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ON-LINE RESPONSE EXPERIMENTS OF STEEL FRAMES SIMULTANEOUSLY SUBJECTED TO HORIZONTAL AND VERTICAL GROUND MOTIONS

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SUMMARY

The column axial force of frames simultaneously subjected to horizontal and vertical ground motions will increase instantaneously due to the composition of an overturning moment and a fluctuating axial force caused by vertical vibrations. In this study, on-line response experiments were carried out for steel frames subjected to horizontal and vertical ground motions simultaneously. In the experiments, it was shown that the frames can maintain stable response behavior even in cases where the axial force reaches a yield axial force instantaneously under the limited conditions for the slenderness ratio and the width-thickness ratio of the columns. A method for easily estimating the maximum axial force of the columns when both horizontal and vertical ground motions are input simultaneously was derived.

INTRODUCTION

The effects of vertical ground motions on the earthquake responses of frames have been investigated from the viewpoint of the input energy, resultant damage distribution, column axial force and so forth.

It was reported that the seismic energy input to the frame simultaneously subjected to horizontal and vertical ground motions equals the sum of the energy in the case of the frame being subjected to only horizontal motions and that in the case of the frame being subjected to only vertical motions. It was also reported that the distribution of damage to the frame subjected to horizontal and vertical ground motions simultaneously is equal to the sum of the damage when the frame is subjected to the two motions separately.(Akiyama [1])

In this study, the column axial force for a steel frame simultaneously subjected to horizontal and vertical ground motions is investigated.

First, on-line tests using a one-mass model are carried out and the maximum axial force ratio of a perimeter column as well as the stability of the frame in cases where the axial force ratio instantaneously attains to a high value are investigated. At the same time, through carrying out inelastic response analyses,

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a method for the considerably easier estimation of the maximum axial force ratio of the perimeter column of a frame simultaneously subjected to horizontal and vertical ground motions is presented.

ON-LINE EARTHQUAKE RESPONSE EXPERIMENTS

Model Outline

The frame models used in the experiments are one-mass models made by concentrating the mass of the structure upon its center of gravity as shown in Fig.1. The restoring force characteristics of the model with regard to horizontal vibrations are thought to present the restoring force characteristics of the lower parts of a multi-story frame.

Both the constant vertical force of P_L, which is equivalent to the vertical load, and the fluctuating vertical force of $P_{UD}(t)$ acting on the lower parts of the structure due to vertical vibrations are imposed on the position of the center of gravity. The value of $P_{UD}(t)$ is obtained in advance from response analyses. The response value for horizontal vibrations is obtained from on-line tests carried out by imposing vertical forces which change momentarily on the model as a load. The value of $P_{UD}(t)$ is determined using an elastic one-mass model (damping factor 2%).

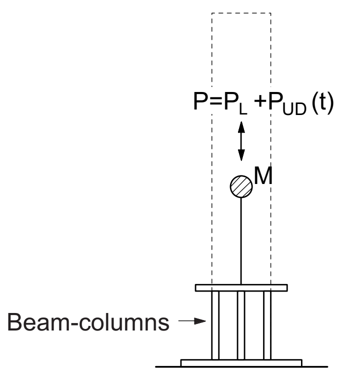

Fig.1 Frame model

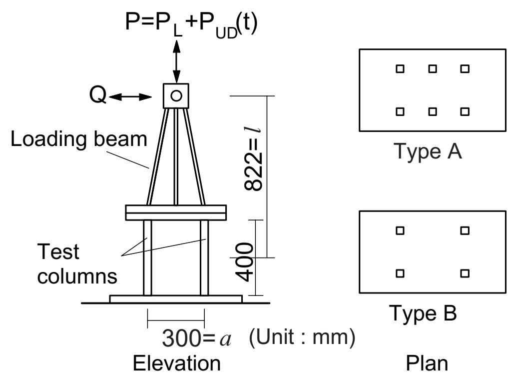

Fig.2 Test specimen

Test Specimens and Vibration Models

Fig.2 illustrates the shape of the test specimen. The column has a box section with □-40×40×3.2 and the length of the column is 400mm. The width-thickness ratio of this box section is 12.5 and the slenderness ratio is 26.5. Four type A specimens each of which is assembled with columns of 3×2 (horizontal direction × across direction) and four type B specimens with 2×2 are used in the tests.

