Inelastic Seismic Design of Tall Structures Considering Anchor-Bolt Yielding*

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This report deals with a fundamental study of inelastic seismic design methodology of tall structures with attention to anchor bolt yielding during earthquakes. To investigate the dynamic behavior of these structures, first, shaking table excitation tests were conducted for a tall slender model structure. Next, to interpret the experimental results, a simple mechanical model was proposed and the numerical response analyses were carried out. The following conclusions were obtained from these experiments and analyses. (1) When the response of the model structure dominantly increases under the resonant condition causing plastic deformation of anchor bolts, a greater amount of reduction of seismic design load for tall structures was observed in comparison with an elastic design. (2) As for the structural response time histories, satisfactory agreement between the experimental results and the numerical simulation results was obtained.

Key Words: Seismic Design, Inelastic Seismic Design, Anchor Bolt, Experiment, Tall Structure, Response Analyses, Rocking Model

1. Introduction

Many tall structures are located at industrial facilities such as energy supply plants. In Japan, the seismic design of such structures has so far been carried out on the basis of elastic seismic design criteria, such as the Seismic Design Code for High Pressure Gas Facilities.⁽¹⁾ Recently, however, the inelastic seismic design, in which the energy absorption due to plastic deformation of the yielding parts, such as skirt and anchor bolts is taken into consideration when the seismic design load is determined, has come under study in light of the rationalization and improvement of the design procedure^{(2),(3)}. For example, in New Zealand the concept of inelastic seismic

design⁽⁴⁾ has been applied and tested to establish seismic design standards for petrochemical plants⁽⁵⁾. Under these circumstances, anchor bolts that can undergo plastic deformation in tall structures have attracted attention, and research on the dynamic response characteristics of structures using such yielding anchor bolts has been prompted^{(6),(7)}. However, detailed experiments and analyses of this consideration have been insufficiently carried out for this type of structure.

In this study, shaking table excitation tests⁽⁸⁾ were conducted for evaluating the seismic design load reduction due to the energy absorption of yielding anchor bolts. A two-degree-of-freedom rocking model was proposed for analyzing the inelastic seismic response of tall structures against earthquake motions. In the excitation tests, the dynamic response characteristics of the model structure were examined when the anchor bolts yielded during excitation, and the amount of energy dissipated due to the anchor bolt yielding was calculated. In the analyses, a two-degree-of-freedom rocking model, of which the anchor bolts were elongated, was proposed to calculate the dynamic responses of the tall structure during earth-

* Received 7th January, 1992. Paper No. 90-1560 A

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quakes. The validity of this model was verified by simulating the responses of the structure under nearly the same conditions as those of the excitation tests.

2. Description of Excitation Tests

2.1 Apparatus and specimens

Figure 1 shows the tower model which simulates a tall structure on the shaking table and Table 1 lists the specifications of this model. The model is composed of a tower body, a mass, and base plate. The tower body is fixed to the base with eight equally spaced anchor bolts. A 1 000 kg weight is placed at the top of the tower body, so that the center of gravity of the tower model is located at a height of 1.51 m from the bottom of the tower. To clarify the effect of the anchor bolt elongation on the vibration responses, the tower is manufactured in the simple geometry shown in Fig. 1. The tower model is designed to prevent plastic deformation of the base plate and any other parts of the tower model except for the reduced section of the anchor bolts. The base plate welded to the tower body is fixed by the eight equally spaced anchor bolts to the base structure, which is anchored to the shaking table. Shear plates welded to the bottom of the base plate prevents transmission of the shearing force from the tower body to the anchor bolts. A rubber sheet 2 mm thick is inserted between the base plate of the tower and the base structure to eliminate the high-frequency spikes that would otherwise occur due to collisions which can occur during

excitation.

