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SHAKING TABLE TESTS ON EARTHQUAKE RESPONSE OF MULTISTORY BUILDING MODEL WITH COLUMN UPLIFT

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Abstract

Currently, the researches have being conducted on vibration control structures that reduce the earthquake response of steel structures by allowing the column base uplifting during an earthquake. However, the quantitative evaluation of the seismic response reduction effect by allowing the column base to uplift and the grasping of the earthquake response characteristics of the superstructure of the multistory building may not fully be clarified.

In order to consider a strong non-linear phenomenon in which a building vibrates as the column bases uplift and land repeatedly during an earthquake, it would be important to verify not only by simulation but also by shaking table tests. In order to investigate the earthquake response characteristics in detail using the characteristics of the input seismic motion and the characteristics of the building structure, it is effective to conduct a vibration experiment using a small-scale building model.

The purpose of this study is to grasp the behavior of a building model with column-base uplift during an earthquake by conducting shaking table tests. The small-scale specimens for the shaking table tests were made so that the tests can be performed when the column bases are fixed and when the column bases are allowed to uplift. Regarding the measurement of vibration behavior, it is difficult to clarify the behavior of each part of the model using a laser displacement meter or the like. In this study, high-speed video recordings are performed on the vibration behavior of the specimen using digital cameras. Image analysis with high analysis accuracy are performed on the moving images, and time history displacements of each part of the test specimen are measured. The reduction effect of earthquake response and the difference of earthquake response characteristics due to the uplifting of the column base are studied in detail.

In this study, it is confirmed that the displacement measurement results of vibration experiments by image analysis are sufficiently accurate. Next, by comparing the results of the shaking table test with the case of fixed columns and the case of allowed columns uplift, it is clarified how much the earthquake response is reduced. Then, based on the results of the time history response displacements, the relationships between the displacements of column uplift and the displacements of each story of the superstructure are examined. Next, the influences of the higher-order vibration mode are examined by considering the vibration characteristics of the superstructure when the column base is uplifted. Finally, it is shown that allowing column bases to uplift has the effect of reducing the seismic responses of the upper structures, while the responses of the upper stories are relatively large due to the effects of higher mode vibrations.

If this system is put into practical use, the distribution of the seismic story shear coefficients in the height direction of the building needs to be different from the those of the building with fixed column base.

In the near future, by analyzing in detail the time history displacement behavior of the specimen obtained by image analysis in this research, basic data for improving the simulation accuracy can be obtained. By continuing this study, the future goal is to develop a new structural system that allows the column base uplift.

Keywords: shaking table test, earthquake response, column uplift, image analysis

1. Introduction

Several researches have been conducted on a vibration suppression system that reduces the response of the superstructure of a building by causing the column base to lift up when a rocking vibration occurs in the building during an earthquake. For example, Midorikawa et al. have proposed a column base system that allows column bases to be uplifted and are conducting research on elucidation of earthquake response by experiments and analyses of building models. [1][2][3][4]

The followings can be considered as reasons why the seismic responses of the superstructure of the building are reduced by the column bases uplifting during the earthquake.
1. Horizontal kinetic energy due to seismic response becomes vertically upward kinetic energy.
2. Horizontal kinetic energy is converted to potential energy by uplifting.
3. Energy absorption ability is given to the column base that uplifts.
4. The vibration characteristics of the base-uplift building differ from the fixed column base building. For example, the natural period becomes longer when the column base uplifts.
5. In the horizontal displacements of the building during an earthquake, the proportions of the displacements of the rocking components caused by the uplift of the column base increase, and the proportions of the deformation of the superstructure decrease accordingly.

It is necessary to consider these phenomena in detail in order to effectively realize a vibration-controlled building using the column base uplifting action. For that purpose, it is considered that verification by precise analytical research and experimental research is necessary. The author has been conducting an analytical study on the seismic response of vibration-controlled building that allows the column base to uplift. [5][6][7]
In order to elucidate the seismic response characteristics of a building that allows column base lifting, it is necessary to consider the effects of column base uplifting, landing, and higher-order mode vibration. For that purpose, it is necessary to perform the vibration experiments on a multi-story building model. However, since it is difficult to carry out a full-scale vibration experiment, it is realistic to carry out experiments using reduced-scale building models.
When vibration experiments are performed, there are various methods for measuring the response. In this study, in order to simplify the measurement device as much as possible, moving images of the vibration experiment were taken, and the displacement responses were measured by performing image analyses on the moving images.

The purposes of this study are as follows.
1. To show the specimen used for the vibration experiment and to introduce the results of the experiment that allowed column base uplifting.
2. To show the accuracy of the measurement results obtained by image analysis.
3. To consider the effect of seismic response reduction based on the results of comparing the response of a column-base uplifting building and a fixed building model.
4. To verify the seismic behavior of a building that allows column base uplifting based on the results of these experiments.

