DESIGN METHOD OF ISOLATING AND ENERGY DISSIPATING SYSTEM FOR EARTHQUAKE RESISTANT STRUCTURES

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SUMMARY

This paper suggests a new design method for earthquake resistant structure using isolating and energy dissipating system. This method is based on shaking table tests and dynamic analysis. A series of experiment on the shaking table have been carried out with a 1/4 scale steel frame. Different sine-wave waveforms and simulated earthquake records were input to shaking table. Different kinds of energy dissipating devices were mounted in structure. Comparing the theoretical results with the testing results shows that both values are very nearly, means the method presented by authors is reasonable and suitable for practical engineering design.

INTRODUCTION

The isolating and energy dissipating system consists of structure, isolating and energy dissipating devices mounted between the structure and ground. It can effectively isolate the structure from ground motion in earthquake, offer high damping to dissipate the energy transmitted to the structure. So it can attenuate the structure response to very small value from ground motion, then prevent whole structure to be destroyed in a severe earthquake attack. This gives engineers a new way for design of earthquake resistant structure. But it is very needful to have an quantitative, reliable and simple method accepted by engineering design.

The method presented by authors uses acceleration control to limit the structural response in earthquake. Depending on the importance of building which relating to different requirement of safety, and the seismic zone the building located which relating to different possible maximum acceleration spectrum values, design an isolating and energy dissipating system which acceleration response can be limited to an acceptable level. In that case, the structure response in severe earthquake is nearly as same as in minor earthquake or wind load, and the structure may work nearly in elastic range only. The whole building, including structure, interior component, decoration, building content, instrumentation and so on, are fully prevented from damage during a severe earthquake attack. Also, the design procedure would change from designing a whole structure for earthquake resistance to only designing an isolating and energy dissipating device. The designing procedure becomes very simple.
The method is based on a series of experiments on the shaking table and dynamic analysis. The testing results show that this new method is very reliable and suitable for practical engineering design.

BASIC SYSTEM AND MATHEMATICAL MODEL

There are four kinds of isolating and energy dissipating devices (Fig. 1) are used in general engineering design:

1. Roller isolator combines with mild steel component energy dissipater (Ref. 1, 2).
2. Rubber pads isolator combines with leadplug dissipater (Ref. 3, 4).
3. Sand layer (Ref. 5)
4. Friction damper (Ref. 6)

Four parameters can be found in any isolating and energy dissipating system:

1. Structural mass $M$
2. Load-displacement curve of device (Fig. 2) given from pseudo statical testing of steel component.
3. Elastic stiffness $K$ of device given from load-displacement curve (Fig. 2).
4. Equivalent viscous damping $C_e$ of energy dissipating device given from the area enclosed by load-displacement curve (Fig. 2).

The structure responds to earthquake motion primarily as a system of single degree of freedom because the structure is very rigid comparing with the soft layer of isolator and energy dissipater (Ref. 1). A mathematical model with $M$, $K$ and $C_e$ is shown in Fig. 3. If the ground acceleration response $X_g$ is known, then the structural acceleration response $X_s$ and maximum relative displacement $D$ can be controlled by designing a suitable isolating and energy dissipating device using the method suggested in this paper.

SHAKING TABLE TESTS

The tests were carried out on an earthquake simulator table which has a floor dimension of 10ft·10ft. The overall dimension of four stories steel frame is 10ft·4.6ft in plan and 12.8ft high. The total mass of structure and loading concrete blocks are 16 kips, see Photo. 1.

The roller and mild steel curved plates were used as isolating and dissipating device (Photo. 2). Five kinds of curved plates were tested. A series of pseudo tests were finished for curved plates (Ref. 1, 7) before shaking table tests. Four sine-waveforms (Freq. $w=1.0, 2.0, 3.0, 4.0, Hz$) and three simulated earthquake records (EL Centro, Sanferando, Parkfield) were inputed to the shaking table, which predominant Freq. $w$ was found from the Fourier spectra of acceleration record.

Four accelerometers were used to measure the structure acceleration response $X_s$ at every stories of structure. The relative displacement $D_s$ between the first story column and the shaking table was measured with linear variable differential transformer (LVDT). All of the measured data were then processed by a computer with a operating software system.

DYNAMIC ANALYSIS AND FORMULA

Equivalent damping ratio $E$. From Fig. 3, the basic differential equation of motion is given as:
\[ M \ddot{X}_s + C_\epsilon \dot{X}_s + K X_s = C_\epsilon \dot{X}_s + K X_s \]  

(1)

where \( M \) is the structural mass, \( C_\epsilon \) is the equivalent viscous damping of isolating and energy dissipating system, \( K \) is the elastic stiffness of isolating and energy dissipating system. \( X_s, \dot{X}_s, \ddot{X}_s \) are the ground response of displacement, velocity and acceleration respectively in earthquake. \( X_s, \dot{X}_s, \ddot{X}_s \) are the structure response of displacement, velocity and acceleration respectively in earthquake.

