Response behavior of steel buildings under pulsive earthquake ground motion during inland shallow earthquake

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ABSTRACT: We study the effect of deformation control systems under pulsive earthquake ground motions. In this paper, we carried out time history response analysis for the models of equivalent SDOF system and MDOF system with hysteretic damper, viscous damper and stopper. The main findings on huge pulsive earthquake ground motion are as follows: (a) It is difficult to control deformation by damper when 1st mode response is distinguished. (b) There is a possibility of controlled unreasonable deformation by stopper.

1 INTRODUCTION

There are the active vibration control systems which control the displacement response against dynamic excitation such as earthquake motion, strong wind and so on. After 1995 Hyogoken Nanbu earthquake, it is increasing to use hysteretic and viscous dampers in Japan (Kitamura et al, 2003).

On the other hand, many buildings suffered serious damage from the pulsive earthquake ground motions observed frequent around the hypocenter of inland crustal earthquakes of late (Hayashi et al, 2009). The pulsive earthquake ground motions have obvious pulsive velocity waveforms and occur around the fault on the side of developing fault destruction.

In this paper, we study the effect of the deformation control systems under the pulsive earthquake ground motion. Here, three systems are used as the deformation control systems: hysteretic damper, viscous dampers and stopper.

2 INPUT EARTHQUAKE MOTION

2.1 Ricker wave

Ricker wave is indicated in Fig. 1(a). Ricker wave is used as the pulsive earthquake ground motion because of a simple mathematical model. Ricker wave can be written as

\[ y_0(t) = A_p (r^2 - 1) \exp(-r^2/2) \]  

\[ r = \sqrt{2} \pi (t - T_p)/T_p \]  

\[ A_p = \frac{V_p}{T_p \sqrt{2\pi}} \left(1 - \frac{1}{\sqrt{2\pi}} e^{-r^2} \right)^{-1} \]

where \( V_p \) is pulsive velocity amplitude, and \( T_p \) is pulsive period. Here, the following values are taken: \( V_p = 150 \) (cm/s), \( T_p = 2.0 \) (s), based on observation records of the latest pulsive earthquake ground motions.

2.2 Design wave

The design earthquake motion is defined in terms of acceleration response spectrum at engineering bedrock in the Building Standard Law of Japan. This wave is called design wave in this paper. Design wave is used to compare with pulsive earthquake ground motion. Acceleration waveform of design wave is indicated in Fig. 1(b) and the acceleration response spectrum of Ricker wave is shown in Fig. 1(c). Here, the time dependence characteristics

\[ \text{Figure 1. Input earthquake motion: (a) Ricker wave, (b) Design wave, (c) acceleration response spectrum of Ricker wave and design wave.} \]
are modeled on Jennigs envelope function, phase characteristics is equal random number, and ground amplification is not made allowance.

3 BUILDING MODELS

We intend for the models of equivalent SDOF system and MDOF system.

3.1 Equivalent SDOF system

The building model of equivalent SDOF system is as follow. The story height \( h_0 \) is 400 (cm), the mass of each story \( m_0 \) is 1.0 (ton⋅s^2/cm), and building stories \( N \) is gone up at intervals of 5 stories between 5th story and 50th story.

As shown in Fig. 2(a), the equivalent SDOF system is substituted for this model on the follow conditions: (a) 1st eigenmode is assumed rectinear distribution, (b) The base shear and the overturning moment is equivalent to this model. Equivalent mass \( M_e \) and equivalent height \( H_e \) can be written as

\[
M_e = 1.5M(N + 1)/(2N + 1)
\]

\[
H_e = H(2N + 1)/3N
\]

where, the building height is \( H = Nh_0 \), gross weight is \( M = Nm_0 \).

The various damping is in proportion to the initial stiffness of main frame. The initial damping factor is \( \gamma_t = 0.02 \). And hysteresis characteristics are assumed bi-linear as shown in Fig. 2(b). The yield shear force \( Q_y \) is calculated by the yield shear force coefficient \( C_y = 3/N_e \). 1st natural period \( T_1 \) can be written as

\[
T_1 = 2\pi \sqrt{\frac{R_y h_0 \cdot N(N + 1)}{6g}} = \frac{2\pi}{21} \sqrt{\frac{N(N + 1)}{5}}
\]

where, yield deformation angle is \( R_y = 1/150 \)(rad).

3.2 MDOF system

The building model of MDOF system is as follow. \( m_0 \) and \( h_0 \) are equal in value to equivalent MDOF system. The elastic stiffness ratio of 1st story to top story is 3 to 1, stiffness of each story is assumed rectinear distribution, and 1st natural period is \( T_1 = 0.0003 Nh_0 \). And hysteresis characteristics of each story are assumed bi-linear, yield deformation angle is 1/150 (rad), and the stiffness ratio of yield stiffness to elastic stiffness is 0.01. The internal viscous damping is in proportion to initial stiffness. The damping factor is 0.02. Here, 1st natural periods and yield base shear force coefficient \( C_y \) are shown in Table 1, and these are equal to relation between \( T_1 \) and \( C_y \) in equivalent SDOF system.

