

# EARTHQUAKE RESISTANCE OF REINFORCED CONCRETE BUILDING CONTROLLED BY DEVICE WITH HARDENING TYPE HYSTERESIS

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# SUMMARY

In this study, the authors propose a new building structure system, which has an energy absorption device with a force-displacement relationship of hardening type hysteresis. This device absorbs energy during a moderate earthquake by the viscoelastic damper component. And in case of a severe earthquake, the displacement limiter component controls the excessive deformations.

In the design stage, generally, the collapse mechanism of the beam yielding type is considered. This design concept is based on, spending the input energy of the earthquake with the absorption capacity of the yielding beam member. In this case, large damage will arise to the structure. And, when a severe earthquake with long duration time and period occurs, resonance arises in the building and excessive damage may be received.

When this proposed system is applied on a multi-story building subjected to a severe earthquake, if the deformation is exceeded in a specific story, the displacement limiter operates and the displacement of the story is controlled. Hence the expansion of the damage is prevented.

# **INTRODUCTION**

In this study, the model of a reinforced concrete building was used with the device of a new proposal installed in it, and detailed time history nonlinear response analysis is carried out [1]. Consequently, the response of the building was reduced by energy absorption of the viscoelastic damper when subjected to a moderate earthquake, and habitability and restoration performance improved.

It is noticed that, during a severe earthquake when the deformation of a specific story becomes larger comparatively, the limiter operates and controls the deformation of that story. As a result, the deformation concentrated on specific stories is dispersed on all stories and exceeding damages are prevented. Furthermore, the deformation of the viscoelastic damper is limited in the allowable strain range.

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#### ANALYSIS MODEL

### **Building Model**

The building model is shown in Figure 1. It is a 4-story model of pure framed structure with  $3 \times 4$ -span. The building has the column section of 600mm × 600mm and the beam section of 400mm × 700mm for a typical floor. The building mass was considered to be 518.4 tons for each floor.



**Figure 1. Building Model** 

A static push over analysis was carried out towards the frame model and the story shear force–relative displacement relation was modeled in tri-linear, which is shown in Figure 2. The modeled hysteresis characteristics results are shown in Table 1. For the following analysis, the multi-mass shear system, which has such hysteresis characteristics, was used as the building model. Where  $k_0$ ,  $\delta c$ , Qc,  $\delta y$  and Qy are initial stiffness, cracking displacement, cracking force, yielding displacement and yielding force, respectively.



Figure 2. Story Shear Force – Relative Displacement Relationship

Story	$k_0(kN/m)$	δc (mm)	Qc (kN)	δy (mm)	Qy (kN)
4	699100	1.3	872	11.6	2732
3	696100	1.6	1134	22.1	4487
2	714300	1.8	1315	28.8	5796
1	669100	2.7	1830	40.4	6803

## **Table 1. Hysteresis Characteristics**

## **Steel Braces**

Steel braces are used on the buildings as earthquake resisting reinforcement members. In this study, the energy absorption devices were installed through the exact points of the building model by using these steel braces, which are shown in Figure 3. The steel braces sections were selected to be  $H-200\times200\times8\times12$ . When two H steel members are considered as one set, the horizontal stiffness of the set has been computed to be 330500kN/m and the shear yielding strength is 2161kN. For this study, buckling effects were neglected.



**Figure 3. Installation of the Steel Braces** 

As shown in Figure 3, such steel braces were installed at six points in the first and the second floors and four points in the third and the fourth floors. Steel braces were used aiming two main purposes. First one is to fix them on the building and let them behave like an earthquake resisting reinforcement member and second one is to use them as the supporting component of the system.

### **Viscoelastic Damper**

The viscoelastic damper mentioned in this paper is made of acrylic polymer viscoelastic material, which operates from the small deformation levels. Force as well as absorbed energy is proportional to the shear area and inversely proportional to the thickness d. Figure 4 shows the basic mechanism of the viscoelastic damper. When the viscoelastic damper is subjected to a harmonic excitation, an elliptical hysteresis loop is obtained for the relationship between shear deformation and shear force. Figure 5 shows the hysteresis

loop of the viscoelastic damper. The area of the hysteresis loop gives the energy absorbed by the viscoelastic damper.



