PROPOSAL OF SOFT-ELASTIC BUILDING STRUCTURE WITH HIGH CAPACITY DAMPER

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SUMMARY

This paper proposes an earthquake resistant VE-frame having slender columns, which are effective in terms of space use and cost, and viscoelastic dampers (VED). In order to design such a frame, it is necessary to evaluate the required number of dampers, which satisfies the allowable displacement during an earthquake, and the axial force imposed on the column near the damper: a method for evaluating these values is presented as well in this paper.
A 20-story frame having slender columns was designed based on the proposed method. Conventional frame and VE-frame with non-slender columns were also designed for comparison. It was verified by the dynamic analysis that these two VE-frames maintain the elasticity even when exposed to earthquakes. Especially the proposed structure enables the diameter and mass of steel of column to be reduced to two-thirds and 60 % of the normal VE-frame, respectively.

INTRODUCTION

Nowadays, earthquakes cause serious economical damages, even if the lives of the occupants are protected. Therefore it is essential to establish an earthquake resistant technology capable of maintaining elasticity of structures when struck by a large earthquake. Use of dampers has attracted considerable interest in designing such buildings [1), 2)] .
This paper proposes an earthquake resistant VE-frame having slender columns and viscoelastic dampers (VED). Although slender columns are effective in terms of space use and cost, it may be necessary to deploy dampers in large numbers to reduce displacement during earthquakes. It is also expected that slender columns could not withstand the axial force caused by provision of dampers. In this paper, a method for evaluating the number of dampers and axial forces imposed on columns is proposed. A 20-story frame having slender columns was designed based on this method. Conventional frame and VE-frame with non-slender columns were also designed for comparison.

SEISMIC DESIGN FORCE

Figure 2.1 (a) shows the acceleration response spectrum for design. As described in section 3, the seismic design force is defined as lateral static force based on this spectrum. This section explains the input earthquake motion for the dynamic analysis based on this spectrum. The input wave is calculated from the target spectrum and phase. The target spectrum is defined as velocity response spectrum shown in Figure 2.1(b), and the phase is calculated from the phase difference conforming to normal distribution.
The damping effect is given as equation (A-3). Figures 2.2 and 2.3 show the target spectrum and time history, respectively.

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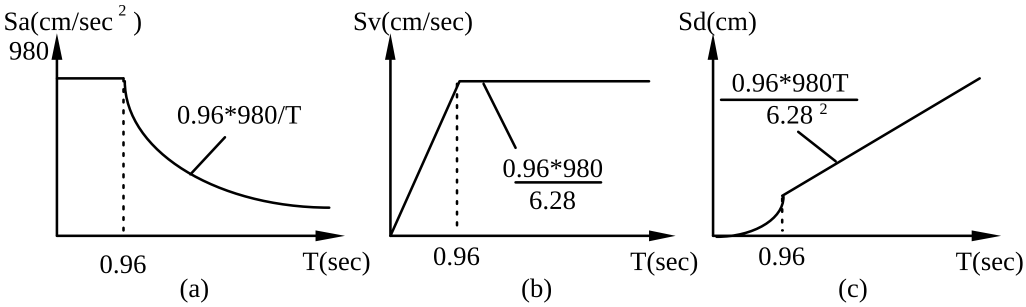

Fig.2-1 Simplified Input Spectrum

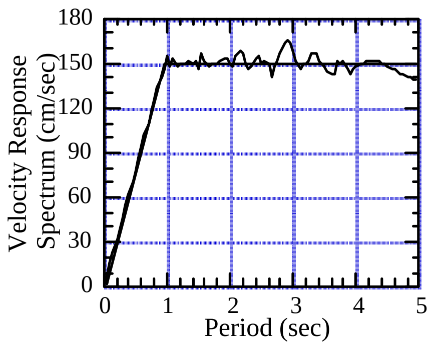

Fig.2-2 Target and Simulated Spectrum

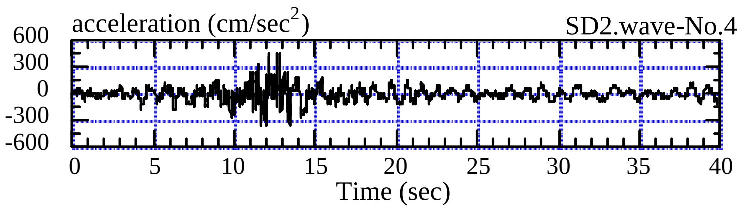

Fig2-3 Time history

STIFFNESS AND DISPLACEMENT OF STRUCTURES

This section explains seismic design force, and stiffness and displacement of conventional frame. Especially discussed is a steel buildings, where the mass and height of each layer are constant. Damping ratio is set to 0.02. Design story force is defined as follows :

