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Seismic response of multi-storey frames equipped with energy absorbing storey on its top

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ABSTRACT: A series of numerical analysis was made on the multi-story frames in which most of the total energy input due to earthquakes is aimed to be absorbed at the top story leaving the other stories undamaged. To attain the aim, it is necessary for the top story to be equipped with an appropriate strength and a ductility. As the result, the possibility of this type of structure and its conditions to attain the aim are clarified.

1 INTRODUCTION

The total input energy to the building due to earthquake is stable amount governed by the total mass and natural period. As for the manner to absorb the total input energy, the earthquake-resistant design method are categorized as follows.(Akiyama 1985)

1. enhancement of the energy absorption capacity of each story of a structure
2. mitigation of damage concentration
3. positive introduction of damage concentration

In those categories, the last one is a clear method in the sense that designers are relieved from troublesome matter to the estimate of the energy absorption capacity large enough to absorb the total input energy. The other stories are released from the various restraints that are imposed in order to secure an adequate energy absorption capacity.

On the other hand, Tuned Mass Damper (TMD) and Active Mass Damper(AMD) are in process of development now to mitigate the vibration of the building caused by wind and earthquake. These mass dampers absorb vibration energy with small mass which is about 2% or less of the 1st mode effective mass of the building. Though it is effective to the stationary vibration, TMD is not effective to the transient state vibration. TMD stores kinetic energy temporary with the small mass when the vibration of the building increases non stationarily, and then the kinetic energy is absorbed as damping energy gradually. Large deformation of the building caused by the earthquake, which is not stable, is not well reduced by TMD. It is not appropriate to improve the safety of the building to the earthquake with use of such a small mass.

In this paper, the possibility of the general building equipped with energy absorbing story on its top is discussed. It consisted of large mass and energy absorber equipped with sufficient plastic deformation capacity, and aimed to improve the safety to the earthquake, not only to reduce the vibration like TMD. For the practical design, it is necessary to restrain the story deformation of the top as well as to absorb enough energy. The investigation is performed with the attention to those two points.

2 ENERGY ABSORPTION RATIO OF THE TOP STORY

The energy absorption ratio W_{pn}/W_p is defined as the ratio of the absorption energy of the top story :W_{pn} to the amount of the absorption energy of the building: Wp. (Akiyama 1987) The critical shear force coefficient is shown in Eq.1 to absorb the energy more than 80% of W_{pn}/W_p. In case of the multi stories building of the following conditions such as the yield shear force distribution of all the stories but top story is optimum yield shear force distribution, while the top story yield shear force is half of the optimum value, its restoring force characteristics are elasto perfect plastic, and hasn't any other damper.

$$\alpha_{1c} = 0.056n\alpha_{E1} \tag{1}$$

where α_{1c} : critical shear force coefficient of the 1st story to be W_{pn}/W_p>0.8
n : No. of the story
α_{E1} : Shear force coefficient of the first story for the elastic system under the total input energy of the elasto-plastic system. It is shown as follows.

$$\alpha_{E1} = \frac{2\pi V_e}{T \cdot g} \tag{2}$$

where V_e : equivalent velocity of the input energy
T : natural period of the system
g : gravity of the earth

When the shear force coefficient of the first story is reduced from the critical value, the energy dissipation ratio decreases as follows.

$$\frac{W_{pn}}{W_p}=\frac{0.8\alpha_1}{\alpha_{1c}} \tag{3}$$

Eq.1 and Eq.3 becomes as follows.

$$\frac{W_{pn}}{W_p}=\frac{14.3\alpha_1}{n\alpha_{E1}} \tag{4}$$

$1/n$ means the top mass ratio to the total mass. Eq.4 is rewritten as follows.

$$\frac{W_{pn}}{W_p}=\frac{14.3\alpha_1 m_n}{\alpha_{E1}\Sigma m_i} \tag{5}$$

In the Eq.5, α_1/α_{E1} is less than 1.0. When W_{pn}/W_p is 1.0, following equation is formed.

$$\frac{M_n}{\Sigma M_i}>\frac{1}{14.3} \tag{6}$$

From those equation, more than 7% of total mass of the building is indispensable to absorb all the energy by the top story.