SS400 steel is used for the models. The solid line in Fig.3 shows the stress-strain relation obtained from stub column tests and coupon tests.

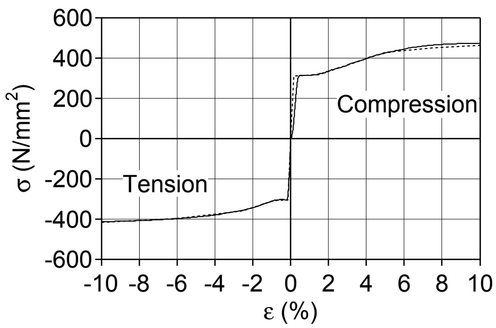

Fig.3 σ-ε relation

Table 1 List of specimens

Specimen	Input wave	Natural period (s)		$\dfrac{P_L}{P_y}$	$\dfrac{P_L + P_{UD\max}}{P_y}$	$\dfrac{Q_{Hp}}{Q_{e\max}}$
		Horizontal	Vertical			
A1	JMA-Kobe (NS)	2.0		0.266	0.266	0.213
A2	JMA-Kobe (NS,UD)	2.0	0.2	0.266	0.6	0.213
A3	El Centro (NS,UD)	1.0	0.2	0.266	0.6	0.233
A4	JMA-Kobe (NS,UD)	2.0	1.0	0.266	0.6	0.213
B1	JMA-Kobe (NS,UD)	2.0	0.2	0.3	1	0.2
B2	El Centro (NS,UD)	1.0	0.2	0.3	0.9	0.2
B3	Taft (EW,UD)	1.0	0.2	0.3	0.9	0.2
B4	Taft (EW,UD)	2.0	0.2	0.3	0.9	0.2

(P_y: Sum of yield axial force of each column)

Table 1 shows the details of the tests. The horizontal natural period is set at 1.0sec or 2.0sec, and the vertical natural period is set at 0.2sec or 1.0sec.

The values for the vertical force are set according to the values of P_L and $P_{UD\max}$ shown in Table 1. P_L indicates the mean vertical force and $P_{UD\max}$ is the maximum value of the fluctuating component for the vertical force. $P_{UD}(t)$ is established by multiplying a certain constant value by the time history axial force obtained from the elastic response analyses so that the maximum value can reach $P_{UD\max}$.

Both specimens A and B are designed under the condition that the axial force ratios of the perimeter columns reach extremely high values during their responses. In particular, specimen B is made so that the column axial force instantaneously attains to a yield axial force, or in its vicinity, due to vertical force only. Furthermore, axial force caused by overturning moment is loaded to the columns of the specimens in addition to this vertical force induced axial force.

Static loading tests in the elastic region are carried out on each of the specimens in order to obtain the horizontal stiffness. Then, by using this horizontal stiffness value the mass of the horizontal vibration model is determined so that the horizontal natural period can become a target value. The damping factor for the horizontal vibration is set at 2%.

The value of the horizontal input seismic motion is established according to the value of $Q_{Hp}/Q_{e\max}$. $Q_{e\max}$ indicates the maximum horizontal force when assuming the elastic response of the model. Q_{Hp} is the full plastic horizontal force in the case of the vertical force being P_L.

El Centro 1940 (NS,UD), Taft 1952 (EW,UD), JMA-Kobe 1995 (NS,UD) are used as input seismic waves.