$$Q_i = A_i\, Rt\, Co\, Wo\, (N+1 - i) \tag{3.1}$$

where

$$A_i=1+(1/\sqrt{[\alpha_i]} - \alpha_i)\, 2T/(1+3T) \tag{3.2}$$

$$\alpha_i=(N+1 - i)/N \tag{3.3}$$

$$Rt=0.96/T \quad (T > 1.0) \tag{3.4}$$

$$T=0.03H=0.03\,(0.01Nho) \qquad (\text{unit of H : m , unit of ho : cm }) \tag{3.5}$$

$$Co=1.0 \tag{3.6}$$

where, Qi, Wo and ho are design shear force, weight and height of each layer, and H, T and N are height of building, natural period of the first mode vibration and number of stories, respectively.

The stiffness of the first story is given in the following equation by assuming that the first mode is inverted triangle:

$$K_1=2(3.14)^2N(N+1)Wo/(T^2g) \tag{3.7}$$

Stiffness of other stores are calculated as follows:

$$K_i= Q_i/d \tag{3.8}$$

where d is the interstory displacement and constant.

Interstory displacement d and interstory deflection angle R are expressed as follows:

$$d=Q_1/K_1=2/(N+1)*Sd \tag{3.9}$$

$$R=d/ho=2/(N+1)*23.83*0.03(0.01N) \tag{3.10}$$

where Sd = 23.83 T = 23.83*0.0003Nho. R is calculated from N and is 1.3 to 1.4%, for N ranging from 10 to 30.

RESPONSE OF VE-SYSTEM

This section explains a method to evaluate the quantity of dampers and axial force of the earthquake resistant frame having slender columns and dampers. Figure 4.1 shows the maximum displacements for the basic building model (Ao), the VE system (A), and the VE system having slender columns (B). Re*uo and Re are allowable displacement and displacement reduction ratio, respectively. Kasai derived a formula for the response of the VE

system [2), 3)] (see Appendix).
For simplicity, let the stiffness of the portion supporting the damper, Kb, be adequately large (e.g. Kb/Kf > 10, Kf: stiffness of frame). From equation (A.4), the quantity of dampers corresponding to Re is derived as follows:

$$Kd/Kf=(1/Re^2 - 1)/(1+25hd/(1+25ho)) \quad (4.1)$$

where Kd, hd and ho= stiffness of damper, 1/2 of loss facter Nd and damping ratio of the frame with slender columns:

$$Kf^B = \alpha * Kfo \quad (\alpha < 1) \quad (4.2)$$

$$To^B = 1/\sqrt{[\alpha]}\ To \quad (4.3)$$

$$uo^B = 1/\sqrt{[\alpha]}\ uo \quad (4.4)$$

$$Re^B = Re\ uo/\ uo^B = \sqrt{[\alpha]}\ Re \quad (4.5)$$

where Kfo, To and uo = damper stiffness, natural period and displacement of the Ao-system , and Kf^B, To^B and uo^B = those of the Bo-system. Re^B is the displacement reduction ratio required for the Bo-system. From equations (4.1) and (4.5), the quantity of dampers for the Bo-system is given as follows:

$$Kd^B/Kfo=(1/Re^2 - \alpha)/(1+25hd/(1+25ho)) \quad (4.6)$$

It should be noted that the required quantity of dampers is expressed as a function of Kfo.