Those investigation was performed in the restricted parameters. In this paper, the energy dissipation ratio and the deformation of the top story is investigated under the follwing parameters, which are yield force, stiffness of elastic range, stiffness of the plastic range, and mass of the top story.And the conditions to increase the energy absorption of the top story, to restrain the top story deformation, and the amount of top mass are clarified.

3 METHOD

The top story consists of the elastic element which supports the top mass and the elasto–plastic element which absorb most of the input energy. Numerical calculations are performed to the shear multi degree of freedom systems shown in Fig.1. The yield shear force of the stories are shown as follows.

$$Q_{Yn}=(1+k_2)rmM\alpha'_n\alpha_1 g \tag{7}$$

$$Q_{Yi}=(N-i+1)M\alpha'_i\alpha_1 g \tag{8}$$

where Q_{Yi} : yield strength of the i–th story
k_2 : stiffness ratio of the elastic element to the plastic element of the top story
r : shear force reduction factor of the top story
m : mass ratio
M : mass
α_i : optimum yield shear force distribution ratio to keep cumulative ductility factors nearly constant to the multi degree of freedom system of the equal masses
α'_1 : shear force coefficient of the 1st story

The yield displacement is determined to make the natural period of the system T=1.0sec. as the standard model. The parameter l, shown in Fig.1, is the yield displacement ratio of the top story. By selecting the value of l, the ratio of T_S/T_L can be arbitrarily changed. Where T_S is the natural period of the top story isolated lower stories, and T_L is the natural period of the system without top story. As the standard model, following values are used, N=5,10, r=0.5, k_2=0.0, l=1.0.

The variation of parameter used in this study is shown as follows.
r= 0.3, 0.4, 0.5
k2= 0.00, 0.02, 0.05, 0.07, 0.10, 0.20
l= 1.0, l(tune), $l(T_S/T_L$=1.0)

l=1.0 means that the yield displacement is constant for all the stories. $l=l$(tune) means that the natural period of the top story is tuned to be TMD. $l=l(T_S/T_L$=1.0) means that the yield displacement is set to be T_S/T_L=1.0.

Three earthquake motions are used in this study, which are El Centro 1940 NS, Taft 1952 EW, and Hachinohe 1968 EW. The maximum acceleration is scaled to make the maximum velocity of the motion to be 34cm/sec. and 50cm/sec. The input energy is absorbed by the elasto–plastic element. Any other energy absorber is not equipped.

4 RESULTS

4.1 *The effects of the stiffness of the top story*

Fig.2 shows the relationship between W_{pn}/W_p and T_S/T_L of the ten stories building. The horizontal axis is obtained by changing the yield displacement. When T_S/T_L is 0.405, the yield displacement of all the stories are equal. In this figure, there are two cases are shown, which are r=0.3 and r=0.5. W_{pn}/W_p has maximum where T_S/T_L is nearly 1.0 in both cases. This shows that W_{pn}/W_p can be raised by tuning T_S/T_L more than the result of displacement constant case. The increase and decrease of W_{pn}/W_p for r=0.5 is greater than that for r=0.3. In case T_S/T_L small, W_{pn}/W_p for r=0.3 is greater than that for r=0.5, but in the case T_S/T_L nearly 1.0, W_{pn}/W_p for r=0.3 is smaller than that for r=0.5 on the top. It is considered that the top story behaves like TMD from those results. In the case r=0.3, as equivalent period of the top story increases due to the plastic deformation, the top story is tuned by that elongated period, when T_S/T_L is small. But when T_S/T_L is nearly 1.0, W_{pn}/W_p is smaller than that of r=0.5 which has less plastic deformation, and hasn't wide band frequency components are contained in this case.

