EFFECTS OF VERTICAL GROUND MOTIONS ON EARTHQUAKE RESPONSE OF STEEL FRAMES

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SUMMARY

This study aims at clarifying the characteristics of the effects of vertical ground motions upon earthquake responses of steel frames. The inelastic response of a multi-story frame is characterized mainly by the restoring force of the frame's lower parts. The effects of the varying axial force caused by vertical ground motions upon the restoring force characteristics of the frame with weak columns are greater than those with weak beams. Therefore, the effects of vertical motions were investigated by conducting on-line tests and numerical analyses using a steel beam-column model which represents the behavior of the lower part of frames. It was made clear from the results of the tests and analyses that the effects of vertical ground motions upon horizontal response are slight when the ratio of the vertical natural vibration period to the horizontal one is 0.2 or less.

INTRODUCTION

Structures are subject to both horizontal and vertical ground motions during a strong earthquake. However, in most cases seismic designs of structural frames are made taking only horizontal ground motions into consideration. It is assumed at design stages for many buildings that the collapse of frames during earthquakes is caused mainly by horizontal ground motions and that vertical ground motions do not have a predominant influence upon the horizontal responses of frames.

The studies made by Akiyama and Yamada [1] have clarified that the amount of total energy input is the sum of the energy input caused by horizontal ground motions and that caused by vertical ground motions, both of which have an independent value respectively. Although some case studies on the effects of vertical ground motions upon the response displacement in a horizontal direction have been carried out, the general characteristics of these effects have yet to be made clear.

This study investigated the effects of fluctuating axial forces induced by vertical ground motions upon the horizontal vibration responses of steel beam-columns. This was done by carrying out on-line tests and numerical analyses. The effects of vertical ground motions are more prominent in the steel beam-column model used in this study than in a frame model. Therefore, from the results of this study information concerning conditions of steel frames which are affected to a smaller degree by vertical ground motions can be obtained.

MODEL FOR INVESTIGATION

In general, a structure with relatively high design stress induced by vertical load tends to be affected to a greater degree by vertical ground motions. As examples of such structures, long-span or high-rise buildings can be taken up. In this study, high-rise buildings are subject to investigation. The ratio of vertical-load-induced beam-column stress for high-rise buildings has a tendency to increase with a rise in the height of buildings.

When investigating the basic inelastic response characteristics of frames using a modal vibration model of the primary mode, the restoring force characteristics of the model should be set up as to represent those of lower part of frames. Fig.1(a) shows the story model representing the lower part of a building. The effects of inertia forces

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acting on the mass supported by beams as well as the effects of the fluctuation of the beam-column axial forces transferring down from the upper stories can be regarded as the effects of vertical ground motions upon the restoring force characteristics of the story. It is deduced that the effects of the vertical inertia force of the mass supported by beams on the restoring force characteristics of the story are small in ordinary high-rise buildings. Therefore, the effects of the former are not considered in this study (Fig.1(b)). Since the varying axial forces affect the restoring force characteristics of the story with weak columns to a greater degree than those with weak beams, a more simplified model with a single beam-column (Fig.1 (c)) was used for the investigation. Conditions of steel structural frames which are affected by vertical ground motions to a smaller degree can be investigated by using this model which is simplified so that the effects of vertical ground motions can be more clearly seen.

ON-LINE SEISMIC RESPONSE TESTS

Model Outline

The model used in the experiments is a single beam-column with the rotation of both ends being restricted as shown in Fig.1(c). Fluctuating axial forces acting on the beam-column occur due to inertia forces on the mass of the stories above it. In the experiments, the coupled effects between fluctuating axial forces and horizontal responses were ignored. Responses for horizontal ground motions were obtained in on-line tests by imposing the fluctuating axial forces acting on the beam-column model, obtained from response analyses carried out in advance. The axial force was determined using a one-mass elastic model with an assumed vertical natural vibration period. As shown in Fig.2, the mean and the maximum axial forces were set at 30% and 80% of the beam-column's yield axial force respectively. In this study, the axial force is set to be positive in the case of compression.