Damper force and frame force of the B-system are also expressed by frame force of the Ao-system. Figure 4.2 shows quantity of dampers, damper force and frame force for each reduction ratio of the frame stiffness a. The following findings are obtained from this figure:
1) As reduction ratio Re decreases, required number of dampers Kd/Kf sharply increases accordingly.
2) As frame stiffness decreases, required number of dampers Kd/Kf also increases. The increase ratio is small where Re < 0.5.
3) Provision of dampers causes a sharp increase in damper forces Vd.
4) As the frame stiffness decreases, both required number of dampers and damper force increase accordingly: the increase ratio is small where Re < 0.5
5) Frame force is reduced by providing dampers.
6) As frame stiffness decreases, forces generated in it also decreases: changes in frame force are larger than those in damper force.
Figure 4.3 shows a frame model for evaluating axial force. Shear forces of outer and inner column are expressed as follows [4)]:

$$Vc_1=D_1/\Sigma D*Vf\ ,\ \ Vc_2=D_2/\Sigma D*Vf \quad (4.7)$$

where

$$D_1=g_1/(2+g_1),\ \ D_2=(g_1+g_2)/(2+g_1+g_2),\quad \Sigma D=2(D_1+D_2),\quad g_1=kb_1/kc,\ g_2=kb_2/kc$$

where Vf, kb1, kb2, and kc = shear force of the frame, relative stiffness of the outer and inner beam, and relative stiffness of the column, respectively. Moments of the outer and inner column are expressed as follows:

$$M_1=Vc_1*yh,\ M_2=Vc_2*yh \quad (4.8)$$

where yh is the height where the moment along the column is zero.
By using shear forces in beams derived from this equation, axial forces of columns are expressed as follows:

$$N_{outer}=yh/L_1[g_1/(2+g_1)+g_1/(2+g_1+g_2)]/\Sigma D*Vf \quad (4.9)$$

$$N_{inner}= yh/L_2[2g_2/(2+g_1+g_2)]/\Sigma D*Vf - Nout + Ndm \quad (4.10)$$

where $Ndm = h/L_2 * Vd$
where Vd is damper force, which acts as axial force in the inner columns.

Figure 4.4 shows axial forces for each Re, which are calculated from equations (4.9) and (4.10), using parameters given in Table 4.1.
The following findings are obtained from this figure:
7) Where dampers are not provided, axial forces generated in outer columns are considerably larger than those in inner columns. However, if dampers are provided, axial forces decrease in outer columns and increase in inner columns.
8) As frame stiffness decreases, axial forces decrease in outer columns, and increase in inner columns. The smaller Re, the smaller the ratio of the axial force increase.
9) Comparing cases of h/L1= h/L2 = 0.67 (shorter span) and h/L1= h/L2 = 0.4 (longer span), the latter shows smaller axial forces in outer columns. A further span expansion of outer columns results in reduction of axial forces in outer columns.
10) In the case above, inner columns with longer span also show smaller axial force. A further span expansion of the outer columns results in increase of the axial forces in inner columns. Increase rate of the axial force is small where Re is small.
11) Increase in beam stiffness has less effect on the above characteristics.
12) Axial force in the inner columns where dampers are provided is almost equal to that in outer columns where dampers are not provided, if Re is approximately 0.4 and stiffness of outer and inner beams are the same.

However, as is predicted from above 9) and 10), if the stiffness of outer beams is decreased, Re that gives this phenomenon is increased to 0.5.
Reduction ratio Re mentioned in 12) represents the limit where the increase of the axial force in inner columns, which is caused by provision of dampers, equals to the axial force in the outer columns of the frame without dampers.

