EFFECT OF UPLIFT ON EARTHQUAKE RESPONSE OF BUILDING

Keizo IWASHITA[1] And Hajime TANIGUCHI[2]

SUMMARY

There was a light damaged office building, which was designed before establishing the new seismic design code, in seismic intensity VII area at the 1995 Hyogo-Ken Nanbu earthquake. According to our study, it seemed that uplift of base reduced the structural damage. So, it is important to understand an effect of uplift on earthquake response. In this paper, the effect of uplift on earthquake response of building was studied by nonlinear earthquake response analysis considering several types of structural characteristics. A simple formula for the condition of uplift was also studied. Analytical models consisted of one span and eleven stories frame and the frame with shear wall. As a result of nonlinear earthquake response analysis considering uplift, the frame with wall tended to cause uplift more than pure frame. Maximum shear force of the frame with wall was about half compare to that of the pure frame. Effects of structural characteristics (distance between supports, support stiffness, building stiffness) were also examined. The uplift occurred easily in case of narrow support and decreased to half base shearing force. The base shearing force varied according to stiffness of support and natural period of structure. Studies were also performed on the condition of uplift of structure through numerical analyses, in which aspect ratio, building stiffness and support stiffness were selected as main parameters using multi-mass model. Based on the analytical results, a simple formula for the condition of uplift was derived as a function of acceleration response spectrum value. It was found that the formula agreed well to the analytical results.

The effect of uplift on earthquake response of building was studied by nonlinear earthquake response analysis. As results of these studies, uplift reduced story shearing force of structure that is related to the damage.

INTRODUCTION

The building, which had been designed by an old aseismic designing method, suffered small damage in region of the seismic intensity VII for 1995 Hyogo-Ken Nanbu earthquake. This building had no basement, a spread foundation and the aspect ratio was about three. The seismic wave at the building was presumed, and the result of 3-D nonlinear seismic response analysis using a model in which uplift of base was restrained showed damage which was far bigger than real damage. On the other hand, the damage level of the uplift model became small as same as real damage. This suggests that uplift decreases damage of building, that is, decrease seismic force. There are two examples besides this to point out the possibility that uplift decreases damage of the building. One is a hospital due to 1971 San Fernando earthquake and the other is an office building due to 1995 Hyogo-Ken Nanbu earthquake.

Uplift during earthquake is one of the important problem in structural design when the aspect ratio is large. It is useful in the future for the design of the superstructure and a foundation to understand the influence which uplift gives to the building response. In this paper, first of all, the overturning condition and the uplift condition were examined. Next, the nonlinear seismic response analysis was executed by using 2-D frame model, and the influence, that uplift gave to the earthquake response in the building, was examined.

[1] *Tech. Development Dept. Research & Development Institute, Takenaka Corp., Japan Email: iwashita.keizou@takenaka.co.jp*
[2] *Tech. Development Dept. Research & Development Institute, Takenaka Corp., Japan*

OVERTURNING CONDITION

The important problem of the building when uplift is allowed is a overturning for the earthquake and the wind. As for a theoretical study concerning the overturning problem of the object, the review which ISHIYAMA did in 1980 becomes reference. It was pointed out that the overturning condition of the solid body like Figure 1 should consider not only acceleration but also velocity, displacement and the input wave cycle. For instance, the condition concerning the velocity by Mallet is shown as Eq. (1).

$$V^2 = \frac{8gr}{3} \quad \frac{1-\cos \alpha}{\cos^2 \alpha} \tag{1}$$

where, V: velocity , g: gravity acceleration, r: half of diagonal length of solid body

α: angle between the vertical line and the line from the base edge to the center of gravity

Figure 2 shows the overturning limit velocity by the Eq. (1). At any aspect ratio the larger the width of the building is, the larger the overturning limit velocity is. The limit velocity becomes small for large aspect ratio in case of the same width of the building. As the limit velocity is about 240kine in case of aspect ratio 6 and 5m in width of the building, it is not thought that the building overturn by the large earthquake usually thought.