2. Building model and Vibration experiment

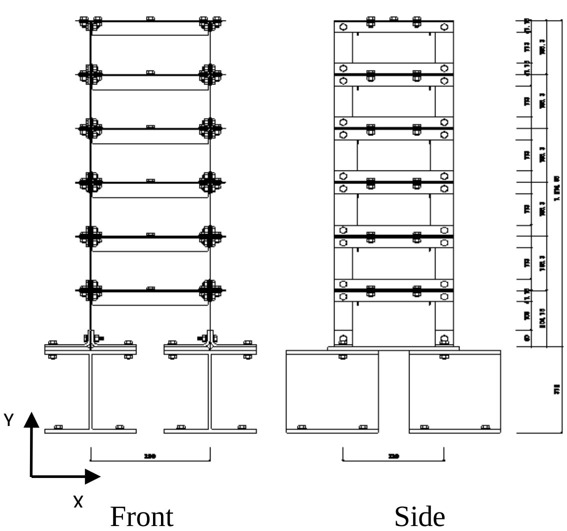
2.1 Building model

In this study, the models of building were assumed to be one span with six stories. The test specimens were made by joining steel plates and angle steel with bolts. As reduced model of the building, the test specimen of approximately 1/20 scale was designed. FIX model in which the column bases were fixed to the shaking table and UPLIFT model in which the column bases were allowed to uplift were prepared. These specimens are different only in the column base and have the same upper structure. The outlines of the FIX model and UPLIFT model specimens are shown in Figs. 1 and 2, respectively. Pictures of each specimen are shown in Picture 1 and Picture 2.

Simple experiments were performed on the behavior of the column base of the UPLIFT model, focusing only on the uplifting behavior. That is, no damper having an energy absorbing function was provided on the column base.

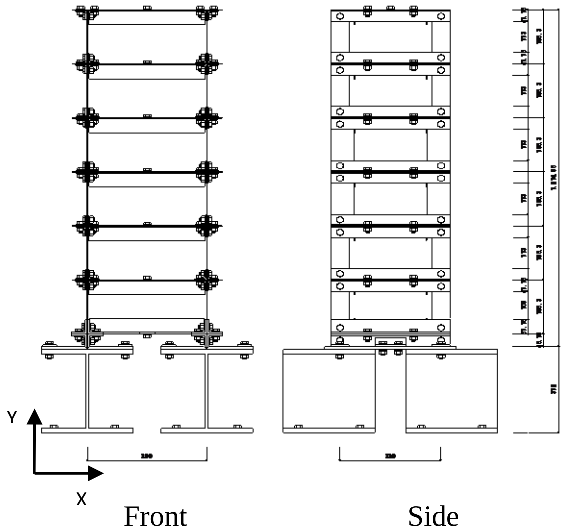
When designing the specimens, the goal was to make the natural period of the specimen as close as possible to the natural period of the actual building. In order to extend the natural period of the specimen, it was required to reduce the horizontal stiffness and increase the mass of the model. However, the design had to be made in consideration of avoiding the buckling of the column, especially the buckling due to the impact when landing after the column base was uplifted.

A small impact force was applied to the vibration model to generate free vibration. Of course, the impact does not uplift the column base even in the UPLIFT model. First order natural period and viscous damping constant were obtained from response measurement results. Table 1 shows them.



Front Side

Fig. 1 FIX model



Front Side

Fig. 2 UPLIFT model

Picture. 1 FIX model

Picture. 2 UPLIFT model

Table 1 Natural period (s) and Viscous damping coefficient of test specimen

	Natural period (s)	Viscous damping coefficient
FIX model / UPLIFT model	0.347 / 0.370	0.0166 / 0.0099

2.2 Vibration experiment

Vibration experiments of this study were performed using a shaking table at University of Fukui.

The ground motion with the maximum horizontal velocity of Kobe NS corrected to 0.15 (m/s) was adopted as the input wave and input in one horizontal direction. Kobe NS is the horizontal NS component of the seismic wave observed at the Kobe Local Meteorological Office during the 1995 Hyogoken-Nanbu Earthquake. The maximum acceleration of the observed seismic wave Kobe NS is 8.18 m/s^2.

Fig. 3 shows the time history of the acceleration of the input wave used in the experiments. Fig. 4 shows the time history of the horizontal displacement of the shaking table. This is data obtained by image analysis during a vibration experiment.

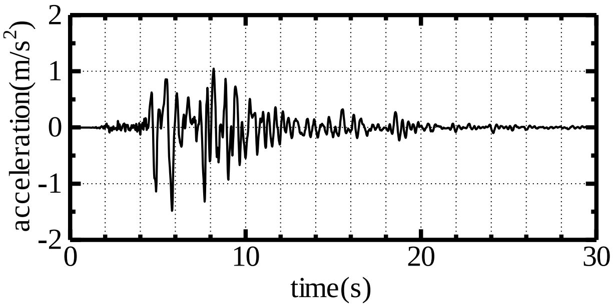


Fig.3 time history of the acceleration of the input wave

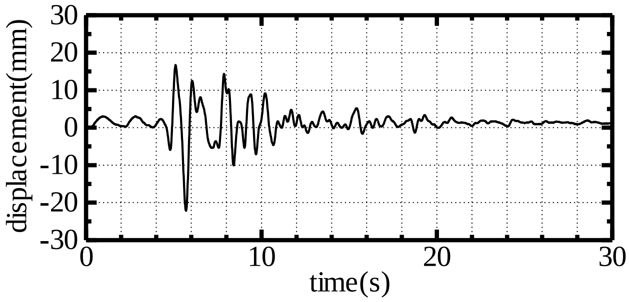


Fig.4 time history of the displecement of the shaking table

2.3 Measurement of experimental results

In the vibration experiments in this study, many measurement points are required to target uplift behavior and behavior of multi-story building model. A method using a number of laser displacement meters, or a method using a number of pickups for measuring acceleration or velocity attached to a test specimen are also considered as methods for measuring experimental data. However, it is desired to measure the vibration behavior at multiple points while aiming for high accuracy and low cost while preventing the system from becoming complicated.