The solid lines in Fig.4 indicate the stress-strain relationship of the steel used in the experiments which was obtained from stub column tests and tensile tests. The broken lines in this figure show the relationship between stress and strain which will be used in the analyses to be described later.

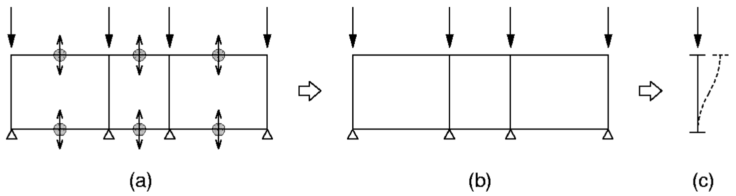


Fig.1. Story model

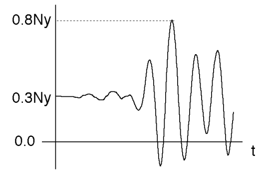


Fig.2. Fluctuating axial force

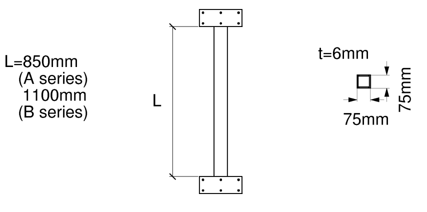


Fig.3. Test specimen

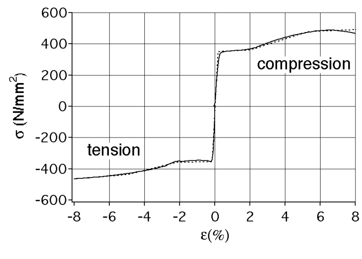


Fig.4. Stress-strain curve

Table 1 shows the testing program. The horizontal natural vibration period T_h was set at 1.0 and 2.0sec and the vertical natural vibration period T_v was set at 0.1 ~ 1.0sec. The ratio of vertical vibration period of the primary mode to horizontal vibration period of the primary mode for an ordinary high-rise building is 0.1 ~ 0.2. In this study, in order to investigate an overall tendency of the effects of vertical ground motions, experiments were carried out in the cases of T_v/T_h being 0.1, 0.5 and 1.0. The waves of El Centro, Taft and JMA-Kobe were used for the seismic input. Responses in the case of a constant axial force were compared with those in cases where beam-columns were subject to fluctuating axial forces induced by vertical ground motions. The damping ratio for horizontal response was fixed at 2%.

Horizontal ground motions were scaled so that Q_p/Q_{emax} is 0.2, where $Q_{e\,max}$ is the maximum shear force under the assumption of elastic responses of the model and Q_p is the yield shear force.

Experiment Results

Fig.5 illustrates the results obtained from the experiments. (a), (b) and (c) show the time history of the beam-column's fluctuating axial force, the time history of the horizontal displacement and the relationship between the horizontal displacement and the shear force respectively. δ_H shows the horizontal displacement and δ_{Hp} shows the elastic displacement at $Q = Q_p$. In (b) and (c), the results of models without a vertical ground motion (solid lines) are compared with those with a vertical ground motion (all other lines). It can be seen in Fig.5 (b) that in some cases responses of models with a vertical motion are greater than those without a vertical motion. In case of models with a vertical motion, a phenomenon where the horizontal strength rapidly falls is found. This is caused by the fact that the instant the axial force increases, the lowering of yield moment and the increase in the P-Δ effects occur simultaneously.

Fig.6 illustrates the ductility factor of each model. Fig.7 shows the maximum response displacement ratio β which can be obtained from the following equation.