On-line Test Results

Fig.4 illustrates the test results. The solid lines in the figure indicate the test results and the broken lines show the analytical results which will be described later. The time histories for the vertical force, column axial force, horizontal force and horizontal displacement for each model are illustrated in order from the top. The figure beneath on the left shows the relationship between the horizontal displacement and the horizontal force. That on the right shows the relationship between the horizontal displacement and the vertical displacement. Both of these relationships are indicated with non-dimensional values.

Following symbols are used in these figures.

P : Vertical force
Q : Horizontal force
N_S : Axial force of the perimeter column
N_y : Yield axial force
δ_H : Horizontal displacement at the top of the column
δ_{Hp} : Elastic horizontal displacement in the case of $Q = Q_{Hp}$
δ_V : Vertical displacement at the top of the perimeter column
δ_{Vp} : Elastic vertical displacement in the case of yield axial force

The test results except for the perimeter column axial force (N_S) are indicated with the actual measurement values. The axial force of the perimeter column can be estimated using equation (1).

$$N = N_L + N_{UD} + N_Q + N_{pd}$$

$$= \frac{P_L}{n} + \frac{P_{UD}(t)}{n} \pm \frac{lQ(t) + \delta_0 (P_L + P_{UD}(t))}{2a} \quad \cdots\cdots (1)$$

$N_L = \frac{P_L}{n}$: Constant axial force caused by vertical loads
$N_{UD} = \frac{P_{UD}(t)}{n}$: Fluctuating axial force caused by vertical vibrations
$N_Q = \frac{l}{2a} Q(t)$: Fluctuating axial force caused by overturning moment due to horizontal loads
$N_{pd} = \frac{\delta_0}{2a} (P_L + P_{UD}(t))$: Fluctuating axial force caused by overturning moment due to P-Δ effects
$P_{UD}(t)$: Fluctuating vertical force
$\delta_0 = \delta_1 - \frac{\delta_H}{2}$, δ_1: Horizontal displacement at the loading point
n: Number of the columns
a: Distance between the centers of columns on both sides (See Fig.2)
l: Distance between the vertical center of the column and the position of the center of gravity of the model (See Fig.2)