In this study, the displacement behaviors of the specimen are measured by image analysis from moving images of vibration experiments. Analysis software DIPP-Motion V 2D (DITECT)[8] was used for image analysis in this research. By image analysis of the vibration experiment, the displacements of the measurement points in the x and y directions, the inter-story deflection angles of the left and right columns of each story, and the distances between the measurement points were measured. From these results, it was confirmed that the distances between the measurement points were almost constant.

This measurement method has the following advantages.

1. If a camera and software for image analysis are prepared, displacements at any point can be measured. Complicated measurement systems are not required, and measurements can be performed relatively inexpensively with a simple system.

2. If a camera with a certain level of performance is used, it is possible to measure the time history of horizontal and vertical two-dimensional displacements of any point of the test specimen on which the vibration test is being performed with sufficient accuracy. The camera used in this research was a

commercially available digital camera (Sony DSCRX100M4). The videos were shot at 120 frames per second and 1920 x 1080 pixels.

3. After the experiment, measurement points can be arbitrarily determined. Further, any number of measurement points can be added.

4. Since the measurements can be confirmed while judging the experimental situation by actually watching at the image, even if there are measurements error or the like, it is easy to judge it.

2.4 Verification of image analysis accuracy

In order to verify the measurement accuracy in this study, the displacement response obtained by the image analysis adopted in this study, the displacement response obtained by the image analysis method performed by T. Saito [9], and the displacement response obtained by the laser displacement meter were compared. The results obtained by the image analysis are the displacements of the measurement points, and the results obtained by the laser displacement are the displacements of the portions where the laser light is applied, so that exactly the same results cannot be obtained. Figs 5 and 6 show the comparison the results obtained by different methods. In Fig. 6, the data by the laser displacement meter indicated by the black line cannot be measured in the range where displacements are large because the range of large displacement exceeds the measurable range of the laser displacement meter. In addition, since the laser displacement meter measures the relative displacement, there are deviations from the data of the image analyses. Although there are some differences, it is considered that almost the same results were obtained as a whole. Based on these results, the accuracy of the data obtained by image analysis in this study is judged to be sufficient.

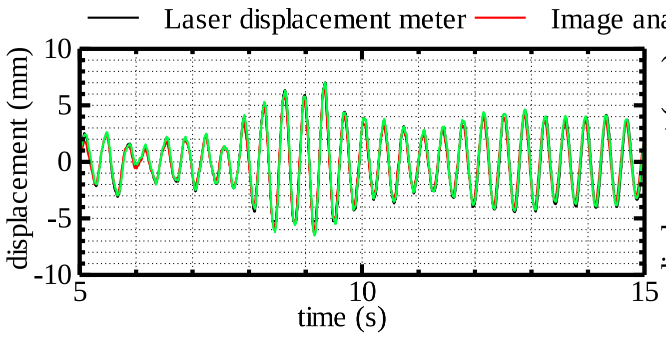


Fig.5 Comparison of X direction displacement obtained by different measurement methods (FIX model, 1st story, left)

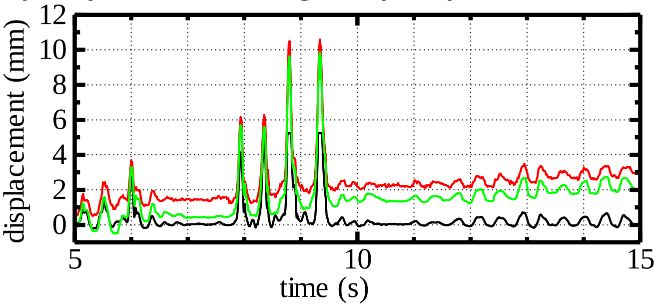


Fig.6 Comparison of y direction displacement obtained by different measurement methods (UPLIFT model, column base, left)

3. Results of vibration tests and consideration

3.1 x direction displacement (relative horizontal displacement from column base position)

Fig. 7 shows the horizontal time history response displacement of the measurement point of 1st story, 4th story, and 6th story of left side column. From the results of the image analyses, it was confirmed that the results obtained were almost the same as the results obtained from the points of right column. The left side of Fig. 7 shows the results of the FIX model, and the right side shows the results of the UPLIFT model. The results of the UPLIFT model are the relative displacements from the foundation including the effect of the rocking vibration displacement due to the column base uplifting. The top of Fig. 7 shows the time history displacement of the 1st story, that is, the bottom story, the figure below shows the displacements on the 4th story, and the bottom figure shows the displacement of 6th story, that is, the point of the top story. From Fig. 7, it can be confirmed that the relative displacement increases toward the upper story. Furthermore, it can be seen that the relative displacement responses of the UPLIFT model are smaller than those of the FIX model. Fig. 8 shows the displacement responses with respect to the time when the displacement response is large (that is, from 5.0 s to 10.0 s) by enlarging the horizontal axis. In these figures, the results of the displacement responses at each story are overlaid. From Fig.8, the followings can be understood.

1. Displacement responses are strongly influenced by first-order mode vibration because the phases of vibration of all stories are similar.

2. The vibration period around the maximum response value from the time history response displacement of the FIX model is about 0.35 (s), which is almost the same as that at the time of small deformation.

3. The vibration period around the maximum response value from the time history response displacement of the UPLIFT model is about 0.56 (s). The period is extended due to the influence of the column base uplifting.