Figure 2 shows the profile of the anchor bolts, which were made of mild steel (JIS Code S 45 C). In order to prevent the anchor bolts from breaking at their threads, shanked anchor bolts with reduced sectional area were used. The diameter and the length of the reduced section of anchor bolts was 4.5 mm and 30 mm, respectively. The initial tightening force on the eight anchor bolts was applied so that strain gauges on the reduced sections showed one-fifth of the elastic limit ($500 \mu\epsilon$).

2.2 Method of experiment

A frequency sweep sinusoidal wave and two kinds of random waves were input to the tower model installed on the shaking table. Figure 3 shows the locations of the sensors to measure displacement and acceleration. Elongation of the anchor bolts was measured with strain gauges at the center of the reduced section. In addition, tensile loads on the anchor bolts were measured with load cells placed to the end of each anchor bolt. Data thus collected were transmitted to a computer at increments of 0.001 sec via an amplifier and an analogue/digital converter.

3. Response Characteristics of Tower Model with Yield Anchor Bolts

In the excitation tests, the natural frequency f_T and the damping ratio ζ_T were measured. A frequency

Table 1 Specification of the tall structure model

Total Height of Tower	2.0 (m)
Total Weight	1,400 (kg)
Mass Weight	1,000 (kg)
Tower Weight	400 (kg)
Height of Center of Gravity	1.51 (m)
Diameter of Base Plate	0.5 (m)
Thickness of Base Plate	0.03 (m)
Bolt Circle Diameter	0.4 (m)

Fig. 1 Photo of tower model and shaking table

Fig. 2 Anchor bolt profile

Fig. 3 Locations of sensors

sweep sinusoidal wave passing through the natural frequency f_r , and a random wave containing a frequency component close to the natural frequency were used as the input waves. In order to generate plastic deformation of the anchor bolts, these input waves were amplified and the dynamic responses of the tower model were measured.

3.1 Natural frequency and damping ratio of the model

Using a random wave of maximum acceleration of 1 m/s^2 input excitation, the natural frequency of the tower model was found to appear in the frequency area of $11\sim 13 \text{ Hz}$, and the damping ratio which was identified by a curve-fitting method was 2.9% . However, this value varied depending upon the tightening strength of the anchor bolts.

3.2 Response characteristics for a frequency sweep sinusoidal input

Figures 4 and 5 show typical examples of the responses to the frequency sweep sinusoidal input. The responses greatly varied, depending on whether the excitation was ascending frequency loading or a descending one. When excited by an ascending sweep (from $2\sim 14 \text{ Hz}$) the acceleration of the top of the tower significantly increased in frequency only at the resonance point and the anchor bolts instantaneously

elongated. After this stage, the tower model displayed a rocking vibration at a lower frequency than that of the excitation.

Whereas the tower was excited by a descending sweep (from $15\sim 2 \text{ Hz}$), the resonance frequency of the tower motion was reduced significantly due to plastic elongation of the reduced section of the anchor bolts. The correlation between the frequency components of the input and the resonance frequency of the model tower was, in some cases, obtained due to the breakage of anchor bolts.

In the case of the descending frequency sweep sinusoidal input shown in Fig. 5, all of the anchor bolts broke after about seven seconds from the start of excitation, after which the tower started rocking as a rigid body.

3.3 Response characteristics for random wave input

Two random waves with a bandwidth of 5 to 13 Hz (No.1) and 1 to 15 Hz (No.2) were used in the tests to assess the response characteristics of the tower during excitation. Figures 6 and 7 show the time histories measured at several locations on the tower.

The natural frequency, which was about 12 Hz when the anchor bolts were responding in the elastic range, gradually decreased in accordance with the

Fig. 4 Responses to ascending frequency sweep sinusoidal input (from 2 to 15 Hz)

Fig. 5 Responses to descending frequency sweep sinusoidal input (from 15 to 2 Hz)

elongation. When the anchor bolts reached their ultimate elongation and became free of the tensile load, the tower started to display rocking motion at a

Fig. 6 Responses to random input (bandwidth of 5 to 13 Hz)

Fig. 7 Responses to random input (bandwidth of 1 to 15 Hz)

frequency of 2~3 Hz in the same way as when it was excited by frequency sweep sinusoidal excitation.