Figure 4. Basic Mechanism of Viscoelastic Damper



Figure 5. Hysteresis Loop of Viscoelastic Damper

The viscoelastic damper has the characteristics, which depend on the changes in frequency and temperature [2]. In this paper, 4-elements model was used for the viscoelastic damper, which considers the frequency-dependent properties shown in Figure 6 [3] and the temperature was assumed to be constant. (T= $20^{\circ}$ C)



**Figure 6. 4-elements Model** 

It is decided to arrange the amount of the viscoelastic material installed in each story of the building model to be the same. Table 2 shows the amount of the viscoelastic material installed in each story of the building model. Where  $\gamma_{allow}$  is allowable shear strain of the viscoelastic material. As the number of the steel braces among the stories is not the same, the viscoelastic material's number of the layers was adjusted due to get the same amount in each story. The allowable shear strain of the viscoelastic material is 300%. For this study, the allowable shear deformation was calculated to be 51mm. The parameters of 4-elements model for this amount of the viscoelastic material are shown in Figure 6.

Story	Shear Area (mm <sup>2</sup> )	Thickness	Number of	$\gamma_{ m allow}(\%)$	Number of
		(mm)	Shear Surface		Installation
4	500×340	17	6	300	4
3	500×340	17	6	300	4
2	500×340	17	4	300	6
1	500×340	17	4	300	6

**Table 2. Amount of Viscoelastic Material** 

### **Cushion Material**

When the building is subjected to a severe earthquake, the steel brace used as the support member of the viscoelastic damper touches the limiter. The steel brace is designed to be a component of the vibration control system. However when the steel brace touches the limiter, it behaves like it is fixed on the building and acts like an earthquake resisting reinforcement member. This behavior of the steel brace prevents the exceeding deformation and damage as well. But this touch causes impact in the building. The cushion material is used to relief the shock in the impact. The cushion material is made of rubber. Three layers of cushion materials with dimensions of  $194 \text{mm} \times 194 \text{mm}$  were used in this study. Hysteresis model of three layers cushion material was obtained by the previous studies about the characteristics of single layer of cushion materials (Figure 7).



Figure 7. Cushion Material and Hysteresis Model for Three Layers

# ANALYSIS CONDITIONS

#### **Ground Motions**

For input earthquake acceleration data, a simulated earthquake ground motion corresponding to the response spectrum specified in the Japanese Code was used. The ground was assumed to be the second type of soil and the ground amplification coefficient given in the Japanese Code was taken into consideration. Phase angles of simulated ground motions were given by uniform random values and Jennings type envelope function. Acceleration time history is shown in Figure 8 and acceleration response spectrum is shown in Figure 9. Where, WaveL and WaveS are the simulated waves with long duration time and that with short duration time, respectively.



Figure 8. Acceleration Time History of Input Ground Motions



Figure 9. Acceleration Response Spectrum of Input Ground Motions

In this study, two levels of earthquake intensity were considered. For the sever earthquake, the simulated earthquake ground motion, mentioned above was used. And for the moderate earthquake, 50% of the severe earthquake's acceleration input data was used.

## **Building Model for Analysis**

Four types of building model were used for analysis.

Type 1. Prototype Building

Type 2. Building with fixed Steel Braces

Type 3. Building with Viscoelastic Damper supported by Steel Braces

Type 4. Building with Viscoelastic Damper and Limiter supported by Steel Braces

Type 4 is shown as an example of the building models in Figure 10.



Figure 10. Building Model for Analysis (Type 4)

The equation of motion is obtained as follows:

$$[M] \{\Delta \ddot{x}\} + [C_f] \{\Delta \dot{x}\} + [K_f] \{\Delta x\} = -[M] \{\Delta \ddot{x}_0\} - \{\Delta F\}$$

$$\tag{1}$$

Where,  $\Delta F$  is the external force terms vector representing the resisting force of viscoelastic damper and limiter. It is a compensation force, obtained by using the damping term of the current step and the residual terms calculated by the response values of the previous step [4] [5].

Even if there occurs an excessive response, the steel brace is assumed not to yield, and is supposed to behave elastic.