Table 2 shows the maximum response displacements of each story. The times when the maximum response occurs are also shown. Furthermore, the ratios between the maximum response value of the UPLIFT model and the maximum response value of the FIX model (UPLIFT / FIX) are shown. From Table 2, the followings can be understood.

1. For the FIX model, the times when the relative displacement of each story is the maximum are almost the same.

2. The times at which the relative displacement of each story of the UPLIFT model becomes maximum are almost the same for the 1st, 2nd, and 6th storys, and substantially the same for the 3rd, 4th, and 5th storys, and are different from each other. From these facts, it can be imagined that the maximum values of UPLIFT model are greatly affected by higher-order modes compared to FIX model.

3. The maximum relative horizontal displacements of each story of the UPLIFT model are reduced to 62.9% to 82.3% compared to those of the FIX model.

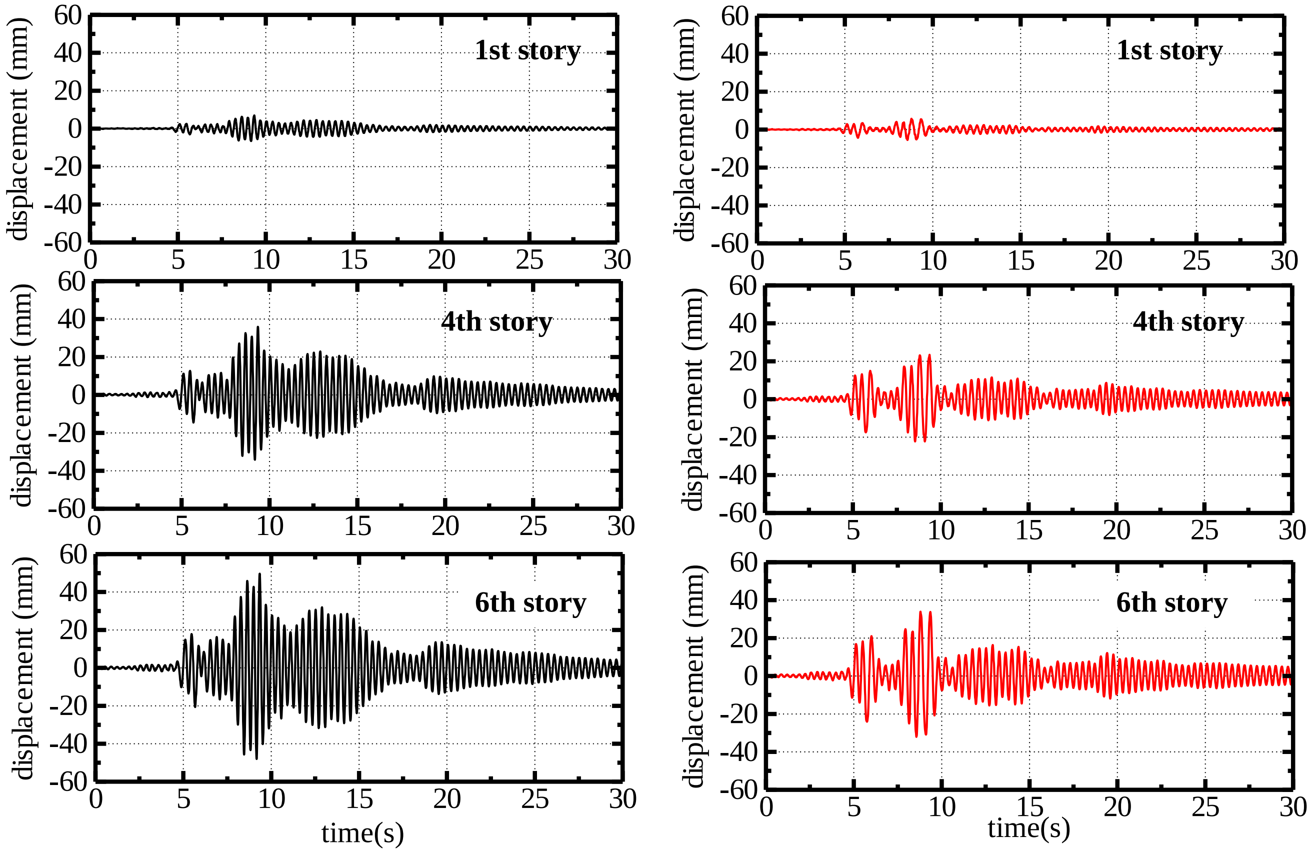
Table 3 shows the ratios of the maximum value of each story to the maximum value of 1st story for each model (d_{max} (i) / d_{max} (1)). From Table 3, the ratios of the maximum value in the upper part of the UPLIFT model is slightly smaller than those of the FIX model. The cause of that is considered to be the influence of the phenomenon that the column base uplifts.