During excitation with the No.1 random input, which did not have the natural frequency component of the rocking motion, the response acceleration time history of the tower decreased at four seconds from the start. Although measurement of the strain on the anchor bolts was possible only up to 20 000 $\mu\epsilon$ due to the limited capacity of the instrumentation, the elongation of anchor bolts exceeded this limit. This elongation of anchor bolts led to a decrease of the response acceleration amplitude of the tower and the tensile load of the anchor bolts.

In tests with the No.2 random input, on the other hand, the natural frequency of the tower descended after plastic deformation of the anchor bolts occurred, but the response acceleration amplitude did not decrease.

4. Energy Absorption by Anchor Bolts When Yielding or Breaking

As far as inelastic seismic design is considered, it is necessary to estimate the amount of energy absorbed, known as the plastic strain energy, by the yielding parts and/or members. In order to calculate this quantity, it is necessary to evaluate the yield stress and the yield strain of the yielding parts and/or members and the yield shearing force of the structures. First, for obtaining fundamental data for this purpose, a comparison of the load-deformation hysteretic curve of anchor bolts in an excitation test with that in a static tensile test is conducted. The tests prove that the dynamic load-deformation characteristics of the anchor bolt can be approximately constructed from the results of the static tensile tests. Secondly, yield shearing force calculated by the single-degree-of-freedom model proposed by Akiyama⁽⁹⁾ is compared with the experimental results. Lastly, the energy absorbed by anchor bolts is calculated.

4.1 Static tensile characteristics of anchor bolts

Static tensile tests, at a tensile speed of 5 mm/min, were conducted using a tensile testing device on the anchor bolts, the same type as used in the excitation tests. Table 2 shows the results of the characteris-

Table 2 Results of static tensile tests of anchor bolts

Ultimate Elongation	2.64 (mm)
Yield Point	7,533 (N)
Yield Stress	473.7 (MPa)
Tensile Strength	11,032 (N)
Tensile Stress	693.6 (MPa)
Breaking Strength	9,009 (N)
Breaking Stress	566.5 (MPa)
Young's Modulus	151.3 (GPa)

tics of the anchor bolts obtained from these tensile tests.

4.2 Hysteretic characteristics and state of breakage of anchor bolts

Figure 8 shows the values of the amount of elongation and the locations of breakage of anchor bolts for two types of input; frequency sweep sinusoidal wave and random waves. Figure 9 compares the load-deformation curves of anchor bolts observed in the excitation tests with those observed in static tensile tests.

The ultimate elongation of the anchor bolts prior to fracture was approximately 3 to 4 mm (100 000 $\mu\epsilon$, measured between marked positions using a precision microscope), and tensile loads were estimated to be 13 000 N to 14 000 N, when they broke. Since the ultimate elongation measured in the tensile tests was 2.64 mm (88 000 $\mu\epsilon$) and tensile loads were 11 000 N, it was suggested that the former were increased by 13 to

Fig. 8 Elongation and breakage of anchor bolts

Fig. 9 Hysteretic characteristics of load-deformation curve of anchor bolts

15%, and 20 to 30%, respectively, in comparison with the latter. Meanwhile, the speed rate of strain applied to anchor bolts was measured to be 200 to 250 mm/min in the excitation tests. The ultimate elongation observed in the excitation tests and that observed in the static tests were independent of the type of input wave, and the anchor bolt position. The same also holds for the tensile load.