$$\beta = \frac{\delta_{Hmax}}{\delta_{Hmax_0}} \quad \text{......} \quad (1)$$

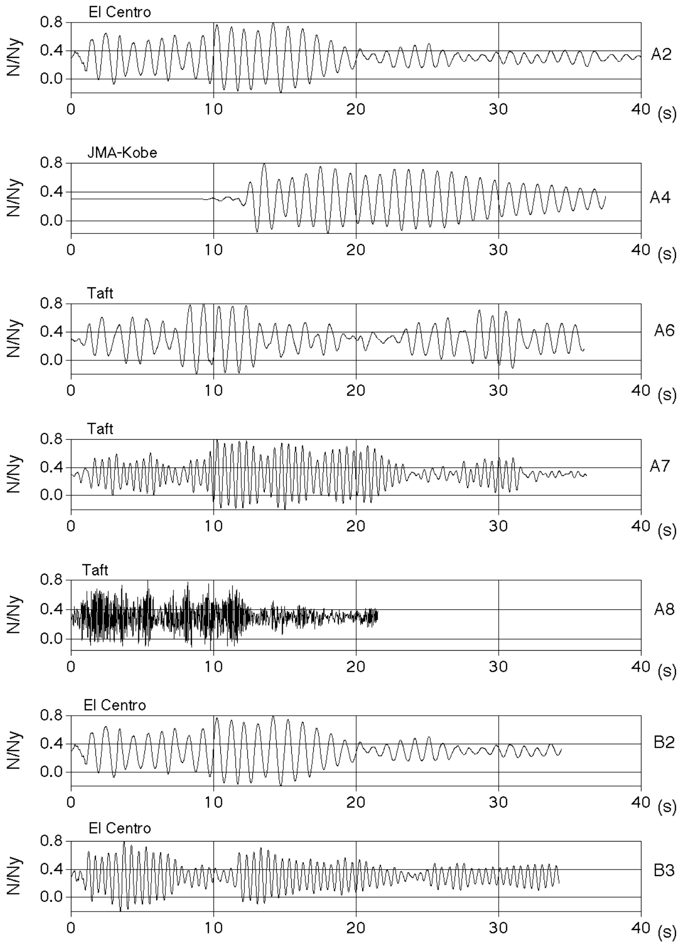
Where δ_{Hmax} : Maximum horizontal displacement,

δ_{Hmax_0} : Maximum horizontal displacement in cases where there is no vertical ground motion.

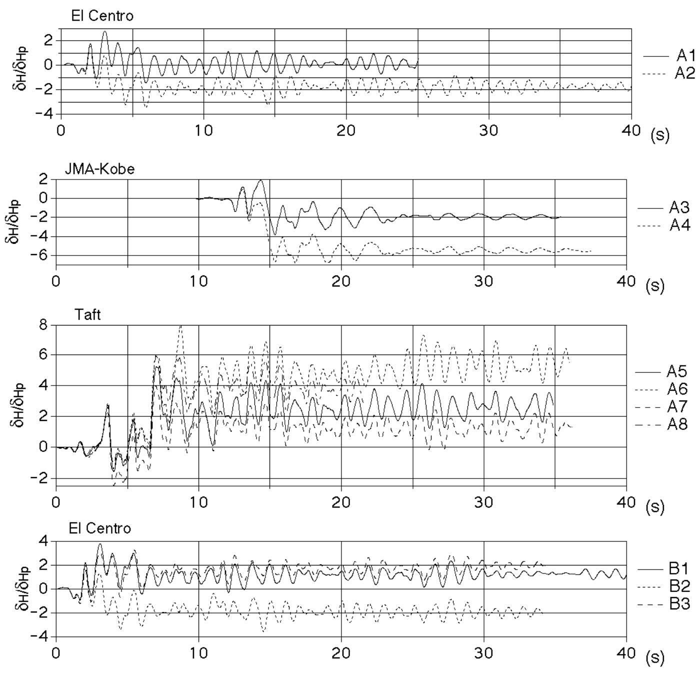
The abscissas in both figures show the ratios of T_v/T_h. The marks at 0 for T_v/T_h show the result obtained when there is no vertical ground motion. When the values for T_v/T_h are 0.5 and 1.0, there are cases where the maximum displacement varies to a relatively large degree due to the effect of vertical ground motions. The values of the maximum response displacement ratio for the three models in the B series are almost equivalent to each other. However, Fig.5(b) shows that the residual displacement of B2 with 1.0 for T_v/T_h can be seen at the reverse side of the area where that of B1 and B3 occurs due to the effects of vertical ground motions.