Table 2 Maximum response displacements of each story

Max. of disp.	1st story	2nd story	3rd story	4th story	5th story	6th story
FIX model	7.03 mm (9.34 s)	17.39 mm (9.33 s)	27.90 mm (9.33 s)	36.00 mm (9.33 s)	44.59 mm (9.35 s)	49.72 mm (9.34 s)
UPLIFT model	5.81 mm (8.78 s)	11.64 mm (8.78 s)	17.54 mm (9.35 s)	23.45 mm (9.36 s)	28.92 mm (9.35 s)	34.00 mm (8.79 s)
UPLIFT / FIX	0.826	0.669	0.629	0.651	0.649	0.684

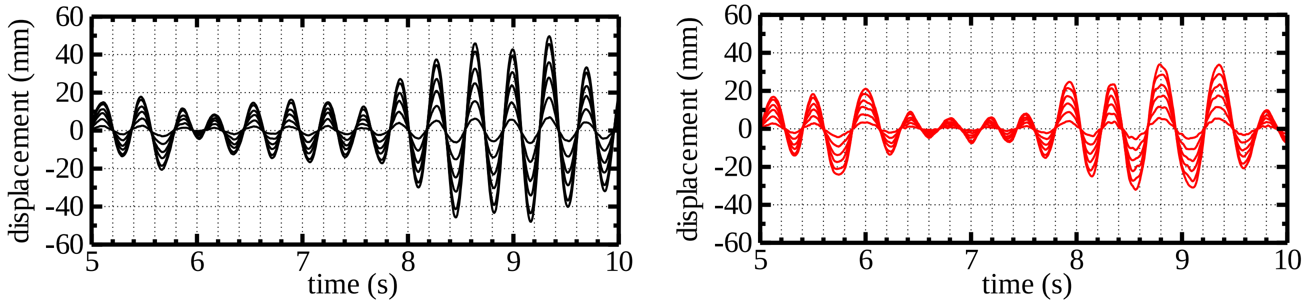
Table 3 Ratios of the maximum value of each story to the maximum value of 1st story

$d_{max}(i) / d_{max}(1)$	1st story	2nd story	3rd story	4th story	5th story	6th story
FIX model	1.00	2.47	3.97	5.12	6.34	7.07
UPLIFT model	1.00	2.00	3.02	4.04	4.98	5.85



FIX model　　UPLIFT model

Fig.7 Relative horizontal displacement from column base position



FIX model　　UPLIFT model

Fig.8 Relative horizontal displacement from column base position in X direction

(enlarging the horizontal axis)

3.2 y direction displacement (vertical displacement)

Fig. 9 shows the time history of the displacement in the y direction (vertical direction) of the point on the left side of each story of the FIX model and UPLIFT model. Fig. 9 also shows all the results from the 1st story to the 6th story. Fig. 10 shows the displacement response for a time when the displacement response is large, here from 5.0 s to 10.0 s, with the scale on the horizontal axis enlarged.

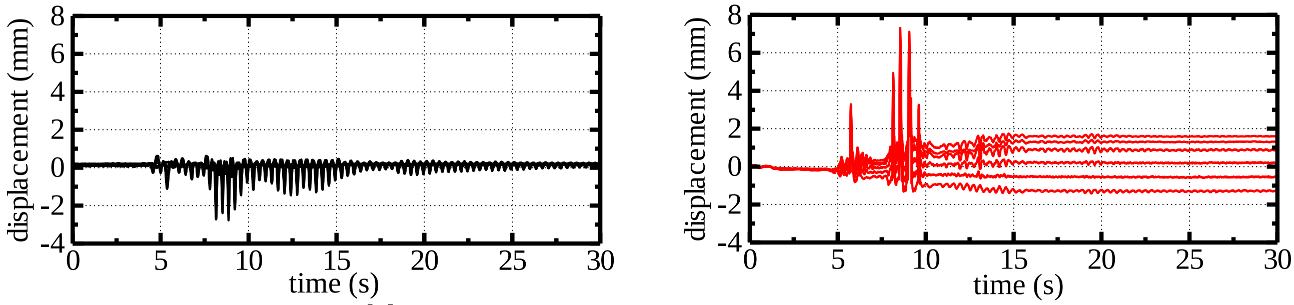
The following can be seen from Fig.9 and Fig 10.

1. It can be seen that the vertical displacement responses of the FIX model are displaced downward at the time when the responses increase. The results shown in Fig. 10 indicate that the higher the story, the larger

the displacements in the vertical direction. The rotation angles of the column members are considered to be a factor. The phases of the displacement response of each story are almost the same.

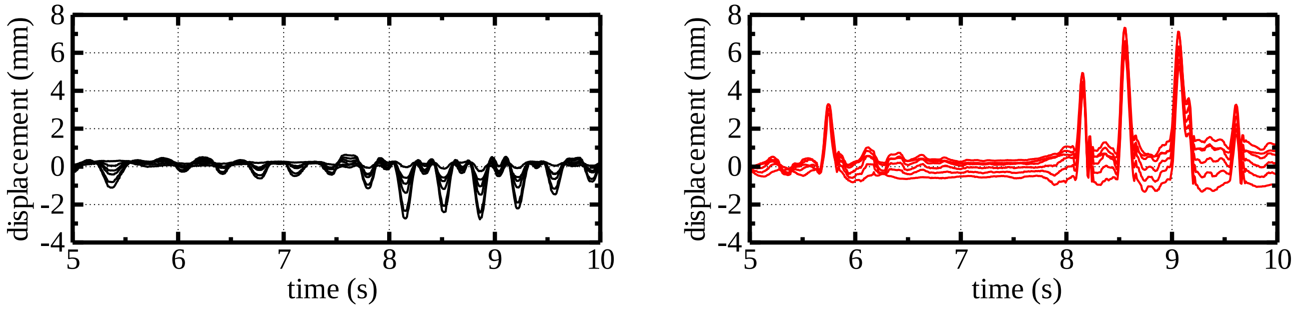
2. The vertical displacements of the UPLIFT model are displaced upward at a time when the responses are large. It can be seen that the y-direction displacement responses of each story have the same phase. The effect of column base uplift displacement is large.