4.3 Hysteretic behaviors of tall structures

When the seismic design procedure for tall structures is carried out, it is important to determine the horizontal shearing force at the bottom of the structure to be designed, and the displacement of the center of gravity relative to the base of the structure. If the tower model is assumed to have single degree of freedom, the center of gravity of the tower shows a slip-type hysteretic characteristic curve, as shown in Fig. 10, and the curve traces from point 0 to point 13 in ascending order. If the eight anchor bolts used in the tests were replaced with two anchor bolts, as shown in Fig. 11, the equivalent total sectional area of anchor bolts A , and the equivalent distance from the neutral axis R , can be expressed as

$$A = \Sigma a \quad (1)$$

$$R = \Sigma (a \cdot r \cdot \cos \theta / A) \quad (2)$$

Figure 12 shows the load resistance mechanism when the tower is subjected to an axial force and a bending moment due to its own weight and horizontal force exerted by the horizontal excitation, where N signifies the axial force, C , the compressive reaction

Fig. 10 Slip-type hysteretic characteristics of force-displacement curve of tower

Fig. 11 Equivalent replacement of anchor bolts

force from the base, which is assumed to work at the outer edge of the base plate; and T , the resultant anchor bolt tensile force acting at distance R from the neutral axis of the tower. If the radius of the base plate is denoted by R_B , Eq. (3) can be derived from the balance of bending moment as

$$M = T(R + R_B) + N \cdot R_B. \quad (3)$$

Equation (4) gives the tensile force acting on the equivalent anchor bolt when it yields:

$$T_Y = A \cdot \sigma_Y, \quad (4)$$

where σ_Y is the yield stress. The yield moment M_Y and the yield shearing force Q_Y are expressed as Eqs. (5) and (6), in terms of

$$M_Y = T_Y(R + R_B) + N \cdot R_B \quad (5)$$

$$Q_Y = M_Y/h, \quad (6)$$

where h is the height of the center of gravity. The contribution Q_N of the axial force due to the self-weight of the tower to the yield shearing force is given by

$$Q_N = N \cdot R_B/h. \quad (7)$$

Table 3 lists the values of Q_Y and Q_N calculated from Eqs. (1)~(7) for the tower. In this case, Q_Y and Q_N were 9 870 N and 2 273 N, respectively.

Figure 13 shows the hysteretic characteristics of anchor bolts up to the state of plastic deformation and subsequent breakage when a frequency sweep sinusoidal excitation (from 15 to 2 Hz) was applied. The shearing force at the bottom of the tower is given

Table 3 Calculation of horizontal yield force Q_Y and the axial force Q_N contributing to horizontal force

Sectional Area of Anchor Bolt Group	A	63.62 (mm ²)
Distance between Anchor Bolt Group and Center of Base Plate	R	130.65 (mm)
Yield Stress	σ_Y	473.7 (MPa)
Tower Weight	N	13,730 (N)
Resultant Force at Yield Point	T_Y	30,136 (N)
Yield Point Moment	M_Y	14,903 (N·m)
Yield Strength	Q_Y	9,870 (N)
Tower Weight Strength in Yield Strength	Q_N	2,273 (N)

Fig. 12 A model of load distribution at the bottom of the tower

by the product of the effective mass, 1 000 kg and the acceleration measured at the top. When the anchor bolts broke in the excitation tests, the horizontal displacement of the top d_Y was measured to be 5 mm, the yield shearing force Q_Y about 10 000 N, and the value of Q_N about 1 000 N. Although the measured values and the calculated values from Eq. (6) of Q_Y were in good agreement, the measured Q_N was less than half that of the calculated value. This would seem to be the result due to the shift of the acting point of the compressive reaction force toward the center due to the compression of the rubber sheet between the base plate and the base structure.

4.4 Relationship between the input energy and the plastic strain energy of anchor bolts

The basic relationship concerning kinetics energy supply and consumption is derived. Equation (8) gives the total amount of energy input $E(t)$ up to time t in a single-degree-of-freedom model,

$$E(t) = -M \int_0^t (\ddot{x}_0 \cdot \dot{x}) dt, \quad (8)$$

where M is mass, $\ddot{x}_0$ input acceleration, and $\dot{x}$ relative velocity at the top of the tower. The total energy input E , can be regarded as the sum of the elastic vibration energy W_e and the plastic strain energy W_p ,

$$E = W_e + W_p \quad (9)$$

$$W_e = Q_Y \cdot d_Y/2 \quad (10)$$

$$W_p = 2 \cdot T_Y \cdot \delta_p, \quad (11)$$

where d_Y is the displacement of the top when the anchor bolts yield and δ_p is the average ultimate elongation of the anchor bolts.