Table 1. Testing program

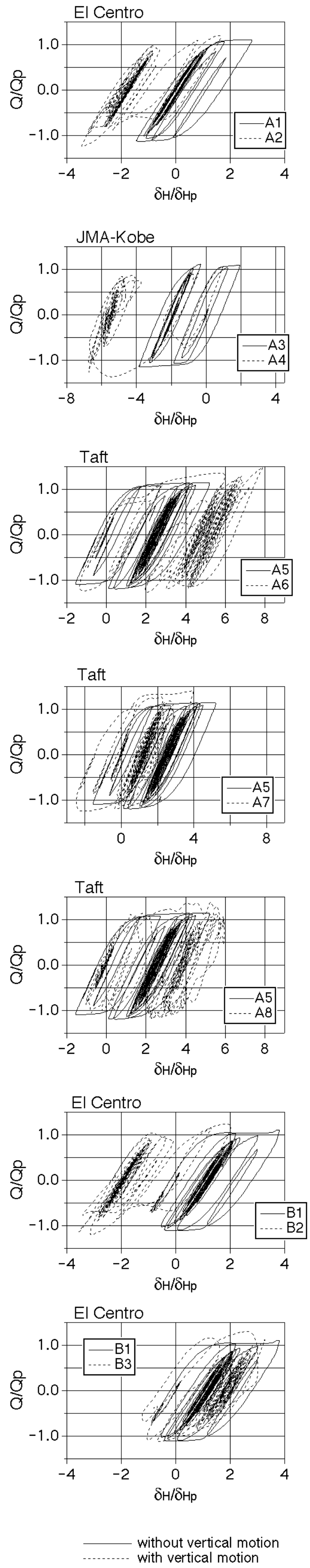
Specimen	Horizontal motion	Vertical motion	Th	Tv
A1	El Centro (NS)	—	1.0sec	—
A2	El Centro (NS)	El Centro (UD)	1.0sec	1.0sec
A3	JMA-Kobe (NS)	—	2.0sec	—
A4	JMA-Kobe (NS)	JMA-Kobe (UD)	2.0sec	1.0sec
A5	Taft (EW)	—	1.0sec	—
A6	Taft (EW)	Taft (UD)	1.0sec	1.0sec
A7	Taft (EW)	Taft (UD)	1.0sec	0.5sec
A8	Taft (EW)	Taft (UD)	1.0sec	0.1sec
B1	El Centro (NS)	—	1.0sec	—
B2	El Centro (NS)	El Centro (UD)	1.0sec	1.0sec
B3	El Centro (NS)	El Centro (UD)	1.0sec	0.5sec



(a) Axial force



(b) Horizontal displacement



(c) Load displacement curve

Fig.5. On-line test results

NUMERICAL ANALYSES

Analytical Model

The analytical method used in this study can be applied to response analyses of plane frame models. The outline of the model for the inelastic behavior of members is as follows:

1) The model of members is a finite element model which is composed of several multi-spring elements at both ends and an elastic beam element at the center as shown in Fig.8.

2) The hysteresis characteristics of the inelastic spring are modeled by relating the unloading point with the target point using the Ramberg-Osgood function [2]. This is shown in Fig.9.

Comparison between Experiment Results and Analysis Results

Fig.10 shows examples for the comparison between the experiment results and analysis results. δ_v shows vertical displacement and δ_{vp} indicates $\varepsilon_y \cdot \ell$ (ε_y : yield strain, ℓ : length of member). The solid lines show the experiment results and the broken lines show the analysis results. Both sets of results accurately correspond to each other. This figure shows the validity of the analytical method.