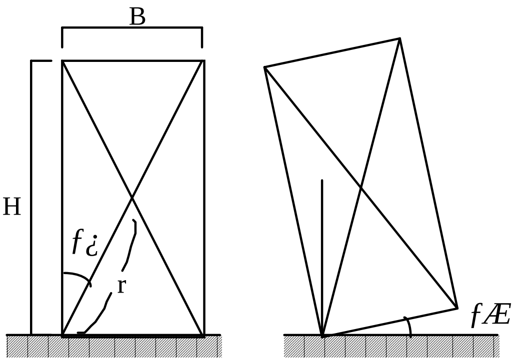


Figure 1: Motion of Rigid Body

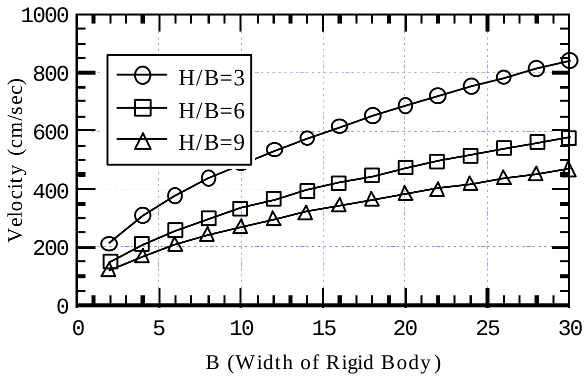


Figure 2: Overturning Condition about Velocity

UPLIFT CONDITION

Outline Of Examination

The uplift condition was studied for various parameters by the earthquake response analysis. A lot of researches have already been done for the overturning of the solid body, and there was an equation of West as an example of the representative of conditional equation by which a solid body begins locking. For a solid body, since the response acceleration of the solid body is corresponding to ground acceleration A by the principle of d 'Alembert, Eq. (2) can be led from the balance condition of the moment.

$$\frac{A}{g} \geq \frac{B}{H} \tag{2}$$

where, A: ground acceleration, g: gravity acceleration, B: width of the building, H: height of the building.

For the general building, the magnitude of the rocking movement which influences uplift is related to not only the size of the earthquake motion but also the dynamic characteristic of the building and the ground. Therefore it is difficult to define by a explicit equation using these parameters (Figure 3). Then, uplift occurring condition was examined by seismic response analysis which the building shape, the building stiffness and the ground stiffness were assumed to be a parameter.

Analytical Model

The analytical model was assumed to be a multi mass model of the bending and shearing type which could consider uplift shown in Figure 4. Beam element were used for representing each story stiffness, and the stiffness of the story was shown by shearing stiffness of the beam element (flexural stiffness is infinity). The upper part of the building and the support spring united by rigid beam element. The ground stiffness was shown by spring constant of the support spring. The weight of the each floor was assumed to be the same, which was 10tonf for each unit length of the depth of the building. The stiffness of each story was provided for the story drift to become specified value r at each floor for the Ai distribution story-shearing force of base shear coefficient 0.2.

The parameter were width of the building B, aspect ratio H/B, spring constant of the support Kp, and story drift specified value r. Table 1 shows the range of each parameter.