3. It can be seen that the displacement response of each story of the UPLIFT model gradually deviates from zero when the column base uplift is large. The result of the largest shift in the positive direction is the result of 1st story (the lowest story). The results are that the upper story shift in the negative direction. The cause of this phenomenon is that the test specimen was displaced in the depth direction of the test specimen due to the effect of a large response accompanied by column base uplifting during the vibration experiment. As a result, the standard of the moving image was shifted, which affected the image analyses. The fact that the specimen was displaced in the depth direction was visually confirmed during the vibration experiments, and also confirmed by moving images taken. As a countermeasure for this problem, the test specimens should be improved in the future.



FIX model UPLIFT model

Fig. 9 Vertical displacements of each story



FIX model UPLIFT model

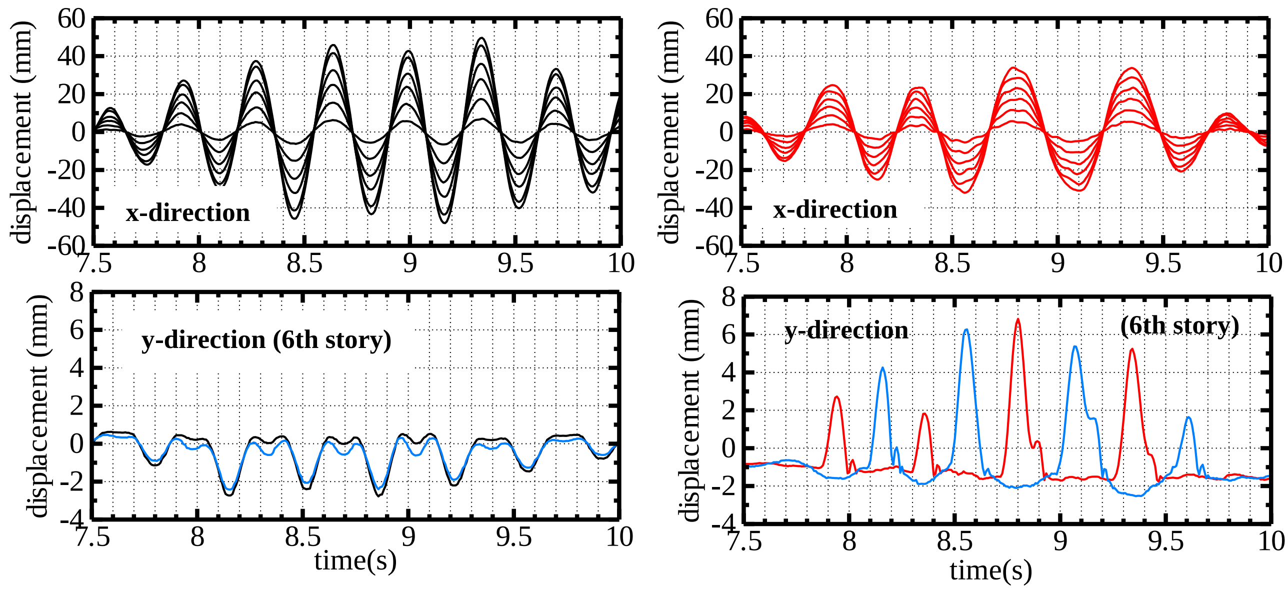
Fig.10 Vertical displacements of each story (enlarging the horizontal axis)

3.3 Relationship between x direction displacement and y direction displacement

Fig. 11 shows the time histories of the x-direction displacements and the y-direction displacements of each stories. However, the horizontal axis of the graphs is enlarged from 7.5 s to 10.0 s where the responses are large. The results of the FIX model are shown on the left, and the results of the UPLIFT model are shown on the right. The upper figures show the relative displacements in the x direction of each story, and the lower figures show the y direction displacements of the 6th story (the top story). As graphs of the displacements in the y direction, the time history of the displacement on the left side of the specimen show by black line and red line, and the time history of the displacement on the right-side show by blue line both.

Regarding the FIX model, it can be confirmed that the left and right points have almost the same response from the y direction displacements results on the top story. That is, it can be seen that the floor of each story of the FIX model does not rotate during the earthquake response. If the y direction displacement of the floor portion of the superstructure is caused by the rotation of the column members in the downward direction, when the x direction displacements of a certain point increase, the displacements should occur in the y direction downward. However, according to Fig. 11, the relationships between the displacement in the x direction and the displacement in the y direction of the FIX model are not such. It is considered that the cause of this phenomenon was that the test specimen was originally tilted and that the camera was slightly tilted. In the future, it is necessary to improve the accuracy of test specimens and the accuracy of camera installation in order to measure the experimental results more accurately.

From the graphs of the displacement in the y direction, it can be seen that the UPLIFT model performs the uplifting displacement alternately left and right. As for the UPLIFT model, it can be seen from the graph of the displacement in the y direction that the uplifting displacements are performed alternately on the left and right. When the x direction displacements of the superstructure are positive (right direction), the left column base uplifts (red line), and when the x direction displacements of the superstructure are negative (left direction), the right column base uplifts (blue line). That is, when the vibration of the column base and the movement of the superstructure are checked in total, it can be seen that they respond to the same phase in a first-order mode shape.