Table 4 shows the values of W_e and W_p for each test. The total energy $E_{\max}$ when all eight anchor bolts broke was 264 Nm. Figure 14 shows one of the results expressing the total input energy $E(t)$ with time calculated by Eq. (8) using the data obtained from the excitation tests with the random wave of No.1. The tests proved that the anchor bolts broke only

Fig. 13 Hysteretic characteristics of force-displacement curve of the tall structure model

Table 4 Elastic vibration energy W_e and plastic strain Energy W_p

INPUT WAVE	Yield Strength Q_Y [N]	Elastic Limit Deformation d_Y [mm]	Elastic Vibration Energy W_e [Nm]	Ultimate Elongation δ_p [mm]	Plastic Strain Energy W_p [Nm]	η ($=W_p/W_e$)	Number of Broken Anchor Bolts
Sinusoidal Sweep 5 Hz $\rightarrow$ 12 Hz Max. = 5 m/s ²	9,870	5	25	1.86	112	4.5	0
Sinusoidal Sweep 2 Hz $\rightarrow$ 15 Hz Max. = 5 m/s ²				2.27	137	5.5	0
Sinusoidal Sweep 15 Hz $\rightarrow$ 2 Hz Max. = 5 m/s ²				3.96	239	9.6	8
Random Excitation No.1 Max. = 30 m/s ²				2.89	174	7.0	3
Random Excitation No.1 Max. = 20 m/s ²				2.54	153	6.1	1
Random Excitation No.2 Max. = 7.5 m/s ²				0.59	36	1.4	0

Fig. 14 Relationship between input energy $E(t)$ and $E_{\max}$

when the input energy exceeded $E_{\max}$ for a short period of time. In the case of input with a maximum acceleration of 20~30 m/s² it was confirmed that the tensile load on the anchor bolts disappeared after 1.5 sec, by which time they seemed to have broken. This suggests that breakage took place immediately after the total energy input exceeded the value of $E_{\max}$, which thus provides a clue to understanding the breakage of the anchor bolts.

The ratio of the required strength of a structure α_0 in elastic design to the required strength of a structure α in elastoplastic design, is calculated by Eq. (12), using the ratio η of the plastic strain energy W_p to elastic vibration energy W_e .

$$\alpha/\alpha_0 = 1/\sqrt{1+1.5\eta}, \quad \eta = W_p/W_e \quad (12)$$

In the excitation tests, the ratio η ranged from 1.4 to 9.6. The strength ratio α/α_0 determined by η ranged from 0.25 to 0.57. This proved that great reductions of design loads are possible with inelastic design in comparison with elastic design.

5. Analyses by Two-Degree-of-Freedom Rocking Model

5.1 Assumptions and equations of motion for modeling

In order to analyze seismic responses for tall structures undergoing anchor bolt yielding, a two-

degree-of-freedom rocking vibration model of a tall structure which considers the elongation due to plastic deformation of anchor bolts was proposed. The responses of the structure in terms of the proposed model by numerical integration were calculated. The results of the calculation were compared with those of the excitation tests.

In order to model the structure as simply as possible, the following premises were made in light of the results of the previous excitation tests and of the previous reports^{(6),(7)}.

(1) Anchor bolts yield prior to the base plate and the plastic deformation of the base plate itself can be neglected.

(2) The tower body of the tall structure deflects only elastically, and the ratio of its vertical component to its horizontal component at the top due to inclination is so small that its vertical component is negligible.

(3) The effect of nonlinear responses such as friction and collisions on the elastic responses of the tower body is so small as to be negligible.