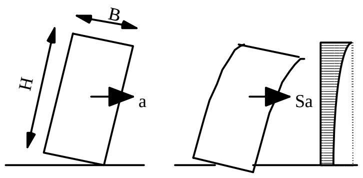


Figure 3: Uplift Features

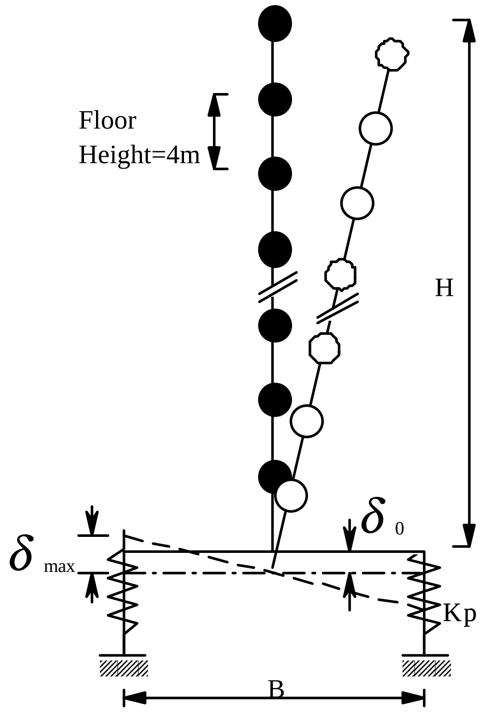


Figure 4: Analytical Model

Table 1: Parameter of Model

Parameter	Unit	Value
B	m	4, 8, 16, 24
H/B	-	2, 3, 4, 5, 6, 7, 8, 9
Ks	rad	1/200, 1/350, 1/500
Kp	t/cm	1000, 3000

Figure 5 shows the relation between aspect ratio and natural periods. When the width of the building was large, the natural period became long for the same aspect ratio. The natural period shortened by becoming small of the story drift specified value. The support stiffness did not influence a secondary natural period so much though influenced a primary natural period. Figure 6 shows from primary normal mode to third normal mode and the base rotation angle Θ of participation vector for a typical model. It was thought that the examination only had to pay attention to a primary normal mode for uplift of the base since the influence of a primary normal mode was superior for the base rotation for all case. El Centro 1940 NS, which was scaled for the maximum velocity 25cm/sec (255.4gal or less), was used for the input earthquake motion. Time history response analysis used the Newmark-β method, and used stiffness proportional damping of 3%. The rotation angle of the base was paid attention to as the response as shown in Figure 4. That is, it was judged that uplift was caused when δmax of the maximum displacement of the base exceeded δo, where an initial subsidence by building self-weight W was expressed to be δo . It was assumed that all element except for support springs were linear.

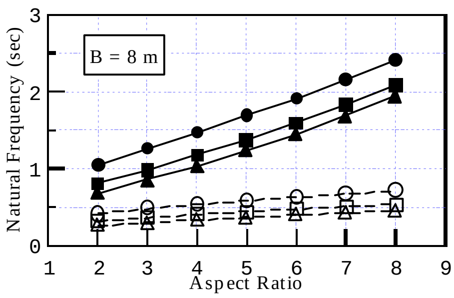


Figure 5: Aspect Ratio and Natural Period

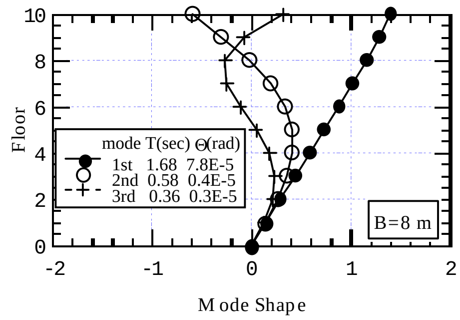


Figure 6: Mode Shape and Rotation Angle at Base

RESULTS AND CONSIDERATION

Uplift of the building is influenced by the aspect ratio of the building and the stiffness of the ground. In addition, as the rocking motion, which rules uplift, is a dynamic phenomenon, uplift closely relates to the response characteristic of the building and spectral characteristics of the input earthquake motion. According to the results of eigenvalue analysis, the rotational motion of the base receives the influence of a primary normal mode of the building. Then, it was attempted to presume response δmax/δ0 by the rocking motion as the Eq. (3), by using the acceleration response spectrum value corresponding to a primary natural period of the building.

$$\frac{\delta_{\max}}{\delta_0} \approx \frac{S_a(T_1)}{g} \times \frac{H}{B} \tag{3}$$

where, Sa(T1): acceleration response spectrum value at T=T1

Figure 7 shows the correspondence of the left side and the right side of the Eq. (3). There was somewhat variation but estimate value and the seismic response analysis result showed roughly good correspondence.

Correlation coefficient between δmax/δ0 and Sa(T1)/g*(H/B) was 0.970 and 0.976 for spring constant Kp=1000t/cm,3000t/cm in respectively. The relation, to which the least square is approximated δmax/δ0, is as follows.

$$\frac{\delta_{\max}}{\delta_0} = \lambda \times \frac{S_a(T_1)}{g} \times \frac{H}{B} \tag{4}$$

$$\lambda = 1.18 \quad (K_p = 1000 \text{ t/cm})$$
$$ 1.16 \quad (K_p = 3000 \text{ t/cm})$$

The relation shown by Eq. (4) is shown with broken line in Figure 7.