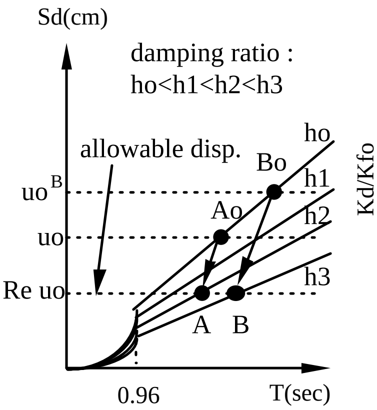

Fig.4-1 Response of VED system

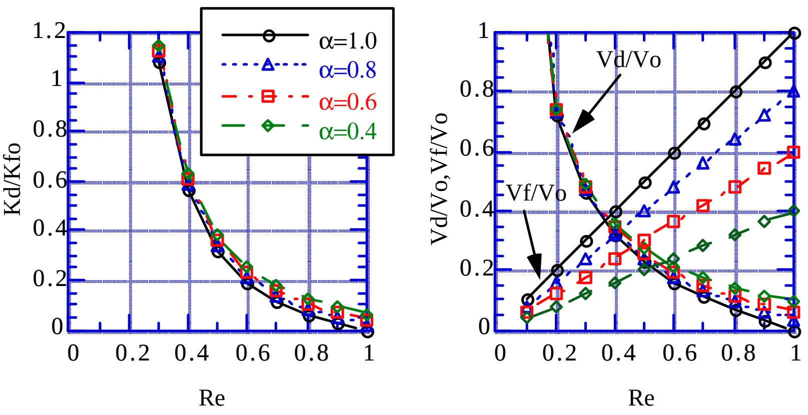

Fig.4-2 Damper and Response

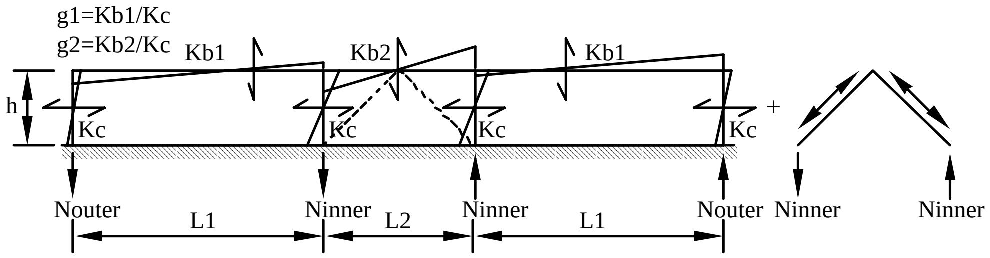

Fig.4-3 Frame Model

Table 4-1 Parameters for example

Nd	ho	f ¿	g_1	g_2	h/L_1	h/L_2	Re
1.0	0.02	1.0, 0.8, 0.6, 0.4	0.2, 1.0	0.2, 1.0	0.67, 0.3	0.67, 0.4	1.0 --- 0.1

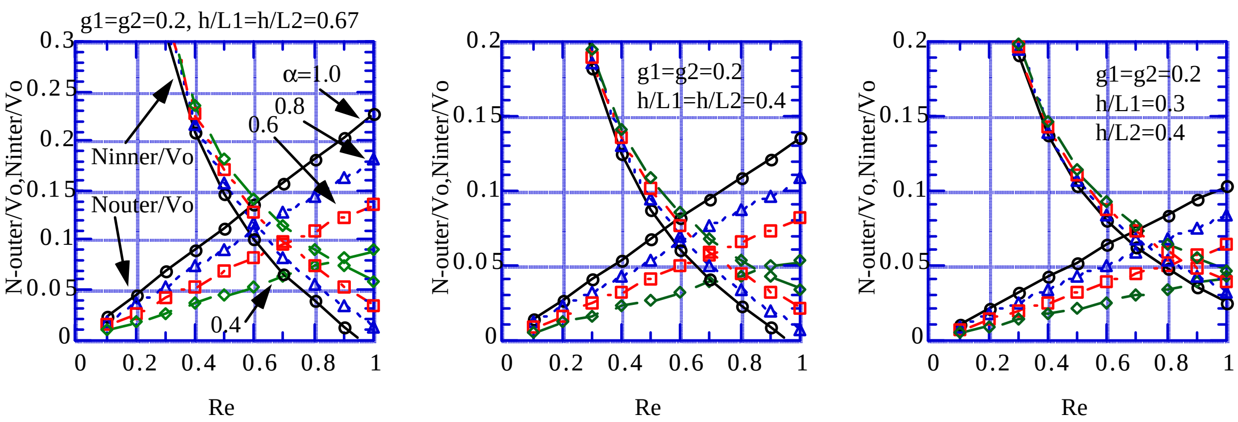

Fig.4-4 Response of VED Structure Frame

SEISMIC RESPONSE OF SOFT ELASTIC STRUCTURE WITH DAMPER

In this section, a method to design a frame comprising slender columns and dampers is proposed based on the theory mentioned in former sections.

Design of conventional frames

A 20-story frame shown in Figure 5.1 was designed. Weight of each floor considering live load and the total weight of the frame are 187.2 tf and 3744 tf, respectively. Damping ratio of the frame is set to 0.02. Stiffness of the layer is calculated based on the method described in section 3. Columns were so designed that the minimum ratio of stationary axial force to compressive strength is 0.25. Tensil strength of steel material is 3.3 tf/cm2. Stiffness of panels at the beam-column junctions is assumed to be rigid. The minimum ratio of relative stiffness of beam to that of column was set to about 25%. Stiffness of all beams was set to 1.4 times that of original one, taking into consideration the slab effect. Dimensions of the frame are shown in Table 5.1: bottom ends of the first floor columns are fixed.