The proposed two-degree-of-freedom rocking model is shown in Fig. 15. The model is based on the above assumption and the response is determined solely by the horizontal motion of the tower and the rotational motion of the base plate (rocking motion).

The equations of motion for the two-degree-of-freedom model can be written in the form of Eq.(13) in terms of horizontal displacement y of the top of the tower, and Eq.(14) in terms of angle of rotation θ of the base plate ;

$$M\ddot{y} + C_t\dot{y} - C_th\dot{\theta} + K_ty - K_th\theta = -M\ddot{u}_0 \quad (13)$$

$$Mh\ddot{y} + I_r\ddot{\theta} + C_r\dot{\theta} + M_r(\theta) = -Mh\ddot{u}_0 - Mgd, \quad (14)$$

where M indicates effective mass, K_t spring constant for the tower, C_t damping coefficient of the tower, y horizontal displacement at the top of the tower, θ angle of rotation of the base plate, I_r moment of inertia about the center of rotation of the base plate, h effective height up to the top of the tower, C_r rotational damping coefficient of the base plate, $M_r(\theta)$

moment about the edge of the base plate caused by the restoring force of the anchor bolts, g acceleration of gravity and d diameter of the base plate.

The excitation tests have proved that the deformation process of anchor bolts consists of the following three steps.

Step 1: Anchor bolts expand and contract with

Fig. 15 Two-degree-of-freedom analytical model of a tall structure

Fig. 16 Trilinear load-deformation hysteretic model

the motion of the tower due to horizontal excitation in the elastic region and the tower deflects elastically in the state of the fixed base plate.

Step 2: The plastic deformation of anchor bolts develops with the increase of tensile force caused by the increase of the overturning moment of the tower about its rotational axis.

Step 3: The tower rotates about its rotational axis, which takes one of the two ends of the base plate alternatively. Since the anchor bolts are sufficiently elongated, the tensile load does not affect the anchor bolts. Therefore, the above rocking motion occurs in the final stage of the process.

Incorporating these steps into the model, the characteristics of anchor bolts, tensile load $F_k(\epsilon_k)$ and the deformation were approximated by using the trilinear hysteretic curves shown in Fig. 16. In this figure, state 1 corresponds to Step 1, states 2 and 3 to Step 2, and state 4 to Step 3. The tensile load $F_k(\epsilon_k)$ can be written as

$$F_k(\epsilon_k) = \begin{cases} K_e(\epsilon_k - \epsilon_0) & [\epsilon_k < \epsilon_k \leq \epsilon_{kmax}] \\ K_{p1}(\epsilon_k - \epsilon_1) + Y_{p1} & [\epsilon_{kmax} < \epsilon_k \leq \epsilon_2] \\ K_{p2}(\epsilon_k - \epsilon_2) + Y_{p2} & [\epsilon_2 < \epsilon_k \leq \epsilon_k] \\ 0 & [0 \leq \epsilon_k \leq \epsilon_{k0}] \end{cases} \quad (15)$$

where ϵ_1 is the deformation of the anchor bolt observed when the bolt undergoes yield stress, ϵ_2 the deformation of an anchor bolt at the point of inflection, ϵ_{kmax} the deformation at the intersection point of line ① with line ②, and with line ③, ϵ_{k0} is plastic deformation, and k_e , k_{p1} , k_{p2} are spring constants of lines ①, ②, and ③ in the load-deformation curve shown in Fig. 16.

5.2 Determination of parameters

The values of parameters which constitute the rocking model were primarily determined by the

Table 5 Parameters for response analyses

Tower and Base Plate	
m : Weight of effective mass	1,000 kg
h : Effective height of tower	1.5 m
I : Moment of inertia	2,250 kgm ²
d : Diameter of base plate	0.5 m
r_b : Diameter of center circle through anchor holes	0.4 m
f_t : Natural frequency	11.4 Hz
ζ_t : Damping Ratio	0.032
Anchor Bolts	
n : Total number	8
E : Modulus of longitudinal elasticity	154.0 GPa
Y_{p1} : Yielding load for region 1	5,000 N
Y_{p2} : Yielding load for region 2	10,200 N
ϵ_1 : Yielding strain 1	2,000 $\mu\epsilon$
ϵ_2 : Yielding strain 2	8,000 $\mu\epsilon$
Δt : Time step for calculation	0.0005 s

excitation tests of the model tower and by the static tensile tests on anchor bolts. These parameters are shown in Table 5.