<table>
<thead>
<tr>
<th>Stories</th>
<th>1st [s]</th>
<th>2nd [s]</th>
<th>3rd [s]</th>
<th>Yield base shear force coefficient: ( C_y )</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1.20</td>
<td>0.45</td>
<td>0.28</td>
<td>0.44</td>
</tr>
<tr>
<td>40</td>
<td>4.80</td>
<td>1.76</td>
<td>1.07</td>
<td>0.10</td>
</tr>
</tbody>
</table>

The relation between the yield shear force coefficient \( C_y \) and 1st natural period \( T_1(s) \) is illustrated in Fig. 3, for reference. The circles indicate the relation between base shear coefficient \( C_b \) for allowable stress on temporary loading design of highrise steel structures and natural period \( T \) (Saito, 2004). The solid line indicates \( R_1C_0 \) curve at \( C_0 = 0.2 \) for soil type 2 (Japan) on 1st design of allowable stress calculation. The fine solid line with squares indicates \( C_y \) in model of equivalent SDOF system. \( C_y \) is distributed the range from about once to twice \( R_1C_0 \) curve. \( C_y \) is a little more than twice \( R_1C_0 \).

![Figure 2. Equivalent SDOF system: (a) Model of the system, (b) Hysteresis characteristics of main frame.](image-url)
4 DEFORMATION CONTROL SYSTEM

We take up hysteretic damper, viscous damper and stopper as deformation control system with main frame. Stopper is possible to restraint large deformation. The hysteresis characteristics of hysteretic damper and stopper added to model of equivalent SDOF system is shown in Fig. 4. Here, changed $H_e$ into $h_p$, this also become hysteresis characteristics of MDOF system.

4.1 Hysteretic damper

The hysteresis characteristic of hysteretic damper is assumed bi-linear accruing on early yield, and yield deformation angle is certain value: $R_y = 1/1500 \text{(rad)}$. The yield shear force ratios of hysteretic damper to main frame are $\beta = 0.1, 0.2$.

4.2 Viscous damper

The stiffness of viscous damper is enough small to neglect. The various damping is in proportion to initial stiffness of the main frame. The damping factor is $h = 0.02, 0.05$. The damping matrix $[C]$ can be written as

$$[C] = \frac{h \cdot T_1}{\sigma} [f \, K]$$

(7)

4.3 Stopper

Stopper is thought as the system which has some effect to control large deformation. This is the system added spring to gap, and demonstrates stiffness in case of exceeding certain deformation angle. The demonstrated deformation angle is certain value: $R = 1/100 \text{(rad)}$. The ratios of stopper’s stiffness to main frame’s initial stiffness are $\beta = 0.2, 0.5$.

5 TIME HISTORY RESPONSE ANALYSIS

In this chapter, we conduct time history response analysis with the models of equivalent SDOF system and MDOF system.

In analysis of equivalent SDOF system, we focus on maximum story deformation angle $R_{\text{max}}$ to grasp the damaged degree of building, compare only main frame with ones added each deformation control systems, and study the effect of deformation control systems. Based on Newmark $\beta$ method, $\beta = 0.25, 0.5$ are taken.

It is supposed that response of equivalent SDOF system is 1st mode, and not able to examine the effect of more than 2nd mode. Therefore we use the model of MDOF system. In MDOF system, based on Wilson $\beta$ method, $\beta = 1.5$ is taken. Here, two models in case of $N = 10, 40$ are used on behalf of models.

Both analyses are done at intervals of 0.005 (s).

5.1 Model of equivalent SDOF system

In this section, we present the analysis result for equivalent SDOF system.

5.1.1 Viscous damper

The relation between $T_1$ and $R_{\text{max}}$ with viscous damper is shown in Fig. 5. In case of $h = 0.05$, all models are within the elastic limits to design wave. The models of $N = 10, 15$ respond about 1/30 (rad) to Ricker wave.

And so, we focus on the model of $N = 10$ which decrease the response most. Time history response about energy in case of hysteretic damper is shown in Fig. 7(a). Here, damping consumption energy is

![Figure 4. Hysteresis characteristics of hysteretic damper and stopper as deformation control system.](image1)

![Figure 5. Maximum response deformation angle with viscous damper: (a) Design wave, (b) Ricker wave.](image2)
the total input energy decrease about 30% at total input energy. In case of hysteretic damper, the natural period is shorter, \( T = 0.81–1.27 \) (s) is plotted in. Because of added damper, the natural period is shorter, \( T = 1.4 \) (s) and yield shear force \( \beta \) on main frame, for reference. Added deformation control system, \( R_{\text{max}} \) change smaller in especially the story damage fixed on without the system.