A further study is necessary to consider a physical meaning of the coefficient (lambda) .

Anyway, if the acceleration response spectrum value corresponding to primary natural period of the building was used as an index of uplift, Eq. (5) was obtained as uplift conditional equation.

$$\frac{S_a(T_1)}{g} \times \frac{H}{B} \geq 1.0 \tag{5}$$

Figure 8 shows the relation between Sa(T1) and g/(H/B). The condition of Eq. (5) means uplift occurring in the region above the solid line in Figure 8. It was shown that uplift caused at small acceleration when the aspect ratio was large. Moreover, circle symbol and x symbol of Figure 8 indicate the case caused uplift and the case not caused respectively in seismic response analysis. There were some tendencies undervalued in the region where the aspect ratio was large but the tendency was roughly caught.

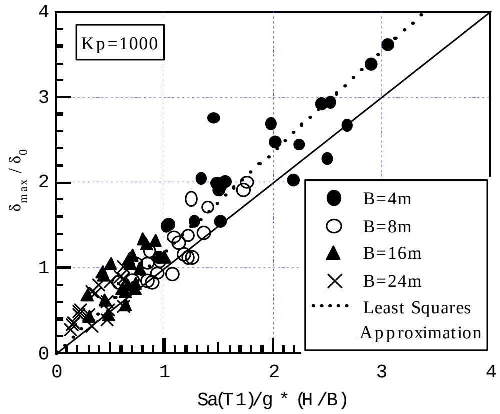


Figure 7: Uplift Displacement and Acceleration Response Spectrum

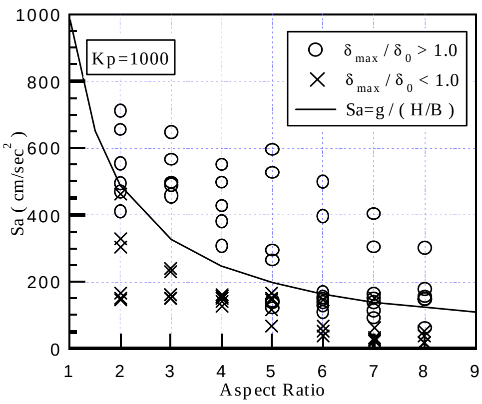


Figure 8: Presumption of Uplift Condition

RESPONSE ANALYSIS OF TWO DIMENSIONAL FRAME

Analytical Model

It was studied that the effect of uplift to earthquake response of 2-D frame by the nonlinear seismic response analysis. The object of the analysis were the pure ramen which was one span and 11 floors and the ramen with shear wall in all floors as shown in Figure 9. The aspect ratio was about eight. Table 2 shows the main section of beam and column. The thickness of the wall was assumed to be 20cm in all floors.

The support condition of the frame was assumed that the horizontal directions were restrained and the vertical direction was supported by the spring. The spring expressed the pail. Figure 10 shows the analytical models.

The natural periods of pure ramen model (F-CT) were 1.47 seconds for primary, 0.40 seconds for secondary. The natural periods of ramen with shear wall model (W-CT) were 1.05 seconds for primary, 0.18 seconds for secondary. Column and beam were modeled by the beam element with rigid- plasticity rotational spring at beam end and the wall was modeled by wall element of the bending and shearing type. The force-displacement relation of the beam element were normal trilinear for bending characteristics, normal bilinear for shear and axial characteristics.