Define \( E_* = \frac{C_\epsilon}{2MW_s} \) as EQUIVALENT DAMPING RATIO,

\[ w_s = \frac{K}{M} \]  

as the NATURAL FREQUENCY of system.

Solve Eq.(1) with finding transfer function and get:

\[ E_* = \frac{1}{2(w/w_s)} \sqrt{\frac{1-AR'}{AR'^2 - 1}} \]  

(2)

where \( AR' = \frac{\ddot{X}_s}{\dddot{X}_s} \) is called ACCELERATION ATTENUATION of system.

Maximum relative displacement \( D_r \) From Fig.3, the basic differential equation of motion can be written:

\[ M \ddot{D}_s + C_\epsilon \dot{D}_s + K D_s = -M \ddot{X}_s \]

where \( D_s, \dot{D}_s, \ddot{D}_s \) are maximum relative displacement, velocity and acceleration respectively between structure and ground.

Solve this equation with finding transfer function and get:

\[ D_s = \frac{\ddot{X}_s}{w_s} \sqrt{\frac{1 - AR'}{(w/w_s)^2 - 2}} = X_{s*} \cdot r \]  

(3)

Define

\[ r = \sqrt{\frac{(1-AR')}{(w/w_s)^2 - 2}} \]  

as DISPLACEMENT FACTOR

Comparing the theoretical value \( D_s \) with measuring value \( |D_s| \) from tests (Table 1) show that the \( \frac{D_s}{|D_s|} = 0.98-1.67 \), \( D_s \) are almost all greater than \( |D_s| \). I means Eq.(3) is suitable and conservative in designing.

Acceleration attenuation ratio \( AR' \) The damping ratio \( E_* \) is related to the area enclosed by the hysteresis loop and find:

\[ E_* = \frac{C_\epsilon}{2MW_s} = \frac{2(1 - 1/U)}{\pi U} \cdot \frac{1}{(w/w_s)} = B \cdot \frac{1}{(w/w_s)} \]  

(4)

Define

\[ B = \frac{2(1 - 1/U)}{\pi U} \]  

as ENERGY DISSIPATION DAMPING RATIO

\[ U = \frac{D_s}{D_r} \]  

as DUCTILITY FACTOR

The value of \( B \) represent the basic value of \( E_* \), and depends on the value of \( U \).

Substitute Eq.(4) into Eq.(2) and get:

\[ AR' = \frac{\ddot{X}_s}{\dddot{X}_s} = \frac{1 + 4B'}{\sqrt{4B' + (1 - (w/w_s)^2)}} \sqrt{w_s} \]  

(5)
This is the final expression of ACCELERATION ATTENUATION AR

Now, comparing the theoretical values AR from Eq.(5) with the measured values [AR], shown in Fig.4.5 and know:
(a) The ratio AR/[AR] approaches 1.0, it means that Eq.(5) gives reasonable estimation.
(b) The theoretical values AR are always larger than measured values [AR], it means that Eq.(5) gives conservative results for practical design.

CONCLUSION

1. The design method of isolating and energy dissipating system suggested by authors is very reasonable and simple. Knowing the site maximum acceleration response $X_0$, suggesting allowed structural acceleration response $X_a$ and the relative displacement (D_a), design the isolator and energy dissipator with yielding force $P_y$, yielding displacement $D_y$ and elastic stiffness $K$ (Fig.2). Using Eq.(3),(5) get AR and D_a. If AR < $X_a/X_0$, D_a < (D_a), then it is satisfied.
2. The formulas presented in this paper can be used in practical design with enough safety.
3. This method not only can be used in general structures, but also in special structures (such as pools, tanks, towers and pipe line etc.), many kinds of equipment and instrumentation for earthquake resistant design.

REFERENCES

1. Roller and Steel Plate  
2. Leadplug-rubber  
3. Sand Layer  
4. Friction Damper

Fig. 1. Isolating and Energy Dissipating Devices

Fig. 2. Load-Disp. Loop  
Fig. 3. Mathematic Model

Fig. 4. Attenuation Ratio over Frequency Ratio for Sinusoidal Excitation

Fig. 5. Attenuation Ratio over Frequency Ratio for Earthquake Excitation
### Table 1. Displacement Ratios for Different Frequencies of Sinusoidal Excitation and Different Energy Dissipator

<table>
<thead>
<tr>
<th>Energy Dissipator</th>
<th>Frequency of Sinewave Inputed (Hz)</th>
<th>w/w₀</th>
<th>(\frac{\ddot{X}_e}{X_e}) from Tests</th>
<th>r</th>
<th>(\Delta_u) from Eq.(3)</th>
<th>(\Delta_u) from Tests</th>
<th>(\frac{\Delta_u}{\Delta_u'})</th>
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