FIX model UPLIFT model

Fig. 11 Relationship between x-direction displacement and y-direction displacement

3.4 Story deformation angles

Fig. 12 shows the time history of the story deformation angle of 1st story, 4th story and 6th story of the FIX model and the UPLIFT model. The figure shows the deformation angles of only the column members obtained by analysis using the image analysis software DITECT. In other words, in the UPLIFT model, even when one side of the test specimen is uplifting and rotating, the angle indicates only the deformation of the column. From the graphs of the FIX model shown on the left side of Fig. 12 and the UPLIFT model shown on the right side, it can be seen that although the top story deformation is slightly small, the story deformation angles are almost the same for each story for each model. Comparing the results of the FIX model and the UPLIFT model, it can be seen that the responses of the UPLIFT model are reduced at the time when the responses increase. In the range where the responses after 15s are not large, there are almost no difference in amplitude due to the difference in model.

Fig. 13 show the responses of each story of FIX model and UPLIFT model between 7.5 s and 10 s in which the response is large. However, note that the two figures have different vertical scales. From the results of the UPLIFT model shown on the right, the amplitude of the response story displacement increases for each half cycle at 7.88 s, 8.10 s, 8.29 s, 8.49 s, 8.725 s, 9.00 s, and 9.275 s. The periods in this range is about 0.39s to 0.51s, which is not constant. From the results of y direction of UPLIFT model shown in Fig. 11, it can be seen that the time at which the response deformation angles increase corresponds to the time at which the base column begins to uplift. In the response part of the UPLIFT model, the response of the superstructure peaks out when the base column uplifts.

For the UPLIFT model, the responses of the superstructure reach the limit while the column base is uplifting. The response of the 1st story is a complex vibration containing waves with a period of about 0.06 s. The responses of the 2nd, 3rd, 4th and 5th storys while the column base is uplifted are pulse-like in which the response of each storys with a period of about 0.1 to 0.12s has the same phase. The response of the 6th story is largely affected by waves having a period of about 0.08 s. Therefore, while column base uplifting, the