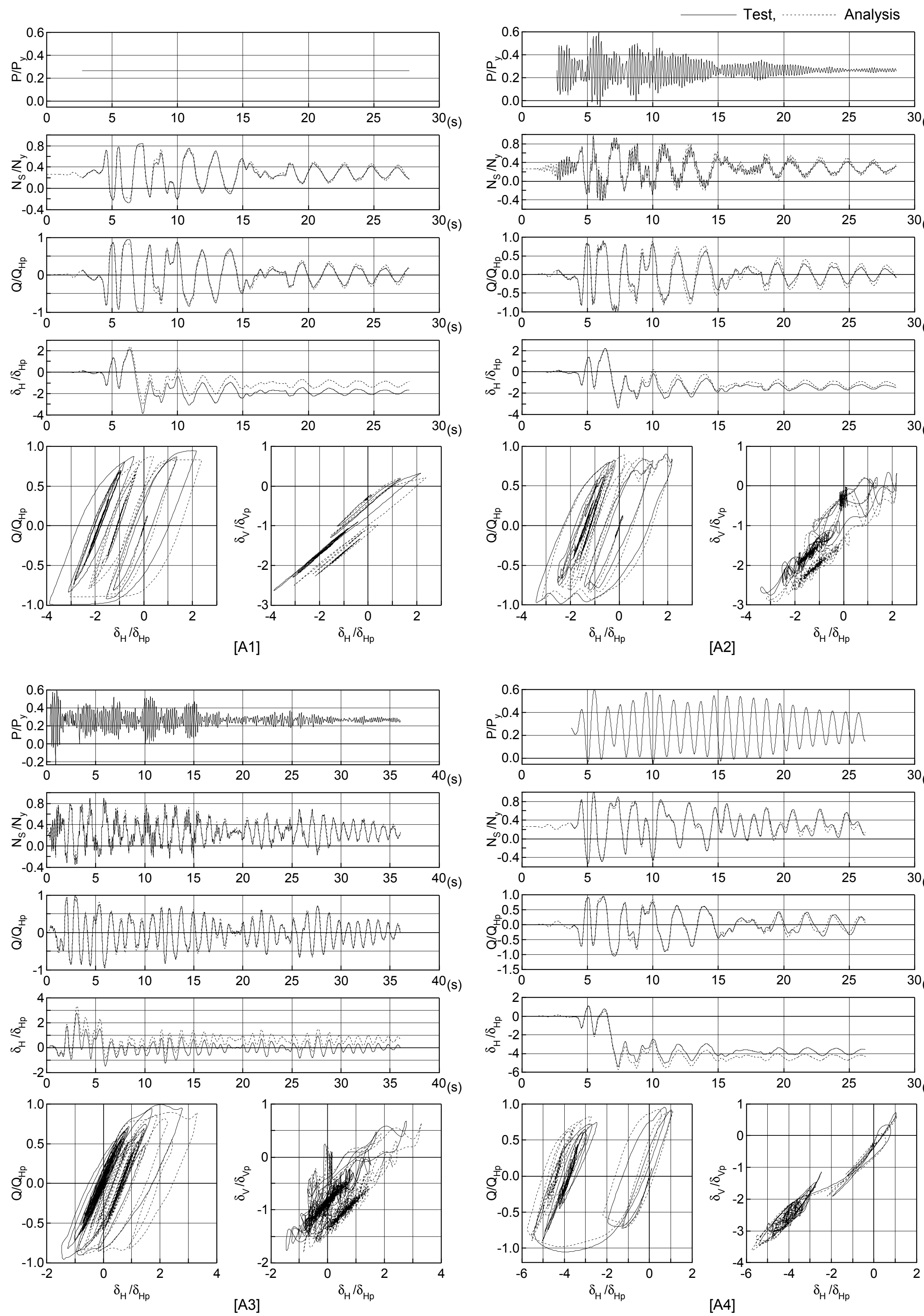

Fig.4 Test results

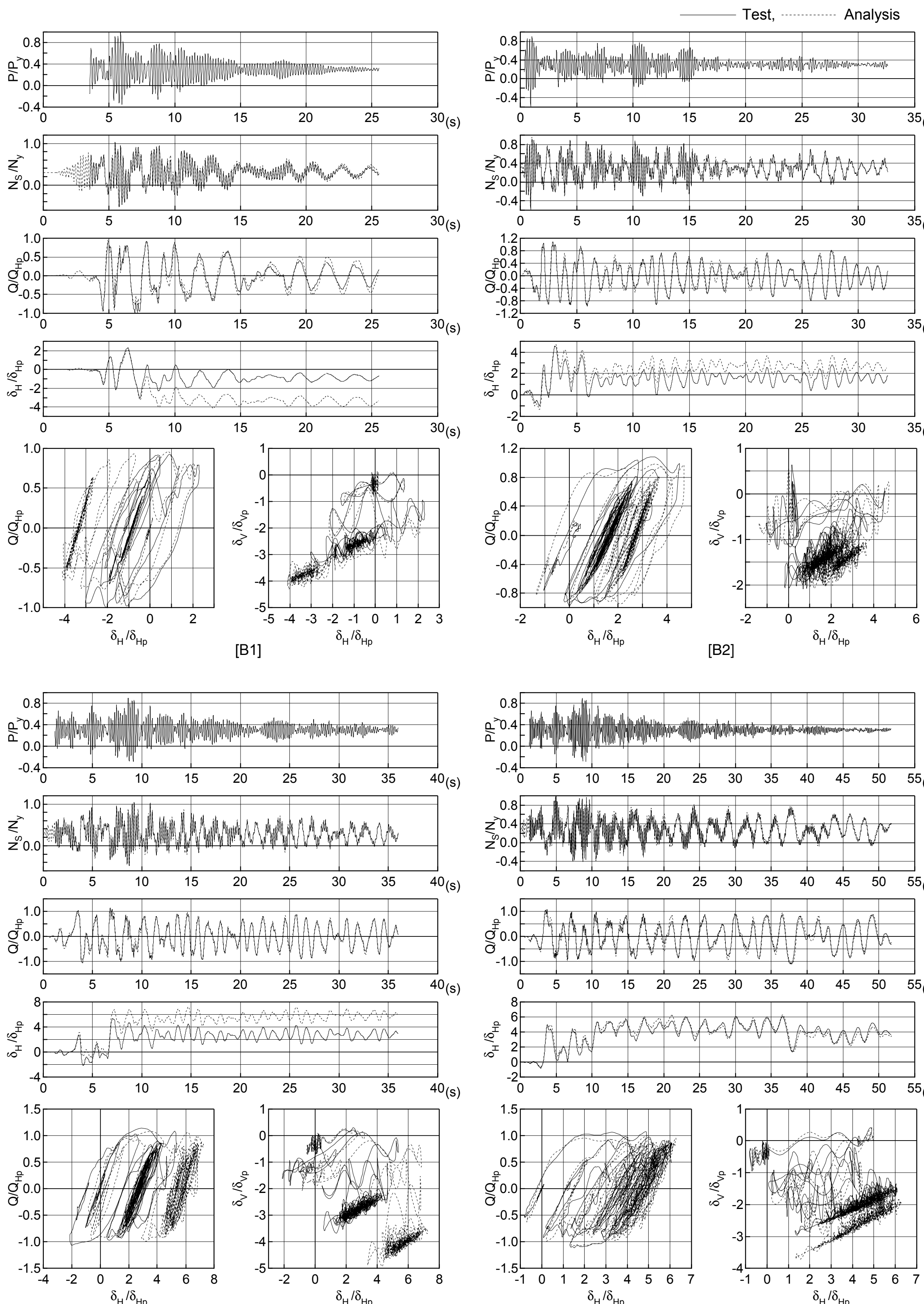

Fig.4 Test results (continued)

Equation (1) is derived from the following assumptions.
a. Inflection point is located at the vertical center of the column.
b. Vertical force is equally distributed to each column.
c. Overturning moment is resisted by the perimeter columns.

Fig.5 shows the comparison between the axial force obtained from equation (1) and that obtained from the values measured using strain gauges attached to the four surfaces at the center of the column. This figure indicates that both axial forces correspond to each other with good accuracy.

From Fig.4, the following can be made clear.

(1) When the vertical force reaches a high value, the horizontal strength is reduced due to the decrease in the full plastic moment of the column and the increases in the P-Δ moment. With regard to the relation of $\delta_H/\delta_{Hp} - Q/Q_{Hp}$, effects of the fluctuating vertical force appear at the point where $\dfrac{d(Q/Q_{Hp})}{d(\delta_H/\delta_{Hp})}$ varies in the positive and negative values in progress of the plastic displacement.
(2) Although the axial force of the perimeter columns for most of the models instantaneously reaches the yield axial force or its vicinity, every model shows stable response characteristics without losing the restoring force. The decrease in the strength caused by local buckling during loading does not occur for all specimens.

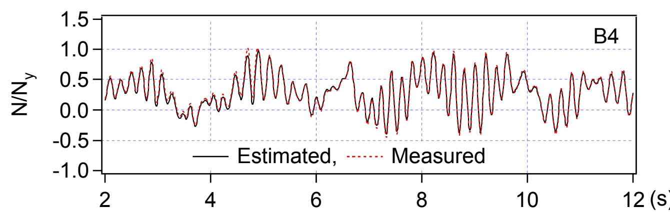

Fig.5 Comparison between estimated axial force and measured axial force

Analysis

Analysis Method

The analysis method is an inelastic response analysis using a member model. A method known as a multi-spring model shown in Fig.6, in which a member is modeled as an inelastic element at each end and an elastic element at its center, has been often used. However, it is difficult to accurately estimate the stiffness in an axial direction using this method. A member model with several inelastic elements as shown in Fig.7 is used in this analysis. The section of each inelastic element is divided as shown in Fig.8 and the instantaneous stiffness is estimated assuming that each minute division is under an equal stress-strain state.