Fig.3 shows the maximum relative displacement of

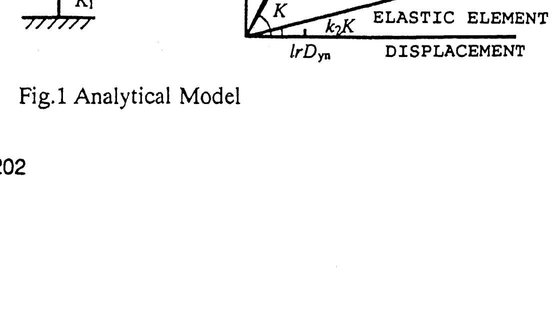

Fig.1 Analytical Model

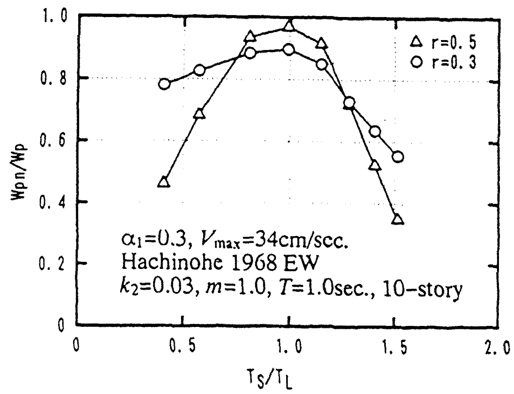

Fig.2 Energy Absorption Ratio

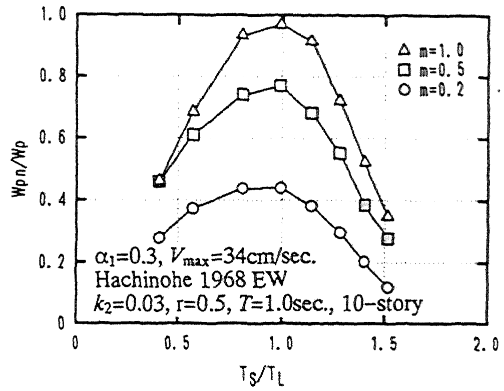

Fig.5 Energy Absorption Ratio

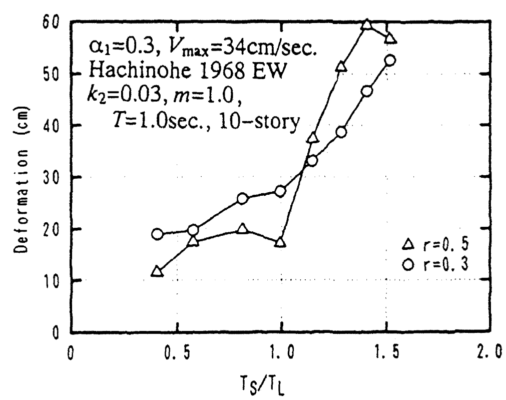

Fig.3 The Deformation of the Top Story

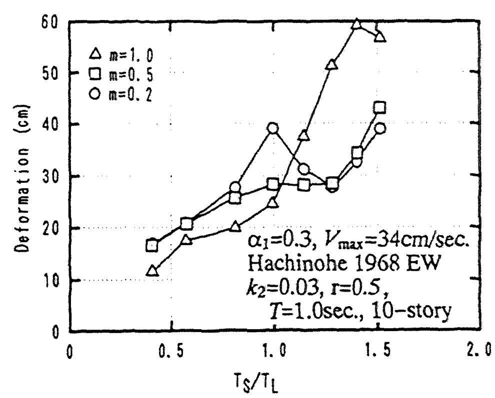

Fig.6 The Deformation of the Top Story

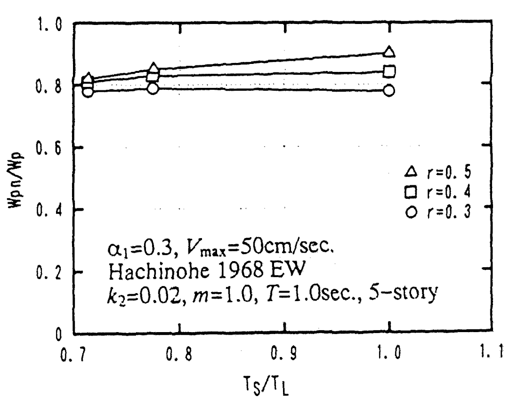

Fig.4 Energy Absorption Ratio

the top story in the same case of Fig.2. The maximum displacement increases as T_S/T_L increases. The maximum displacement for r=0.3 is greater than that for r=0.5, in case T_S/T_L less than 1.0, because the yield strength for r=0.3 of the top story is smaller than that for r=0.5 and then the plastic deformation becomes large. The results loses reality in case T_S/T_L is greater than 1.0. T_S/T_L should be less than 1.0 not to increase the top story displacement.