5.3 Examination by comparing with the results of the excitation tests

The validity of the analytical rocking model proposed in section 5.2 was examined by comparing the response time histories obtained from the analytical model with those obtained from the excitation tests. The comparison of the time histories is shown in Fig. 17. For the period of the first five seconds after the start of excitation, the deformation of anchor bolts is minor, and the amplitudes for that period and the response acceleration time histories at the top of the tower by numerical simulation agreed well with those by the excitation tests.

Although the time histories for the excitation tests for the period beyond the first five seconds has high-frequency spikes caused by the collisions of the base plate of the tower with the base, which is not considered in the analytical model, good agreement can be observed between the results of the excitation

tests and those of the simulation calculations.

The loads on the anchor bolts and deformations of the anchor bolts in the excitation tests and analyses are also compared in terms of the load-deformation hysteretic curves in Fig. 18.

It was confirmed that the hysteretic curves from analyses agrees well with those of the excitation tests.

Therefore, the trilinear load-deformation hysteretic curve of the anchor bolt group constructed from the results of the static tensile tests of the anchor bolts approximates well the dynamic load-deformation hysteretic curve until the vibration due to the large rocking motion of the tower becomes significant.

This suggests that the two-degree-of-freedom rocking model proposed and shown in Fig. 15 can be applied to inelastic response calculations of tall structures.

6. Conclusions

In this paper, the dynamic responses of tall structures with anchor bolts that can undergo plastic deformation were studied from the results of the shaking table excitation tests and the results of the two-degree-of-freedom rocking model.

First, comparison of load-deformation characteristics of anchor bolts by static tensile tests and by dynamic excitation tests were made. The results of comparison proved that the load-deformation curve obtained from static tensile tests could be used for inelastic response analyses when the anchor bolts undergo dynamic tensile load.

Secondly, yield shearing stress of the tower in the excitation tests was simulated by a single-degree-of-freedom model proposed by Akiyama⁽⁹⁾. Calculated yield shearing forces agreed well with these obtained from excitation tests. Based on the results, the amount of energy E_{max} required to break all eight of the anchor bolts was calculated and the ratios of the required strength of elastic design to that of inelastic design for tall structures was evaluated. From these, it was verified that anchor bolt breakage took place just after the total energy input exceeded the value of E_{max} , which provided important information for understanding the breakage of anchor bolts, and that inelastic design load, considering plastic deformation of anchor bolts, can be reduced as compared to elastic design load.

Lastly, a two-degree-of-freedom model taking into account the rocking of the structure was proposed and the equation of motion for this model was formulated. Numerical response by this model was carried out under similar conditions as for the excitation tests. As far as the structural response time histories and load-deformation characteristics of the

Fig. 17 Comparison of response time histories from an excitation test and an analysis (input No. 2)

Fig. 18 Comparison of anchor bolt load-deformation hysteretic curve from an excitation test and an analysis (input No. 2)

anchor bolts were concerned, a good agreement could be achieved in the results of the excitation tests and numerical simulation.

The authors will continue the study of effectiveness of the inelastic design method described above by computing the amount of dissipative energy due to the plastic deformation of the anchor bolt.

At the close of this report, the authors wish to express their sincere gratitude to Professor Hiroshi Akiyama, Faculty of Engineering, the University of Tokyo, and Dr. Nobuyuki Kobayashi, Research Institute, Ishikawajima-Harima Heavy Industries Co., Ltd, who kindly extended their valuable advice for undertaking this research.

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