As for the cyclic hysteresis characteristics of the material, the Takanashi-Ohi model [2] made with consideration to the Bauschinger's effect is used. The results of stub column tests and those of coupon tests are used as a skeleton curve for the stress-strain relations. (See Fig.3)

Numerical integration is carried out using the Newmark-β method (β=0.25). A time interval for the integration is set at 0.001sec.

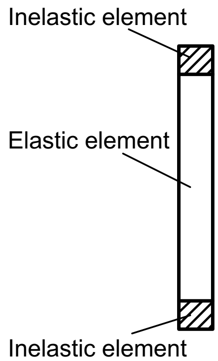

Fig.6 Multi-spring model

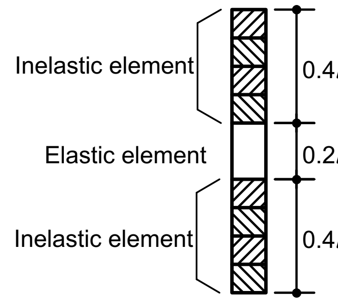

Fig.7 Member model used in this study

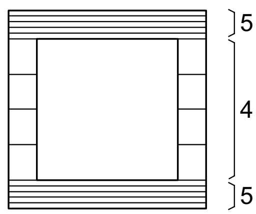

Fig.8 Divided section

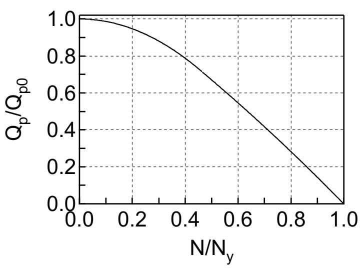

Fig.9 *N*-Q_p interaction

Comparison between Test Results and Analytical Results
Fig.4 illustrates the comparison of the test results with the analytical ones. The solid lines and broken lines indicate the test results and analytical results respectively.

The analytical results correspond very accurately to the test results as a whole. The validity of this analysis method is comfirmed.

Maximum Axial Force Ratio of the Perimeter Columns
Estimation of the Maximum Axial Force Ratio
When ignoring N_{pd} in equation (1), the axial force of the perimeter columns can be expressed by the following equation.

$$N = N_L + P_{UD}(t) \pm \frac{l}{2a} Q(t) \quad \cdots\cdots (2)$$

Fig.9 shows the interaction between the axial force N and the shear force Q_p (yield shear force) for a single column when plastic hinges occur on both ends of the column. (In this figure, Q_{p0} represents Q_p in the case of N=0.) When the vertical force $P = P_L + P_{UD}(t)$ acts on the column, if neglecting the effects of strain hardening, the upper limit value for the horizontal force Q equals the sum of Q_p when assuming that the same axial force $P/n = (P_L + P_{UD}(t))/n = N_L + N_{UD}(t)$ acts on each column. This is so because of the following reasons.

(1) In cases where the plastic hinge occurs on each column, the sum of the shear force of each column is not greater than ${}_nQ_p$, because the interaction of N and Q_p is a convex function as shown in Fig.9.

(2) In cases where no plastic hinge occurs, the shear force of each column is smaller than the shear force in the case of the plastic hinge occurring.

Namely, the following equation can be formed.

$$Q \le nQ_p^{N_L+N_{UD}} \quad \cdots\cdots (3)$$

Where $Q_p^{N_L+N_{UD}}$: Q_p in the case of the axial force being $N_L + N_{UD}$.