The correlation of bending moment and axial force was considered in the column. The rigid floor assumption was used at the each floor in consideration of the slab. When uplift was considered, the support spring was compression stiffness 1582t/cm, tensile stiffness 0.01t/cm. When uplift was not considered, the support spring was same stiffness 1582t/cm for compression and tensile. The weight of the building was considered at the node as concentrated mass for the dead load of the member and the live load. After the self-weight analysis was done, the response analysis was executed for horizontal acceleration by the direct integral calculus. Damping was assumed to be a stiffness proportional type, and the damping constant was assumed to be 3% for a primary normal mode. JMA KOBE 1995 NS (818.0gal, 91.0kine) which was observed at Kobe Marine Observatories during 1995 Hyogo-ken Nanbu earthquake was used for the input earthquake motion. Figure 11 shows the time-history of acceleration and the velocity response spectrum of the seismic wave. The influence, which the frame characteristic gave to uplift response, was studied by the nonlinear seismic response analysis which uplift was considered.

ANALYTICAL RESULTS

It was extent in the F-C model which uplift slightly but about 6cm uplift was caused in the W-C model.

Figure 12 and Figure 13 show the maximum story-shearing force and the maximum story drift of the F-C model, the W-C model, and the W-CT model. The W-C model which uplift was caused became about 1/2 of W-CT models for the maximum story-shearing force. The F-C model and the W-CT model were almost the same for the maximum story drift, and the W-C model became small with about 1/2 of other models.

Effect of distance between the support points

To study how the uplift displacement changed depending on the distance between the support points about pure ramen, the F-C model and the F-C-N model were compared. Figure 14 shows the displacement time history and the maximum story-shearing force of the left support spring for both models. Uplift displacement was 0.03cm or less in the F-C model and 1.4cm or less in F-C-N model. The uplift tended to occur by the distance between support short for the same building. Maximum story-shearing force of the F-C-N model with large displacement of uplift decreased by about 20% every the third floor or more compared with the F-C model.

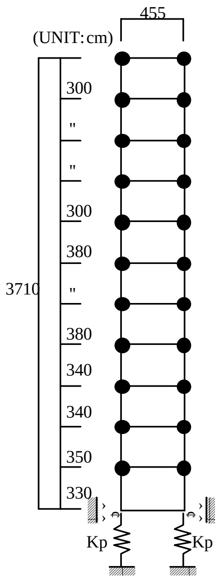
Effect of support stiffness

The support spring stiffness of the F-C-N model and the W-C model was changed and the response results were compared. Uplift was occurred for all cases with the W-C model and basic model (Kp=1582t/cm) of the F-C-N model. Figure 15 shows shearing force of the first story. When the support spring stiffness grew, the story-shearing force grew large. However, since the natural period changed, too, when the support spring stiffness was changed more study is necessary.

Effect of natural period

The same study as the effect by the support spring stiffness was executed about the effect of the natural period of the frame. The natural period has been adjusted by increasing and decreasing all mass at same rate.

Uplift was occurred for all cases of the W-C model and for basic model (T=1.4sec) and shorter period models than basic model of the F-C-N model. Figure 16 shows shearing force of the first story. Shearing force were minimized at the natural period of about 70% of basic model for both the W-C model and the F-C-N model.



Floor	W (tonf)
RF	38
11	40
10	38
9	48
8	52
7	51
6	51
5	54
4	76
3	85
2	214
1	0
Total	746

Figure 9: Analytical Model

Table 2: Main Section of Member

Floor	Column			
	D x B	Main Bar	Hoop	Steel
11F	700x650	14-HD25	LD13@100	H325x150x 9x12
1F	700x700	14-HD25	LD13@100	H375x400x 16x28

Floor	Girder			
	B x D	Main Bar	Stirrup	Steel
RF	550x650	2-HD25	LD13@200	H400x250x 6x12
2F	600x800	2-HD25	LD13@200	H450x300x 12x22
1F	1600x1500	3-UD25	LD13@200	

