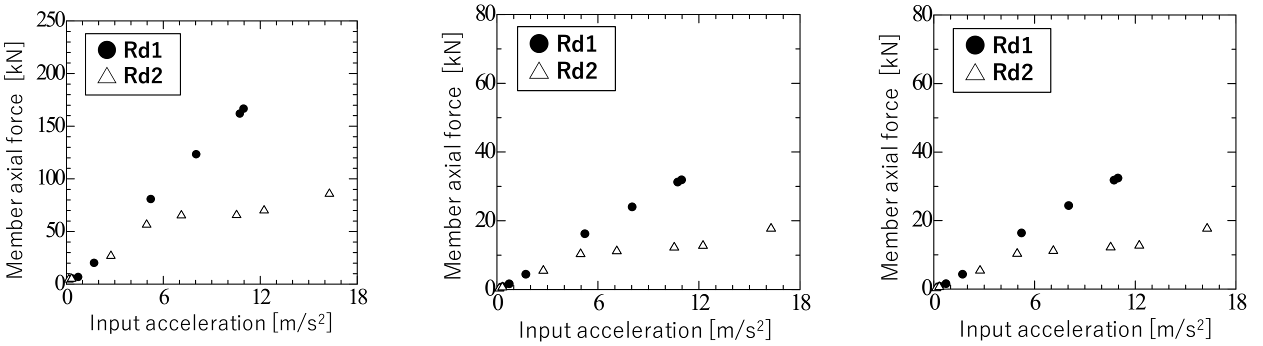
(a) XZ plane (b) YZ plane

Fig.13 – Overall diagram of the analysis model

## 4.2 Verification analysis of shaking table tests

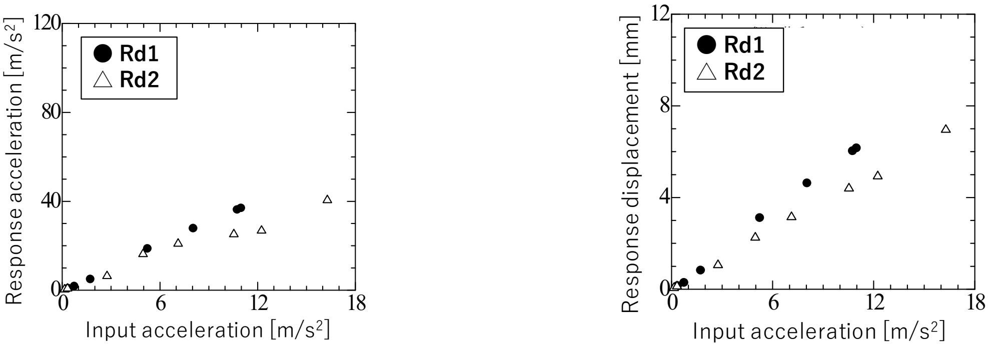
The shaking table experiment was simulated using a numerical analysis model that considered the joint slip. Fig.13 shows the overall diagram of the analysis model used in numerical simulation. Fig.13 also shows the coordinate system used in the analysis. The X-axis was set as the excitation direction (east-west direction), the Y-axis was set as the orthogonal direction (north-south direction), and the Z-axis was set as the vertical direction. The output positions for the acceleration, displacement and member axial force were the same in the experiment (Fig. 4).

Panels 1, 2 and the support for dummy weight were modeled by beam elements, all of which were made of elastic materials. In addition, the dummy weight was modeled by the mass element and was evenly distributed on the upper surface of the support. Of the member joints, the joints between the main leg member and the brace members (marked with circles in Fig.13 (a)) in the front and back (XZ plane) of panel were modeled by the element that took into account the joint slip. All other joints were rigidly connected. The base of the main leg member, that is, the shaking table and the partial tower model were modeled as completely fixed. The analysis was a time history response analysis in which the acceleration was input to this completely fixed point, and the acceleration waveform on the shaking table obtained in the shaking table experiment was used. For the damping, a stiffness proportional damping constant of 1% with respect to the primary natural frequency of the specimen was set. The primary natural frequency was the value obtained by eigenvalue analysis under the condition where no bolt joint slippage occurred. Among the parameters given to the material constitutive law of joint slip, the slip load was set based on the experimental results. Specifically, slip did not occur in D1, so the slip load was set to 120kN to prevent slip. In D2, the slip load was set to 10kN. The bolt clearance was 1.5 mm because the bolt used in the experiment was M16.



(a) G01-S-W (b) G17-S-4 (c) G18-S-2

Fig.14 – Relationships between input acceleration and member axial force obtained by numerical results



(a) acceleration (b) displacement

Fig.15 – Relationships between input acceleration and response of experimental model by numerical results

### 4.3 Comparison with the results obtained by the shaking table experiment

Fig.14 shows the relationship between input acceleration and member axial force obtained by numerical analysis. Here, the numerical analysis for the shaking table experiment D1 was called Rd1, and the numerical analysis for D2 was called Rd2. In Rd1, the member axial force was proportional to the input acceleration. On the other hand, in the case of Rd2, the member axial force was proportional to the input acceleration up to the input acceleration of 5.0m/s$^2$, but after that, the rate of change of the member axial force with respect to the input acceleration decreased. It is presumed that the decrease in the rate of change in the member axial force was caused by the slip at the joint. Compared with the experimental results shown in Fig.9, the numerical results tended to have a higher axial force than the experimental results. However, it is indicated that the tendency that member axial force decreases due to joint slip can be simulated by numerical analysis.

Fig.15 shows the relationship between the input acceleration and the response of the experimental model at Rd1 and Rd2. In Rd1, both response acceleration and response displacement were proportional to input acceleration. In Rd2, both the response acceleration and the response displacement were proportional to the input acceleration up to the input acceleration of 5.0m/s$^2$, but after that, the rate of change with respect to the input acceleration changed. Specifically, both the response acceleration and the response displacement decreased once at an input acceleration of 5.0 m/s$^2$ and increased at an input acceleration of 12.0 m/s$^2$. Compared with the experimental results shown in Fig.10, although the response acceleration differed in the magnitude of the response value, the changes due to the occurrence of the joint slip coincided. On the other hand, in response displacement, the rate of change with respect to the input acceleration once decreased in the experiment due to the occurrence of the joint slip, but it did not decrease in the numerical analysis. However, after the input acceleration of 12.0m/s$^2$, the rate of change with respect to the input acceleration increased similarly to the experimental results.

## 5. Conclusion

In this paper, a static cyclic loading experiment and a shaking table experiment were performed to construct a numerical analysis model capable of considering the bolt joint slip. Furthermore, in order to verify the validity of the numerical analysis model, time history response analysis was performed to simulate the shaking table experiment. The results obtained in this paper are as follows.

- The load-joint displacement relation of bolt joint slip can be roughly classified into four sections: proportional section, gradually increasing section, slip section and bearing section.
- We propose a constitutive law for bolted joint slip and proposed that its main parameters are slip coefficient, clearance, and slope of proportional section.
- It is confirmed that the axial force of the member is reduced due to the occurrence of joint slippage.
- A numerical model for elements including bolt joints is proposed. Specifically, the element including the bolted joint is modelled by a truss element and a beam element that does not bear the axial force. In addition, the constitutive law of the joint slip is given to the material constitutive law of the truss element.
- Compared with the shaking table experiment, the experimental results are agreed in terms that the member axial force and response acceleration are reduced due to the slip at the joint.

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