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-storey 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 nonstationarily, 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 $W_{ed}/W_p$ is defined as the ratio of the absorption energy of the top story $W_{ed}$ to the amount of the absorption energy of the building $W_p$. (Akiyama 1987) The critical shear force coefficient is shown in Eq. 1 to absorb the energy more than 80% of $W_{ed}/W_p$. 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, 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.

$$\alpha_{el} = 0.056 \alpha_{cr}$$

where $\alpha_{cr}$ : critical shear force coefficient of the 1st story to be $W_{ed}/W_p > 0.8$
$n$ : No. of the story
$\alpha_{el}$ : 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.

$$\alpha_{el} = \frac{2\pi V_s}{T g}$$

where $V_s$ : 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.
\[
\frac{W_{pn}}{W_p} = 0.8 \alpha_1 \\
\frac{W_{pn}}{W_p} = \frac{14.3 \alpha_1}{\alpha_{e1}} \tag{3}
\]

Eq. 1 and Eq. 3 becomes as follows.

\[
\frac{W_{pn}}{W_p} = \frac{14.3 \alpha_1 m_n}{\alpha_{e1} M_1} \tag{4}
\]

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

\[
\frac{W_{pn}}{W_p} = \frac{14.3 \alpha_1 m_n}{\alpha_{e1} M_1} \tag{5}
\]

In the Eq. 5, \(\alpha_1/\alpha_{e1}\) is less than 1.0. When \(W_{pn}/W_p\) is 1.0, following equation is formed.

\[
\frac{M_1}{\alpha_{e1} M_1} > \frac{1}{14.3} \tag{6}
\]

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 following 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.

\[
Q_{yi} = (1+k) r m M_1 \alpha_1 \alpha_2 \tag{7}
\]

\[
Q_{yi} = (N-i+1) M \alpha_1 \alpha_2 \tag{8}
\]

where \(Q_{yi}\) : yield strength of the \(i\)-th story

\(k\) : 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

\(\alpha_1\) : optimum yield shear force distribution ratio to keep cumulative ductility factors nearly constant to the multi degree of freedom system of the equal masses

\(\alpha_2\) : shear force coefficient of the 1st story

The yield displacement is determined to make the natural period of the system \(T = 1.0\) sec. as the standard model. The parameter \(i\), shown in Fig. 1, is the yield displacement ratio of the top story. By selecting the value of \(i\), the ratio of \(T_3/T_1\) can be arbitrarily changed.

Where \(T_3\) is the natural period of the top story isolated lower stories, and \(T_1\) is the natural period of the system without top story. As the standard model, following values are used, \(N = 5.10, r = 0.5, k = 0.0, l = 1.0\).

The variation of parameter used in this study is shown as follows.

\(r = 0.3, 0.4, 0.5\)

\(k_2 = 0.00, 0.02, 0.05, 0.07, 0.10, 0.20\)

\(l = 1.0, 2.0\) (tuning), \(l(T_3/T_1 = 1.0)\)

\(l = 1.0\) means that the yield displacement is constant for all the stories. \(l(T_3/T_1 = 1.0)\) means that the yield displacement is set to be \(T_3/T_1 = 1.0\).

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 34 cm/sec. and 50 cm/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 \(T_3/T_1\) of the ten stories building. The horizontal axis is obtained by changing the yield displacement. When \(T_3/T_1\) 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 \(T_3/T_1\) is nearly 1.0 in both cases. This shows that \(W_{pn}/W_p\) can be raised by tuning \(T_3/T_1\) 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 \(T_3/T_1\) small, \(W_{pn}/W_p\) for \(r = 0.3\) is greater than that for \(r = 0.5\), but in the case \(T_3/T_1\) 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 \(T_3/T_1\) is small. But when \(T_3/T_1\) 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. 2 Energy Absorption Ratio

Fig. 3 The Deformation of the Top Story

Fig. 4 Energy Absorption Ratio

Fig. 5 Energy Absorption Ratio

Fig. 6 The Deformation of the Top Story

The results shows that 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. $W_{pl}/W_p$ 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 $W_{pl}/W_p$ for certain $r$-value is small, in a wide range of $T_s/T_l$. 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 $W_{pl}/W_p$ 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. $W_{pl}/W_p$ increase as $m$ increases. And $W_{pl}/W_p$ 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. $W_{pl}/W_p$ 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.
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 $W_{pl}/W_p$ does not appear for the case $r$ greater than 0.4. The peak value of $W_{pl}/W_p$ increases as $r$ decreases. This figure shows that the optimum combination of $r$ and $k_2$ exists which maximize $W_{pl}/W_p$.

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 tends to develop towered one side for $k_2=0$. 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 $W_{pl}/W_p$ and the equivalent natural period of the top story calculated from the mean deformation of the plus and minus maximum ones. $W_{pl}/W_p$ 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 $W_{pl}/W_p$ and natural period of the system. $W_{pl}/W_p$ 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 1.4 sec.

Fig. 12 and Fig. 13 show $W_{pl}/W_p$ and maximum displacement for the case $T_s/T_1=1.0$ respectively. By softening the top story, $W_{pl}/W_p$ increases 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 1.0 sec., for the case that the yield displacement is constant. Because the equivalent period of this case $T_s/T_1=1.0$ is larger than that of the case yield displacement constant. The displacement is influenced considerably by the frequency of the system, though $W_{pl}/W_p$ is not influenced.

4.5 The effects of the difference of earthquakes

Fig. 14 shows the relationship between $W_{pl}/W_p$ 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 $T_s/T_1=1.0$.

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
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 an 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 $k_2$. 

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Fig.10 Energy Absorption Ratio

Fig.13 The deformation of the top story

Fig.11 The Deformation of the Top Story

Fig.12 Energy Absorption Ratio

Fig.14 Energy Absorption Ratio

of the top story increases.
1. $T_g/T_1$, 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
In case of $T_s/T_L$ greater than 1.0, the deformation becomes 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 towarded one side for $k_z=0.0$, which is often used on idealistic analysis. The parameter $k_z$ 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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REFERENCES