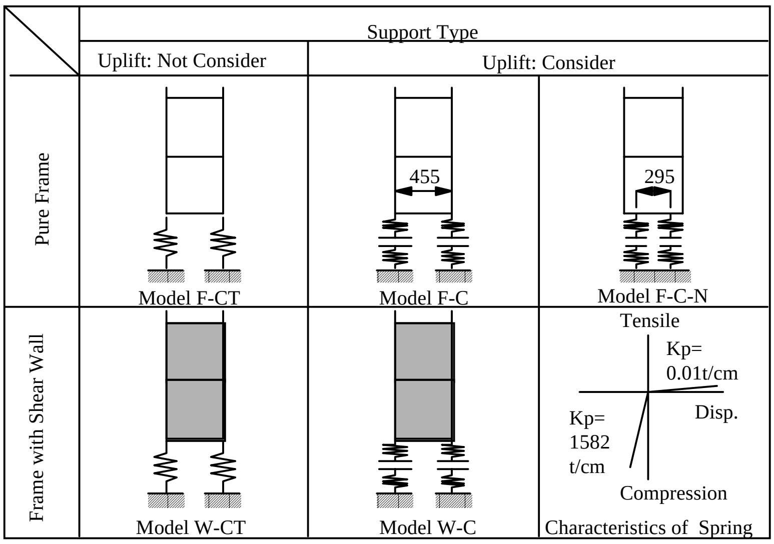
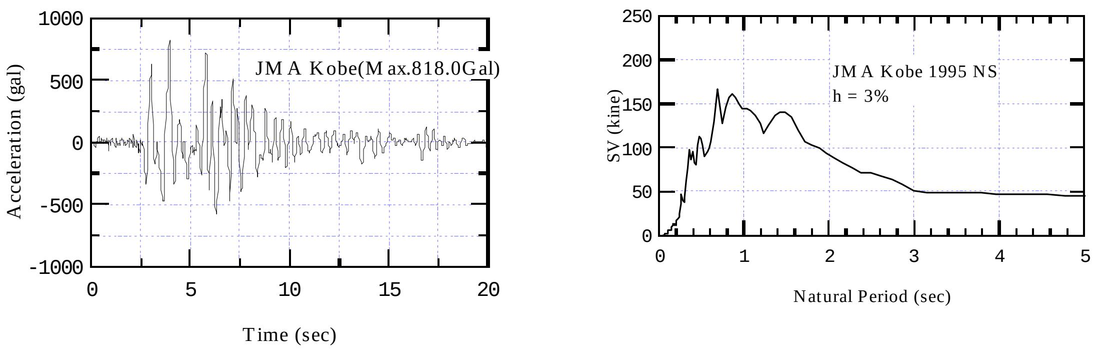


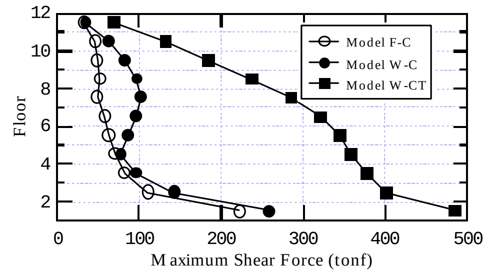
Figure 10: Analytical Case



(a) Time History of Acceleration

(b) Response Spectrum of Velocity (h=3%)

Figure 11: Input Earthquake Motion



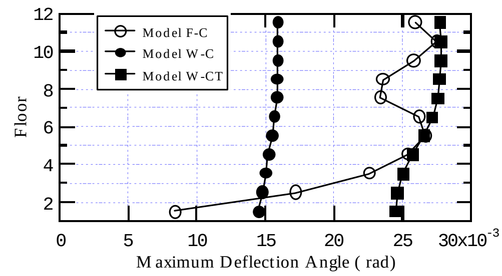
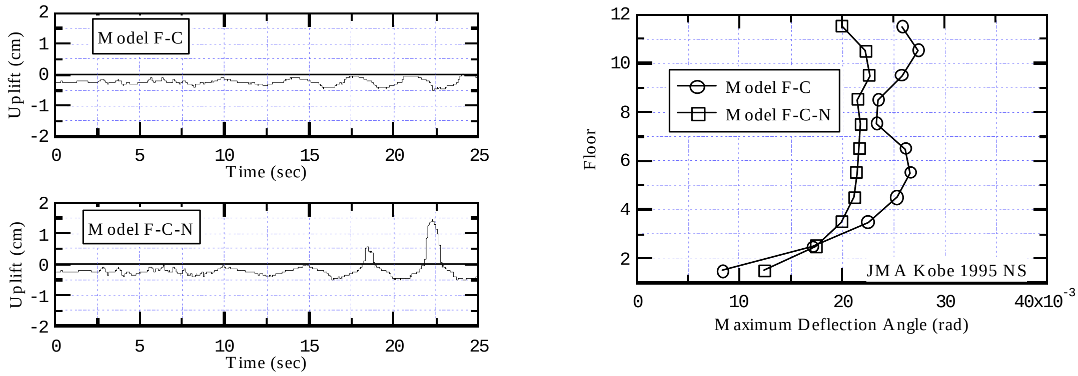