From equations (2) and (3), the upper limit value N_{S1} for the axial force N_S of the perimeter column in the case of $P = P_L + P_{UD}(t)$ can be obtained using the following equation.

$$N_{S1} = N_L + N_{UD} + \frac{nl}{2a} Q_p^{N_L+N_{UD}} \quad \cdots\cdots (4)$$

The relationship between $(N_L + N_{UD})/N_y$ and N_{S1}/N_y for type A specimens and type B specimens are illustrated in Fig.10. From this figure, N_{S1} reaches its maximum value when $N_L + N_{UD}$ is maximum. Therefore, the upper limit of axial force ratio for perimeter columns $(N_S/N_y)_{\max}$ can be expressed by the following equation.

$$\left(\frac{N_S}{N_y}\right)_{\max} = \frac{(N_L + N_{UD\max})}{N_y} + \frac{nl}{2a}\frac{Q_p^{N_L+N_{UD\max}}}{N_y} \quad \cdots\cdots (5)$$

Where $N_{UD\max} = \dfrac{P_{UD\max}}{n}$

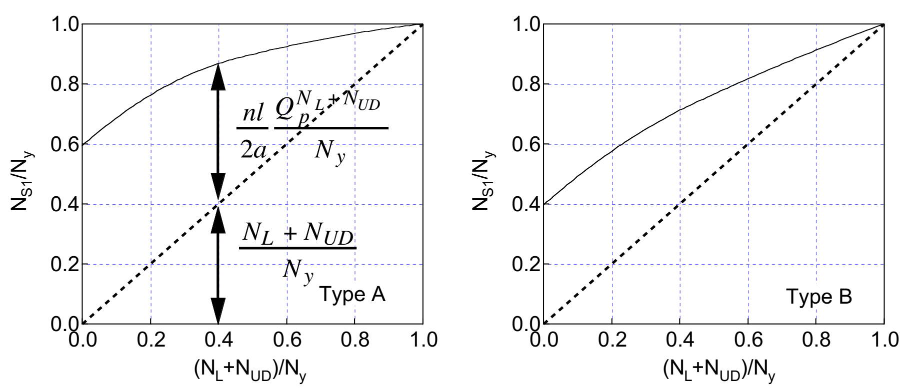

Fig.10 Relation between N_{S1}/N_y and $(N_L+N_{UD})/N_y$

Comparison between Estimation Equation and both Test Results and Analytical Results

Fig. 11 illustrates the comparison between the estimation equation (equation (5)) and both the test results and the analytical ones. The solid lines show the results obtained from equation (5). Marks ● and ■ indicate the test results. Mark ○ shows the results obtained from the response analyses carried out by changing the size of vertical ground motions only under the condition that the values for P_L, seismic wave and horizontal ground motion are equal to those in the on-line tests. With regard to the results of the tests and the analyses, only the larger values of the maximum axial forces of the perimeter columns on both left and right sides are plotted. The estimation equations correspond quite well to the test results and the analytical ones as a whole.

This estimation equation can also be applied to multi-story frames. (Yamazaki [3])