The value of the limiter's Gap of each story was arranged as follows.

Case A: Response maximum displacement for moderate earthquake input

Case B: Displacement, obtained by using external forces assuming yield base shear coefficient,  $C_B=0.33$ . Determination of external force is based on Ai distribution. Here, Ai denotes "vertical distribution factor" of story shear coefficients defined in Japanese Code.

These arrangements of Gap values make the limiters to operate in all stories almost at the same time. Gap values for Case A and Case B for each story are shown in Table 3.

Story	Case A (mm)	Case B (mm)
4	7.5	11.1
3	16.7	21.5
2	23.2	28.5
1	30.5	40.4

#### Table 3. Gap values

#### **RESPONSE RESULTS**

Analysis was performed using two types of simulated ground motions as input ground motions, WaveL and WaveS. First of all, the hysteresis loop for the moderate earthquake was found out and is shown in Figure 11, and maximum response values are shown in Figure 12. During a moderate earthquake, the displacements of the dampers do not reach the Gap value, therefore Type3 and Type4 building models behave identical.



Figure 11. Story Shear Force – Relative Displacement Relationship (Moderate Earthquake)



Figure 12. Maximum Responses (Moderate Earthquake)

As shown in the above figures, building structures of all stories yielded in the case of Type 1 for both WaveL and WaveS. And especially at the first and the second stories large displacements arised. And as Type 2 has a high stiffness value, the relative displacement values of all stories were reduced. However the response of story shear force is almost larger two times more than the other types in comparison.

Although this study assumes the steel braces to be elastic, the high valued story shear force will cause early yielding of the steel braces actually. Therefore, larger displacements will occur in the building as well. And for Type 3, relative displacements of all stories were found under the yielding values. That is because viscoelastic damper was installed and damping of the structure increased in this case. Moreover, the story shear force didn't increase comparing Type 1, and it was found out that steel brace didn't yield, as well.

In the next step, the hysteresis loop of severe earthquake is shown in figure 13, and maximum response values are shown in Figure 14. In the case of Type 1, it was found out that the relative displacement of the first story almost proceeded to the region of the ductility factor 5. Although responses were decreased in Type 3 comparing with Type 1 due to the increase in the damping, relative displacement was concentrated on the first and the second stories. Hence the shear strains of the viscoelastic materials have been calculated as 369.2% for the first story and 304.5% for the second story in the case of WaveL, and 355.5% for the first story in the case of WaveS and they exceeded the 300%, allowable shear strain of the viscoelastic material.

As opposed to these, Type 4 building's relative displacement for the first two stories obviously reduced comparing with Type 3 building. Only the first story exceeded the allowable shear strain for the viscoelastic material in Case B. Furthermore, in Type 4, the deformation concentrated on the first and the second story dispersed in each story, and deformation concentration to the specific story was prevented, and this means that the expansion of the damage was prevented. On the other hand, as the absolute value of the story shear force increases in Type 4 for a severe earthquake, it is still less than the story shear force level of Type 2 subjected to the moderate earthquake, and the steel brace didn't yield, either.



(a) Type 1

(b) Type 3

(c) Type 4: Case A

Figure 13. Story Shear Force – Relative Displacement Relationship (Severe Earthquake)



Figure 14. Maximum Responses (Severe Earthquake)

#### CONCLUSIONS

In this study, the behavior of a reinforced concrete building controlled by a device with hardening type of hysteresis was investigated. By the results of analytical studies, the effects of the proposed vibration controlling system on the building model were observed. The results can be summarized as follows.

1. Response for the moderate earthquake:

By installing the viscoelastic damper in the building model, damping of the structure increases and the relative displacements of all stories are reduced under the yielding displacement. Moreover, the acceleration response of the building decreases and this improves the habitability of the building as well.

2. Response for the severe earthquake:

The proposed system, which has an energy absorption device with hardening type of hysteresis, successfully prevents from the exceeding displacement in all stories of the building model. Furthermore, the concentration of deformation in specific stories is prevented without much increase in acceleration response. The energy absorption property of the viscoelastic damper and the deformation controlling property of the limiter are combined to disperse the concentrated deformations. Hence the expansion of the damage can be avoided effectively.

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