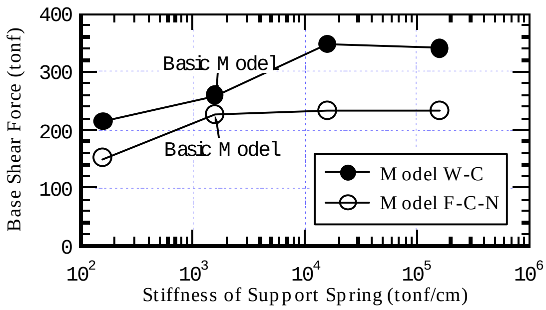
Figure 12: Maximum story shearing force of inter story

Figure 13: Maximum Story Drift



(A) Time History Of Uplift Displacement **(b) Story Shearing Force**

Figure 14: Effect Of Support Distance



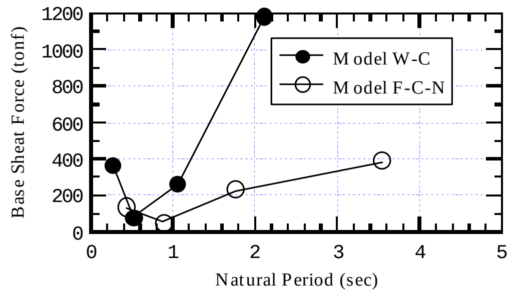


Figure 15: Effect Of Support Stiffness

Figure 16: Effect Of Natural Period

CONCLUSIONS

The following conclusions are derived by the above studies.

According to a theoretical study when the building was assumed to be a solid body, the overturning limit depended on not only the aspect ratio but also the width of the building. Therefore, it is thought to be no overturning of a building of the large aspect ratio (for instance, 5m in width and aspect ratio 9) for the large earthquake usually thought.

1. The presumptive condition of uplift is proposed, which is using the acceleration response spectrum value at a primary natural period of the building and the aspect ratio. Prediction of uplift by this condition corresponded roughly well to the results of the seismic response analysis using the multi mass model which the building shape, the building stiffness and the ground stiffness are considered.

2. Uplift occur easily in the frame with shear wall more than the pure ramen frame according to study by the nonlinear seismic response analysis.

3. There is the effect to decrease seismic force in uplift since the maximum story-shearing force decrease about 1/2 allowing uplift in the frame with shear wall.

4. The effects of the support stiffness at the base and the natural period of the building on the uplift response are studied by seismic response analysis. More studies are necessary to clarify the effect of the uplift in the future.

REFERENCES

1. Akiyama, H., Iyama, J. and Harada, Y. (1996), " Estimate of Overturning of Rigid Bodies with Energy Spectrum", *J. Struct. Constr. Eng., AIJ*, No. 488, pp49-55.

2. Hayashi, Y. (1996), "Damage Reduction Effect due to Basemat Uplift of Buildings", *J. Struct. Constr. Eng., AIJ*, No.485, pp53-62.

3. Ishiyama, Y. (1980), *Review and Discussion on Overturning of Bodies by Earthquake Motion*, BRI Research Paper, No. 85.

4. Rutenberg A, et al. (1982), "The Response of Veterans Hospital Building 41 in the San Fernando Earthquake", *Earthquake Eng. Struct. Dyn.* , Vol. 10, No. 3, pp359-379.

5. Takenaka Corporation (1995a), *Great Hanshin Earthquake (1995 Hyogo-ken Nanbu earthquake) Fourth Investigation Report*, Takenaka Corporation.

Takenaka Corporation (1995b), *Document at the Conference of Great Hanshin Earthquake Damage Investigation*, Takenaka Corporation.