5.1.3 Stopper
The relation between \( T_1 \) and \( R_{\text{max}} \) with stopper is shown in Fig. 9. Because of \( R = 1/100 \) (rad), stopper don’t act on design wave. The maximum response acceleration \( A_{\text{max}} \) for Ricker wave is shown in Fig. 10. In case of Ricker wave, the bigger \( R_{\text{max}} \) model has, the more \( R_{\text{max}} \) can be gone down, but \( A_{\text{max}} \) also increase drastically. For instance, added stopper on \( \beta = 0.5 \). \( R_{\text{max}} \) is less than 1/30 (rad) in the model of \( N = 15 \) which has the biggest response. Then \( A_{\text{max}} \) with stopper is about twice as much as one without stopper.

5.2 Model of MDOF system
In this section, we present the analysis result of MDOF system.

In case of only main frame or ones with deformation control system on \( N = 10, 40 \), deformation angle distribution as height for Ricker wave are shown in Figs. 11 and 12. The gray bold solid line in Figs. 11(b) and 12(b) indicates the elastic response of only main frame, for reference. Added deformation control system, \( R_{\text{max}} \) change smaller in especially the story damage fixed on without the system.

\[
W_a, \text{ potential energy is } W_p, \text{ hysteresis consumption energy is } W_h; W_s \text{ on damper and } W_r \text{ on main frame, and kinetic energy is } W_k. \text{ These are lost dimension by equivalent height } H \text{ and yield shear force of main frame } Q, \text{ and express with apostrophe.} \]

Next, Fig. 7(b) shows time history response about total input energy. In case of hysteretic damper, the total input energy decrease about 30% at \( t_{\text{max}} \). It is said that decreasing response isn’t caused by the energy consumption of damper. 

\[
A_{\text{max}} \quad \text{ with stopper}
\]

\[
R_{\text{max}} \quad \text{ without stopper}
\]

\[
S_a (\text{Gal})
\]

\[
W_s \quad \text{ on damper and } W_r \text{ on main frame}
\]

\[
W_k \quad \text{ kinetic energy is } W_k
\]

\[
W_h \quad \text{ hysteresis consumption energy is } W_h
\]

\[
W_p \quad \text{ potential energy is } W_p
\]

\[
\beta = 0, 0.2, 0.5
\]

\[
\beta = 0, 0.2, 0.5
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\beta = 0, 0.2, 0.5
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\beta = 0, 0.2, 0.5
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\beta = 0, 0.2, 0.5
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\beta = 0, 0.2, 0.5
\]
With hysteretic damper, the response decrease drastically in $N = 10$. Similarly to equivalent SDOF system, the natural period is shorter, the response of more story models decrease hardly: for instance, the model of $N = 20$ as shown in Fig. 13. There is tendency that response decrease on the whole in $N = 40$. This is different from equivalent SDOF system.

Viewed in modal analysis, story difference of 1st-3rd participation function are shown in Fig. 14 to compare directly with $R_{\text{max}}$ distribution, 1st-3rd natural periods in $N = 10,40$ are shown in Table 1, and displacement response spectrum as Ricker wave is shown in Fig. 15. In consideration of the period increase by plasticity, it is greatly influenced by 1st mode in $N = 10$, 2nd mode in $N = 40$.

With stopper, $R_{\text{max}}$ of the upper stories increase but one of the bottom stories decrease on $N = 10$. The maximum shear force $Q_{\text{max}}$ distribution as height is shown in Fig. 16. In $\beta = 0.5$, There are
some stories that shear force which stopper owed is about the same as one which main frame owed. So, when stopper is used in practice, the points to be consideration are follow measures: (a) Owed some shear force, stopper yields, and (b) the strength of stopper joints is become stronger.

6 CONCLUSIONS

We study the effect of the deformation control systems under the pulsive earthquake ground motions. Here, three systems are used as the deformation control systems: hysteretic damper, viscous dampers and stopper.

The main findings include:

− The main frame with damper is controlled the deformation under the input wave which has the level of earthquake motion and duration time like the design wave.

− Under huge pulsive earthquake ground motion, the main frame with damper is reduced the concentrated damage a little. But, it is difficult to control the deformation when 1st mode response is distinguished.

− There is a possibility of controlled unreasonable deformation against huge pulsive earthquake ground motion by stopper. But the more effective stopper is, the larger the peak floor acceleration values are, and it can’t prevent the contents from suffering damage. So, the designers need to decide appropriate stopper’s stiffness.

REFERENCES