Fig.4 shows the results of the 5 stories frames. W_{pn}/W_p increases as r increases. This corresponds to the same tendency which takes place in 10 stories frames with T_S/T_L around 1.0 as shown in Fig.3. Increase and decrease of W_{pn}/W_p for certain r-value is small, in a wide range of T_S/T_L, because the mass of the top story is large, which is 20% of the total mass of the frame.

4.2 *The effects of the mass ratio*

Fig.5 shows the relationship between W_{pn}/W_p and T_S/T_L to the mass ratio m for the ten stories building. This figure shows three cases for m, which are m=0.2, 0.5, 1.0. W_{pn}/W_p increase as m increases. And W_{pn}/W_p has maximum when T_S/T_L is nearly 1.0 for each cases. Fig.6 shows the relationship between relative story displacement and T_S/T_L for the same case of Fig.5. The displacement increases as T_S/T_L increases up to 1.0. W_{pn}/W_p can increase more than 0.8 by tuning T_S/T_L even a small mass for m=0.5. But for m less than 0.5, it can not increase.

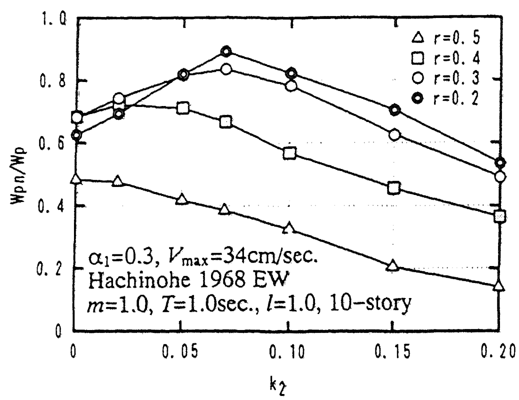

Fig.7 Energy Absorption Ratio

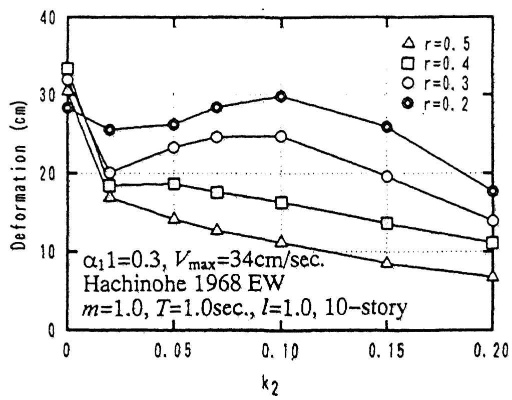

Fig.8 The Deformation of the Top Story

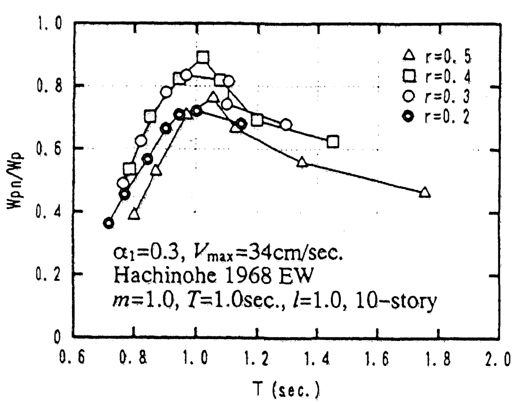

Fig.9 Energy Absorption Ratio

4.3 *The effect of the second stiffness and the shear force reduction factor of the top story*

Fig.7 shows the relationship between W_{pn}/W_p and k_2 for different r, which are from 0.2 to 0.5. W_{pn}/W_p increases as k_2 increase up to 0.7 and decreases as k_2 increases beyond 0.7 for the case of r less than 0.3. But the increment of W_{pn}/W_p does not appear for the case r greater than 0.4. The peak value of W_{pn}/W_p increases as r decreases. This figure shows that the optimum combination of r and k_2 exists which maximize W_{pn}/W_p.