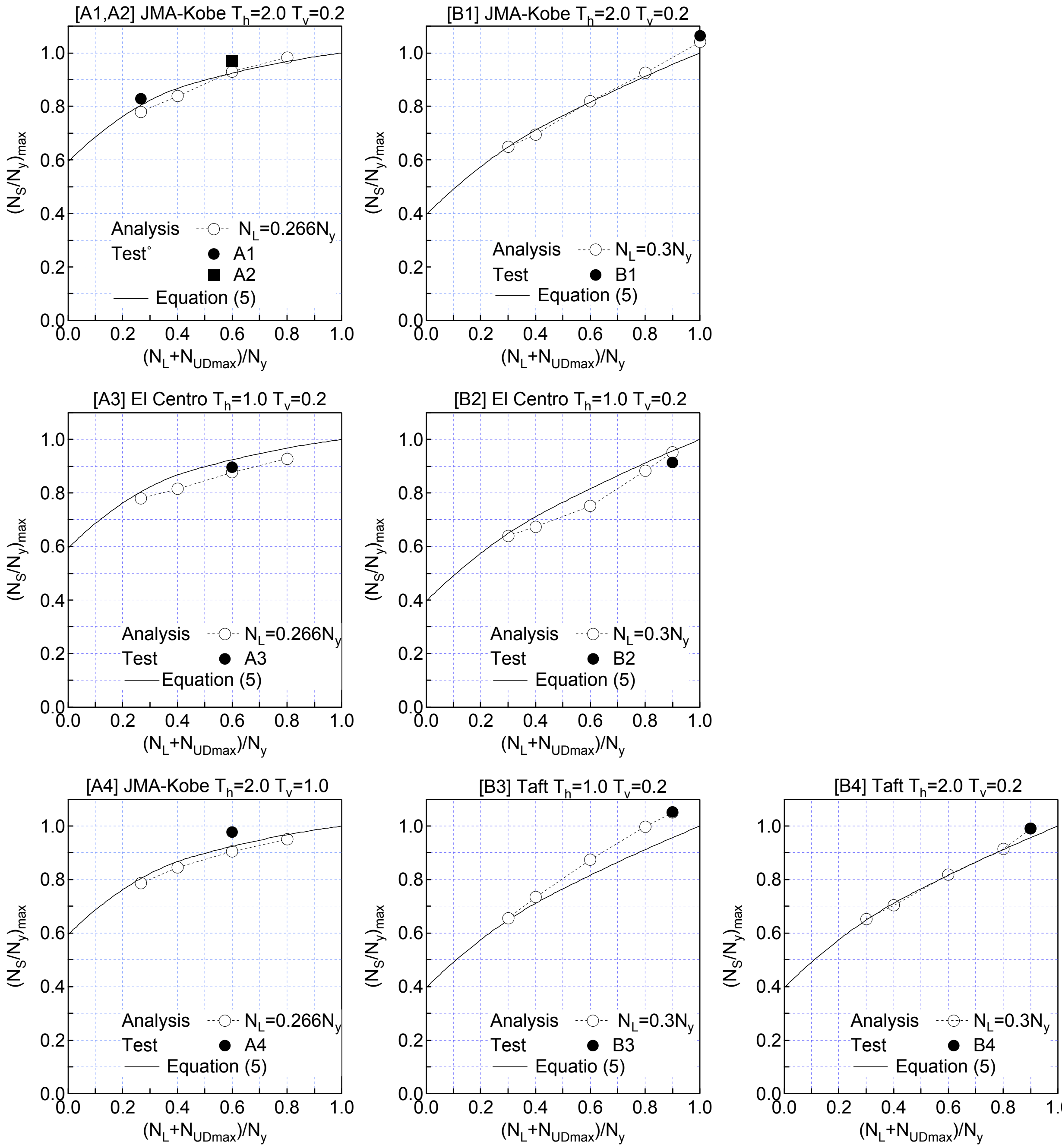

Fig.11 Comparison between estimation equation and both test results and analytical results

CONCLUSIONS

The column axial force of steel frames simultaneously subjected to horizontal and vertical ground motions was investigated by carrying out on-line earthquake response tests and inelastic response analyses. The conclusions obtained from this study can be summarized as follows:

(1) Even when the maximum axial force of a perimeter column instantaneously reaches a yield axial force in the on-line tests, the frame showed stable response characteristics against horizontal ground motions. The column with a box section used in the tests has a width-thickness ratio of 12.5 and a slenderness ratio of 26.5. A decrease in the strength of the column caused by local buckling was indiscernible.
(2) The displacement, shear force and axial force of the frame obtained from the on-line tests accurately correspond to the analytical results. The validity of the response analysis method used in this study was confirmed.
(3) A method for estimating the maximum value of the axial force ratio for perimeter columns in cases where steel frames are simultaneously subjected to horizontal and vertical ground motions was proposed.

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