The basic model without dampers consists of columns measuring 700 mm x 700 mm to 600 mm x 600 mm (maximum plate thickness: 60 mm) and beams measuring 110 mm x 300 mm to 600 mm x 300 mm (maximum flange thickness: 34 mm). Although the stiffness of each layer, which is derived from the D-value method, is 40 to 100% larger than the expected value for the first, 19th and 20th floors, those of other floors are almost equal to the target values.

Dynamic response of basic frame and VE-frame

Both static and dynamic analysis were carried out for the basic model.

The interstory displacements derived from the analyses are given in Figure 5.2. The displacements are almost the same excepting near the top and bottom layers: those derived from the dynamic analysis appear to be approximately 20% smaller than those of the static analysis. The possible reasons for this are: 1) base shear of multi-story model is roughly 10% smaller than that of the single-mass system, and 2) bending deformation is developed. Yielding started at edges of 5th story's inner beams in the static analysis, with a base shear of 0.16, a maximum displacement of 2.19 cm, and an interstory deflection angle of 1/183. Considering the results of the static analysis, the reduction ratio of displacement is defined as Re = 2.0/5.45 = 0.367. The quantity of dampers Kd/Kf is calculated as 0.69 from equation (4.1) (loss factor Nd = 1.0). Kd of each floor is calculated by defining each floor's stiffness as Kf.

Figure 5.3 shows the interstory displacement derived from the dynamic analysis on the VE-frame using time history. The results approximately equal to the expected values. It should be noted, however, that the reduction ratio of displacement Re is 2.0/4.5 = 0.44, less effective compared to the result of the dynamic analysis on the basic model. The reason is probably that bending deformation is developed and the response reduction effect of dampers is reduced.

Figure 5.4 shows axial forces caused by seismic loads. Axial forces in the outer columns decrease, while those in inner columns increase due to dampers. Kd/Kf, Vd, Vf , Nouter, and Ninner, which are calculated based on the theory in section 4, are given in Figure 5.5. This figure clearly illustrates the variation of axial force of the first floor, where larger shear force and smaller bending deflection are generated.

Figure 5.6 shows the interaction of axial force and bending moment for the columns of the first floor (C101: outer column, C301: inner column, axial force: positive in tension).

Table.5-1 Member of Model

N	Column	Beam(outer)	Beam(inter)	N	Column	Beam(outer)	Beam(inter)
20	600x600x19	800x300x14x26	588x300x12x20	10	700x700x40	1000x300x19x34	
19				9			
18			700x300x13x24	8			
17				7	700x700x50		
16	600x600x28	912x300x18x34	800x300x14x26	6			
15	650x650x25			5			900x300x16x28
14				4			
13	650x650x32			3	700x700x60	110x300x19x32	
12				2			
11	700x700x40			1			