Fig.8 shows the relative displacement for the top story. The displacement decreases as k_2 is varied from 0.0 to 0.02, because the displacement tend to develop towered one side for k_2=0.0. This is the special and nonrealistic case. The displacement decreases as k_2 increases for r between 0.3 and 0.5. From this figure, k_2 should be greater than 0.02 and r should be greater than 0.3 to restrain the deformation.

Fig.9 shows the relationship between W_{pn}/W_p and the equivalent natural period of the top story calculated from the mean deformation of the plus and minus maximum ones. W_{pn}/W_p is maximized when the equivalent natural period is tuned to the natural period of the system. It is found that the energy absorption of the top story is much influenced by the maximum deformation and equivalent stiffness calculated from it.

4.4 *The effect of the natural period of the system*

Fig.10 shows the relationship between W_{pn}/W_p and natural period of the system. W_{pn}/W_p is not influenced by the natural period in this range of period for the case r=0.3–0.5. Fig.11 shows the deformation of the top story for the same case of Fig.10. The displacement increases as the natural period increases and as r decreases. In case r=0.3, in which a preferable energy absorption is attained as shown in Fig.10, the deformation of the top story grows abruptly, as T increases to beyond 1.4sec.

Fig.12 and Fig.13 show W_{pn}/W_p and maximum displacement for the case T_S/T_L=1.0 respectively. By softening the top story, W_{pn}/W_p is increase as r increases, contrary to the case that the yield displacement is constant as shown in Fig.10. The deformation of the top story is large in a wide range of T, which is more than 1.0 sec., though the deformation is not large at 1.0sec., for the case that the yield displacement is constant. Because the equivalent period of this case T_S/T_L 1.0 is larger than that of the case yield displacement constant. The displacement is influenced considerably by the frequency of the system, though W_{pn}/W_p is not influenced.

4.5 *The effects of the difference of earthquakes*

Fig.14 shows the relationship between W_{pn}/W_p and the natural period under the three earthquake motions. The difference of earthquake motions makes no significant difference in the response of the system for 2 cases, which are the case displacement constant and the case T_S/T_L=1.0.

5 THE DEFORMATION AND THE ENERGY ABSORPTION OF THE TOP STORY

Based on the results described above, the following conditions are obtained, in which the energy absorption