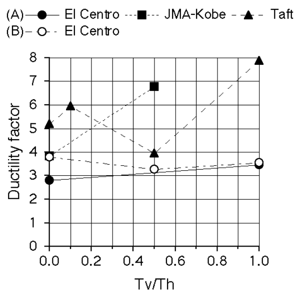


Fig.6. Ductility factor

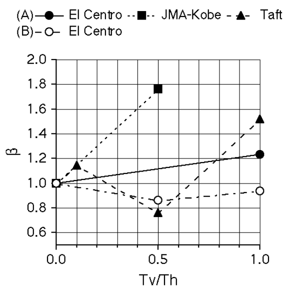


Fig.7. Maximum response displacement ratio

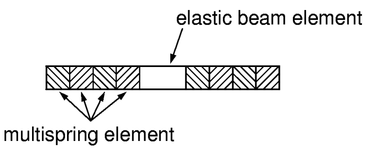


Fig.8. Finite element model of members

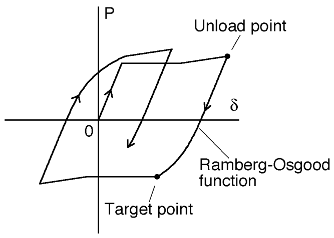


Fig.9. Hysteresis rule for inelastic spring

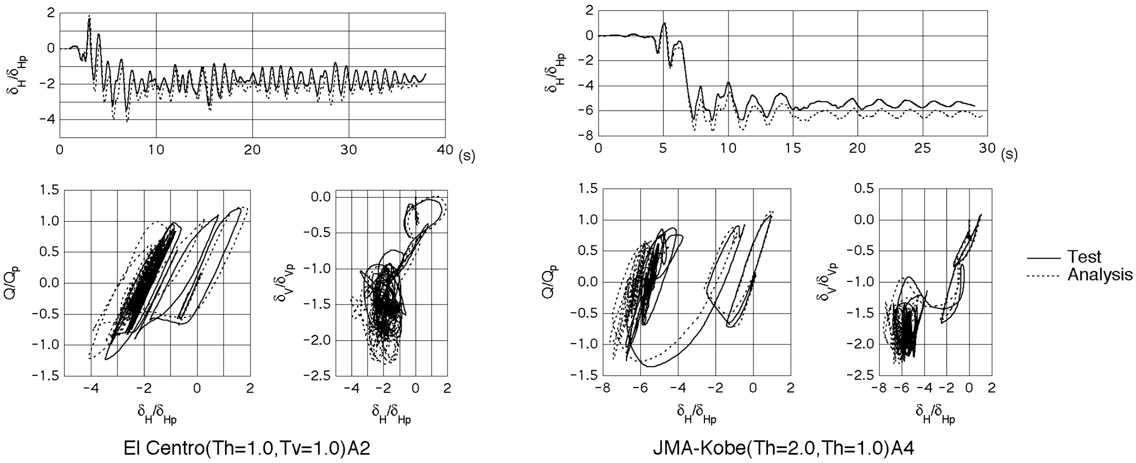


Fig.10. Comparison between on-line test results and analysis results

Analyses of the Same Model as Used in Experiments

In on-line tests, there is a limit to the combination of the horizontal natural vibration period and the vertical natural vibration period. Therefore, in this study response analyses of the combinations over a wide range were carried out to investigate the effects of vertical ground motions.

(1) Analytical Conditions

Seismic wave: El Centro NS+UD, Taft EW+UD, JMA-Kobe NS+UD, Hachinohe NS+UD
Horizontal natural vibration period T_h : 1.0, 2.0, 3.0, 4.0, 5.0s
Vertical natural vibration period ratio T_v/T_h : 0.1, 0.2, 0.5, 0.8,1.0
Column shape: Model for A series of on-line tests

Q_p/Q_{emax} (See 3.1) was set at 0.2 in the case of T_h being 1 ~ 3sec and at 0.3 in the case of 4, 5sec so that the ductility factor would be about 5 when there is no vertical ground motion.

Other conditions were the same as those for the on-line tests.

(2) Results of Analyses

Results of the analyses are shown in Fig.11. The axis of abscissa indicates T_v/T_h and the ordinate indicates the maximum response displacement ratio β (Equation (1)). From this figure, the following can be noted.

1) The maximum response displacement ratio β varies widely in a range of 0.7 ~ 2.5.

2) The tendency can be seen where with a rise in the value of T_v/T_h the maximum response displacement ratio increases. The effects of vertical ground motions when T_v/T_h is 0.2 or less are smaller than those when T_v/T_h is 0.5 or more.