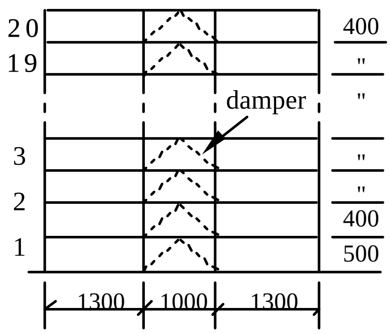

Fig.5-1 Structure Model

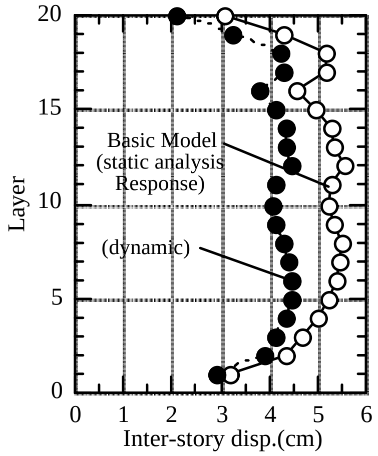

Fig.5-2 Static and Dynamic Response

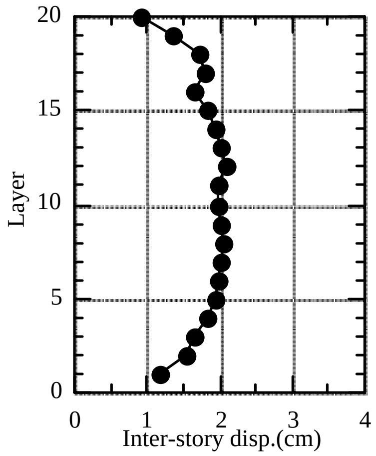

Fig.5-3 Dynamic Response

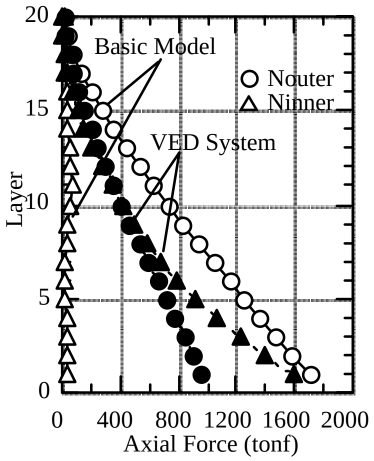

Fig.5-4 Comparison on Axial Force

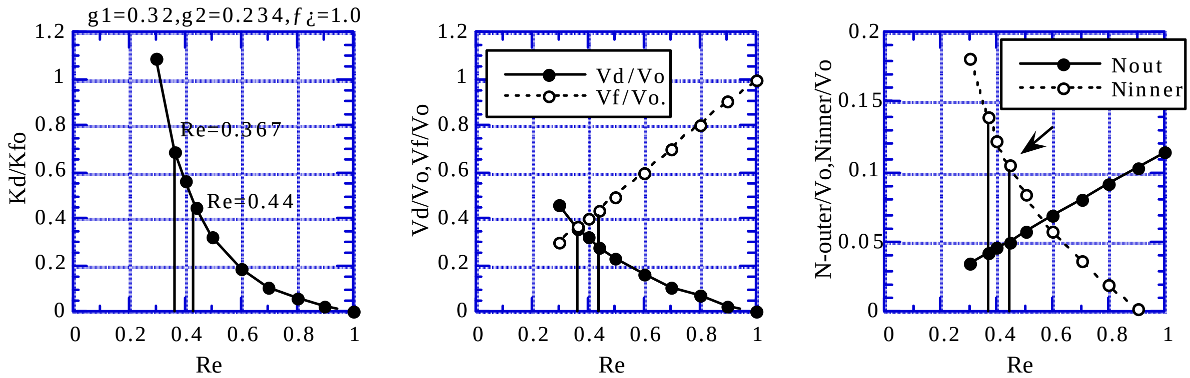

Fig.5-5 Response of VED system

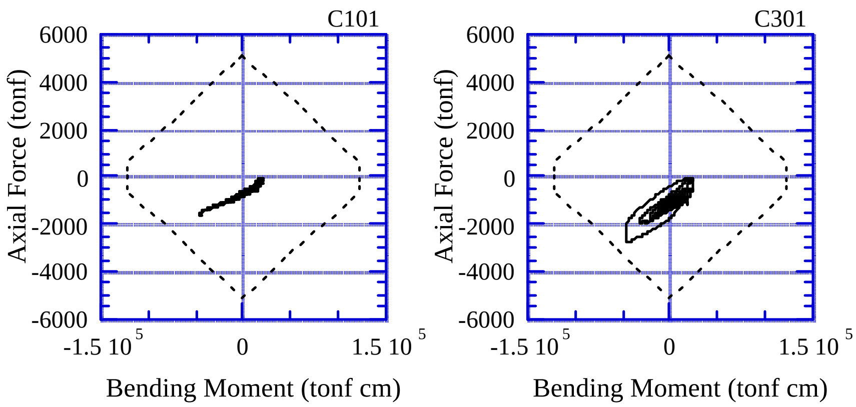

Fig.5-6 NM interaction

VE-frame with slender columns

VE-frame discussed here is a structure with Re of 0.4 to 0.5. Judging from the results shown in Figure 5.5, the axial force in the inner column equipped with dampers is expected to be almost equal to that in outer column of the frame without dampers. Therefore, concrete filled steel tube [5)] (CFT) which has a larger compressive and bending capacity for its stiffness, was selected for columns; beam members were unchanged. Stiffness reduction ratio of the frame was set to about 0.6, and required number of dampers Kd/Kf was calculated as 0.73.