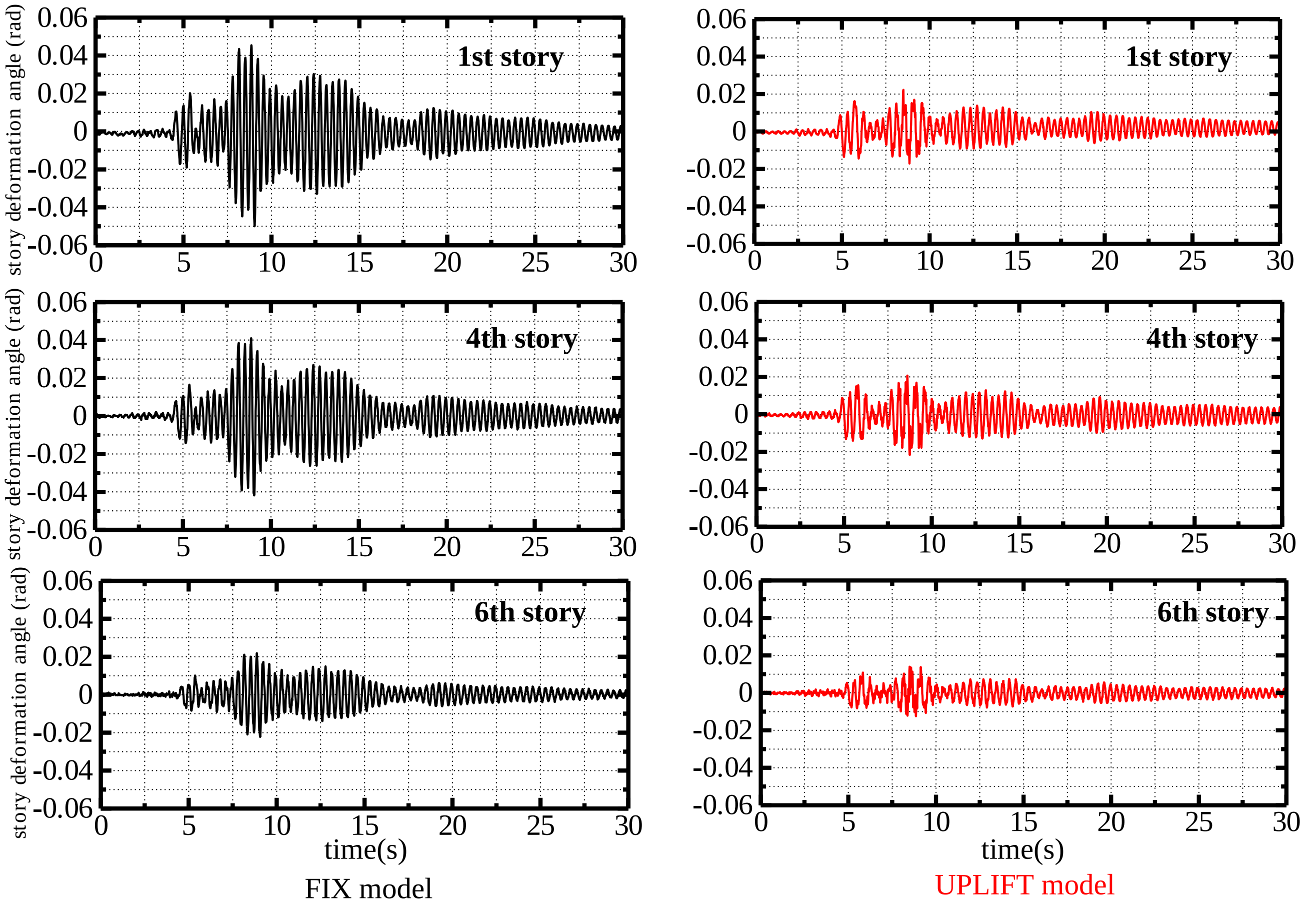


Fig.12 Story deformation angles of 1st,4th, and 6th story

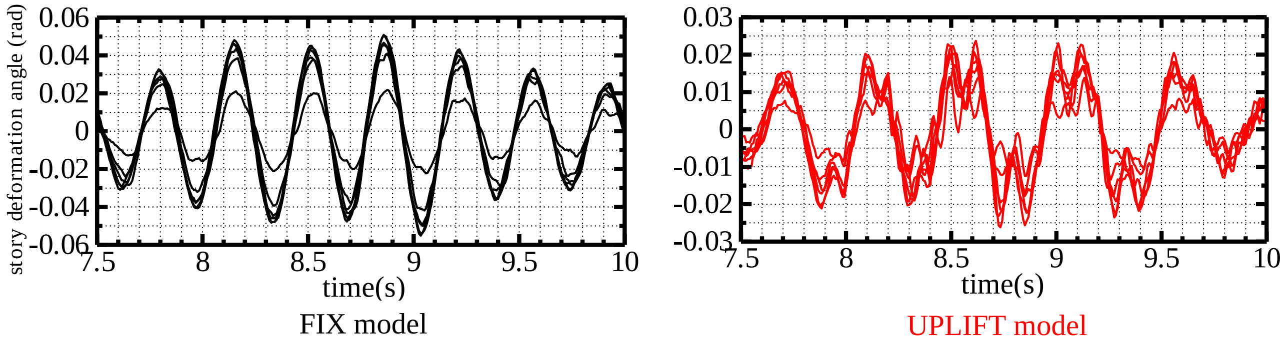


Fig. 13 Story deformation angles of each story (enlarging the horizontal axis)

upper structure vibrates with a short period, but the 1st story and the 6th story vibrate particularly with a short period, so that the whole structure has a complicated vibration.

From these results, when the seismic response of the superstructure of the UPLIFT model increases, the column base starts to uplift, and the effect of the higher-order vibration mode increases during the column base uplift.

As a result, by the vibration tests using the reduced model, it was confirmed that the response of the superstructure reach the limit and the response were reduced compared to response of the FIX model.

Table 4 shows the Maximum response story deformation angle of each story. For the FIX model, each story has a maximum at almost the same time, confirming that the first-order mode vibration is dominant. For the UPLIFT model, the times at which the response of each story becomes maximum are different, which reflects that the influence of higher-order mode vibration is large. The ratio between the maximum value of the FIX model and the maximum value of the UPLIFT model is about 0.446 to 0.632, which indicates that the story deformation angles can be greatly reduced by the uplifting of the column base.

Table 5 shows the ratios of the maximum value of each story to the maximum value of 1st story for each model (R_{max} (i) / R_{max} (1)). From Table 5, the differences between the FIX model and the UPLIFT model are not so large, but the UPLIFT model tends to be larger than the FIX model, especially in the top story. The result shows that the influence of the higher-order mode is large.

These results indicate that while the UPLIFT model is expected to reduce the seismic response, it is necessary to consider that the distribution of the story shear coefficient in the height direction of the building is largely affected by higher-order modes.

Table 4 Maximum response Story deformation angle of each story

Max. of story deformation angle	1st story	2nd story	3rd story	4th story	5th story	6th story
FIX model	0.04993 rad (9.04 s)	0.05510 rad (9.03 s)	0.05376 rad (9.03 s)	0.04183 rad (9.05 s)	0.04917 rad (9.04 s)	0.02220 rad (9.05 s)
UPLIFT model	0.02228 rad (8.50 s)	0.02564 rad (8.85 s)	0.02620 rad (8.73 s)	0.02165 rad (8.74 s)	0.02193 rad (8.86 s)	0.01403 rad (8.49 s)
UPLIFT / FIX	0.446	0.465	0.487	0.518	0.446	0.632

Table 5 Ratios of the maximum value of each story to the maximum value of 1st story

Max. of story deformation angle	1st story	2nd story	3rd story	4th story	5th story	6th story
FIX ($R_{max}(i)/R_{max}(1)$)	1.00	1.10	1.08	0.838	0.985	0.445
UPLIFT ($R_{max}(i)/R_{max}(1)$)	1.00	1.15	1.18	0.972	0.984	0.630

4. Conclusion and future issues

In this study, a vibration tests were conducted on a reduced model of a building model that allowed the column base to uplift, and comparisons were made with the case where the column base was fixed.

In this study, the followings were shown.

(1) It is easy to measure the displacement by image analysis in the vibration test of the reduced model as in this study, and its accuracy is sufficient.

(2) Comparisons of the seismic response between the model with the uplifted column base and the model with the fixed building show that the effect of reducing the seismic response was recognized by allowing the column base to be uplifted.

(3) In this vibration experiments using a reduced building model, it was shown that small-amplitude vibration with a short period was observed in the inter story deformation angle of the superstructure while the column base was uplifted.

Future issues include the following.

development of vibration model with higher accuracy, improvements of displacement measurement accuracy by image analysis, vibration test of model with damper on column base, accumulation of experimental data when building structural characteristics and input wave characteristics are different, comparison of simulation results with experimental results and improvement of simulation accuracy, quantitative understanding of seismic response reduction effect.

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