Effects of Phase Difference

It is anticipated that phase difference between vertical ground motions and horizontal ones have influences upon responses. In this study, the vertical ground motion was input with a time lag τ to the horizontal ground motion in order to investigate these influences.

(1) Analytical Conditions

Seismic wave: EL Centro NS+UD, Taft EW+UD, JMA-Kobe NS+UD
Horizontal natural vibration period T_h : 1.0, 2.0, 3.0s
Vertical natural vibration period ratio T_v/T_h : 0.1, 0.2, 0.3, 0.4,0.5, 0.8, 1.0
Phase difference between vertical ground motions and horizontal ground motions τ : $\tau = \alpha T_v$, $\alpha = \pm 0.2$, ± 0.4, ± 0.6, ± 0.8
Other conditions are the same as those for 4.3.

(2) Results of Analyses

Results of the analyses are shown in Fig.12 and Fig.13. Fig.12 illustrates the relationship between T_v/T_h and the maximum response displacement ratio β. The solid lines in the figure show the response values when the phase deference is 0 and the broken lines show the response values when the aforementioned eight phase differences are applied. From this figure, the following can be noted.

1) There are cases where the maximum response displacements change to a considerably great degree due to the variation of phase differences between vertical and horizontal ground motions.

2) The larger the value of T_v/T_h, the more widely the maximum response displacement ratio varies. The results of the analyses show the same tendency as that seen in Fig.11 on the whole.

Fig.13 illustrates the variation in the residual displacement. The values on the ordinate show the residual displacement variation ratio γ which can be obtained from the following equation.

$$\gamma = \frac{\delta_{Hr} - \delta_{Hr_0}}{\delta_{H\max_0}} \quad \text{.......} \quad (2)$$

Where δ_{Hr} : Residual horizontal displacement,

δ_{Hr_0} , $\delta_{H\max_0}$: Residual horizontal displacement and maximum horizontal displacement in cases where there is no vertical ground motion.

It can be seen that the variation in the residual displacement is caused by changing the phase differences and that with an increase in the value of T_v / T_h the values for γ change widely.

The following can be made clear from Figs.11, 12 and 13. In the case of T_v / T_h being 0.2 or less, the maximum response displacement ratio β is about 1.5 or less and the residual displacement variation ratio γ is about 0.5 or less. In this case, the effects of fluctuating axial forces induced by vertical ground motions upon the inelastic horizontal responses of steel beam-columns are relatively slight.