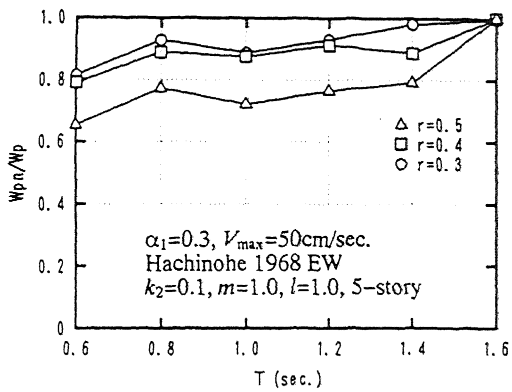

Fig.10 Energy Absorption Ratio

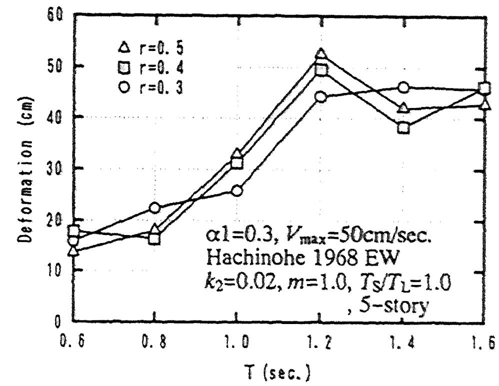

Fig.13 The deformation of the top story

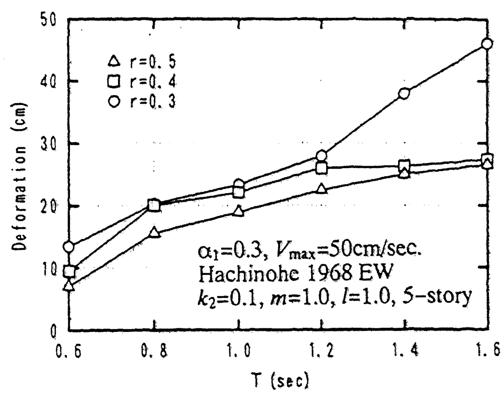

Fig.11 The Deformation of the Top Story

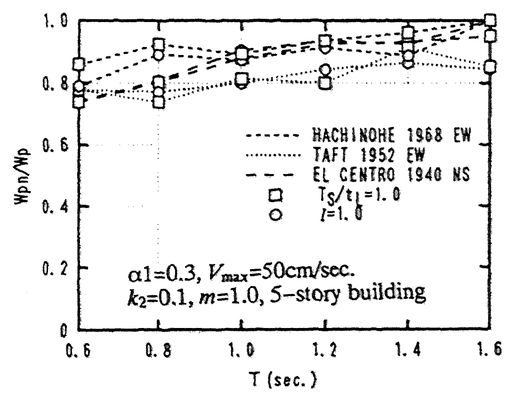

Fig.14 Energy Absorption Ratio

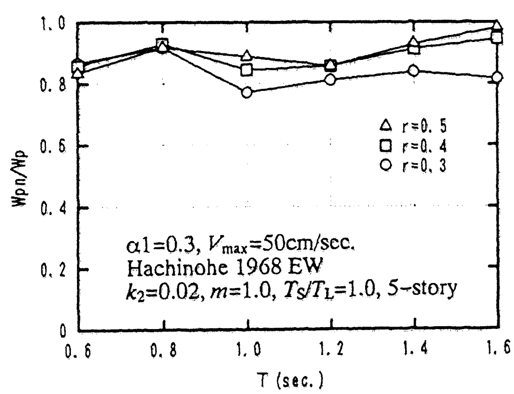

Fig.12 Energy Absorption Ratio

of the top story increases.

1. T_S/T_L of the top story is tuned to be nearly 1.0

2. The equivalent period of the top story is tuned to the natural period of the structure as a whole. The equivalent period is obtained from the top mass and the equivalent stiffness, which is the ratio of the maximum force response to the maximum deformation response.

In both cases, the energy absorption of the top story increases as the top story vibrates more similar period of the system. For condition 1, the natural period in a elastic range of the isolated top story resembles the natural period of the standard model. Because the top story has high yield strength and hasn't much plastic deformation. And for condition 2, the equivalent period of the top story is similar to the natural period of the standard model, because the natural period of the top story is elongated by the large plastic deformation which is caused by the low strength.

The energy absorption increases as r increases under the condition 1. But on the contrary, the energy absorption decreases as r increases under the condition 2. The energy absorption increases as the width of two frequencies for the top story vibration decreases, if the elasto-plastic vibration considered to consists of 2 frequency components, which are higher and lower frequency components than the equivalent natural frequency of the top story.(Akiyama 1985)

The possibility to absorb most of the energy at the top story is expected, even if the yield displacement of the top story is decreased less than the constant yield displacement type. Because the equivalent frequency can be tuned by modifying r and k_2.

In case of T_S/T_L greater than 1.0, the deformation become undesirably large under the small earthquake. In case condition 2, the deformation of the top story becomes small under small earthquake. Because the yield strength is high and the yield displacement is small.

The deformation tends to develop towered one side for k_2=0.0, which is often used on idealistic analysis. The parameter k_2 should be more than 0.02 for the investigation of deformation and for the actual building.

6 CONCLUSION

A series of numerical analysis was made on the multi story frames in which most of the total energy input due to the earthquakes is aimed to be absorbed at the top story leaving other stories undamaged. Based on the analysis, to get the highest efficiency of energy concentration at the top story, it was found that the equivalent frequency of the top story as the isolated body must be tuned to the fundamental natural period of the structure as a whole, and that the width of the frequency range must be narrowed.

It is possible to get the 80% energy absorption, even if the top mass weight is 5% of total mass, by tuning the strength and the inelastic stiffness of the top story. But considering the deformation of the top story, 10% of total mass is preferable as the top mass.

The difference of earthquake motions makes no significance in response of the system.

Then it is possible to realize the structural system which absorb most of the input energy at the top story leaving the other story undamaged. The way to absorb energy efficiently is clarified.

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