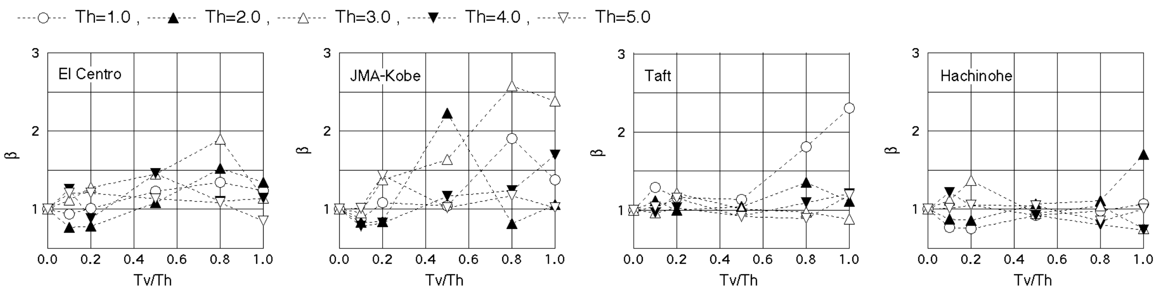


Fig.11. Maximum response displacement ratio

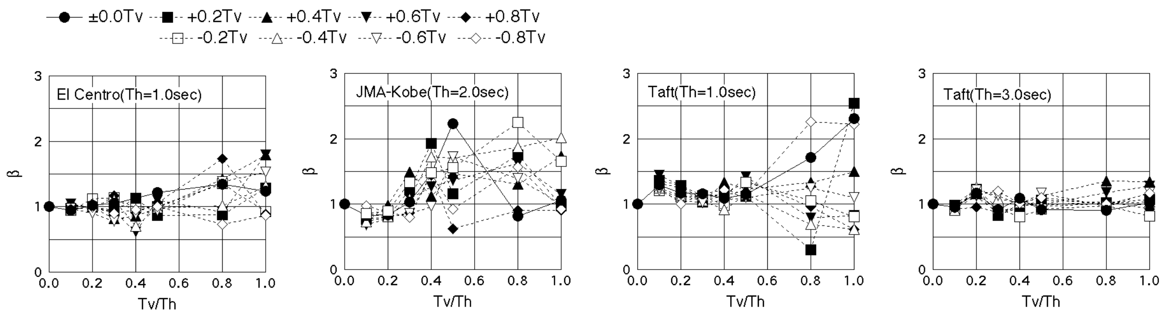


Fig.12. Maximum response displacement ratio (Effect of phase difference)

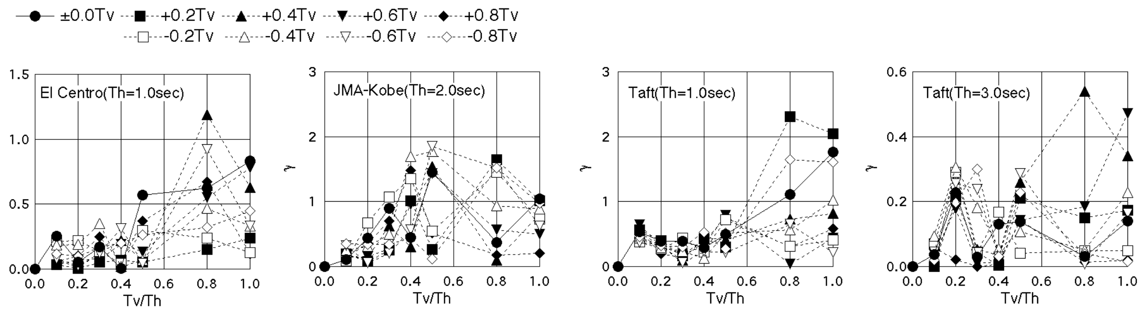


Fig.13. Residual displacement variation ratio (Effect of phase difference)

CONCLUSIONS

The effects of fluctuating axial forces induced by vertical ground motions upon the horizontal earthquake responses of steel beam-columns were investigated by carrying out both on-line tests and numerical analyses. The results obtained from this study can be summarized as follows:

1) In the on-line tests, the effects of vertical ground motions when the values of T_v/T_h (the ratio of vertical natural vibration period T_v to horizontal natural vibration period T_h) are 0.1, 0.5 and 1.0 were investigated. As a result, it was clarified that there are cases in which vertical-ground-motion-induced fluctuating axial forces have a relatively large influence upon horizontal responses.

2) The results of analyses corresponded quite well to the results obtained from the on-line tests. The validity of the analytical method used in this paper was confirmed.

3) A series of response analyses were carried out on the same model as that for the on-line tests by changing the values of T_v/T_h from 0.1 through 1 for each of the four different seismic waves. As a result, a tendency in which there is a positive correlation between T_v/T_h and the effects of vertical ground motions as a whole was discovered. Furthermore, analyses in cases where phase difference is applied to the input of horizontal and vertical motions were made. It was shown that the effects of the phase difference on responses also have a positive correlation with T_v/T_h. It was also made clear that when T_v/T_h is 0.2 or less, the effects of fluctuating axial forces caused by vertical ground motions upon the inelastic horizontal responses of steel beam-columns are relatively slight.

4) The effects of vertical ground motions on the steel beam-column model used in this study are more conspicuous than those on a frame model. Since the value of T_v/T_h for ordinary high-rise buildings is approximately 0.1 ~ 0.2, it is deduced that when unstable behavior does not occur on beam-columns of the frame through excessive axial forces, the effects of vertical ground motions upon horizontal responses of steel high-rise buildings are slight.

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