Earthquake response analysis on the VE-frame with slender columns were carried out. Interstory displacements obtained from the analysis are shown in Figure 5-7. Although elasticity of the frame is retained, the response displacement exceeds the expected value by approximately 10%: reduction ratio Re is 2.2/4.5 = 0.49. The reason is probably that a large bending deflection is generated due to slender columns with a small bending stiffness.

Figure 5.8 shows axial forces caused by seismic loads, and Figure 5.9 shows the relationship between Re and Kd/Kf, Vd, Vf, Nouter, and Ninner, which are calculated from the theory in section 4. The variation of axial force of the first floor derived from the dynamic analysis is well illustrated in these figures.

Axial force-bending moment interaction of the columns on the first floor is given in Figure 5.10 (C101: outer column, C301: inner column, axial force: positive in tension).

Earthquake response of VE-frame where dampers are added to the basic model and VE-frame with slender columns were studied in this paper: it was found for both types of the frames that interstory displacements due to seismic forces are reduced, and the elasticity is retained. It was also found that VE-frame with slender columns enables the column diameter and mass of steel of the column to be reduced to two-thirds and 60% of that of conventional frame, respectively.

Table.5-2 Member of Model

N	Column	N	Column
20	400x40	10	500x36
19		9	500x40
18		8	500x45
17		7	
16	450x32	6	
15		5	
14		4	
13	450x40	3	
12	500x36	2	
11		1	600x60

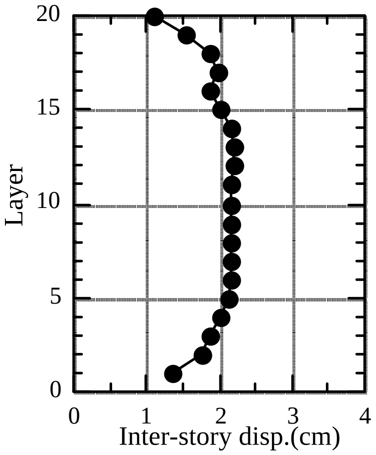

Fig.5-7 Dynamic Response

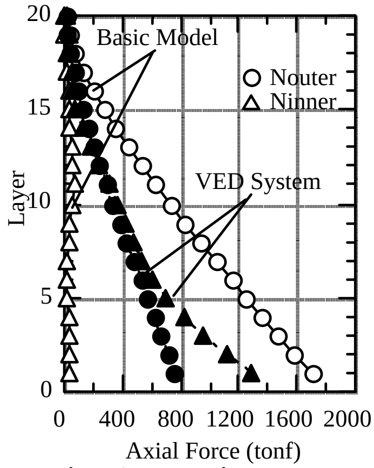

Fig.5-8 Dynamic Response

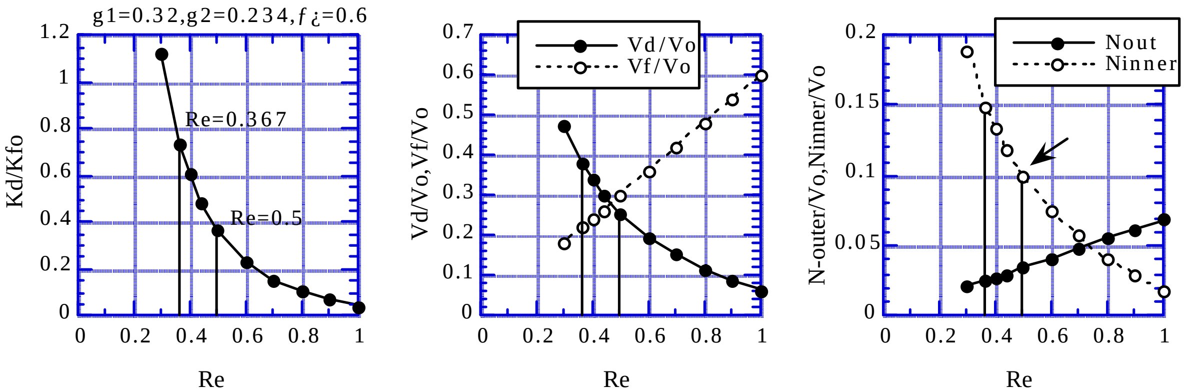

Fig.5-9 Response of VED system

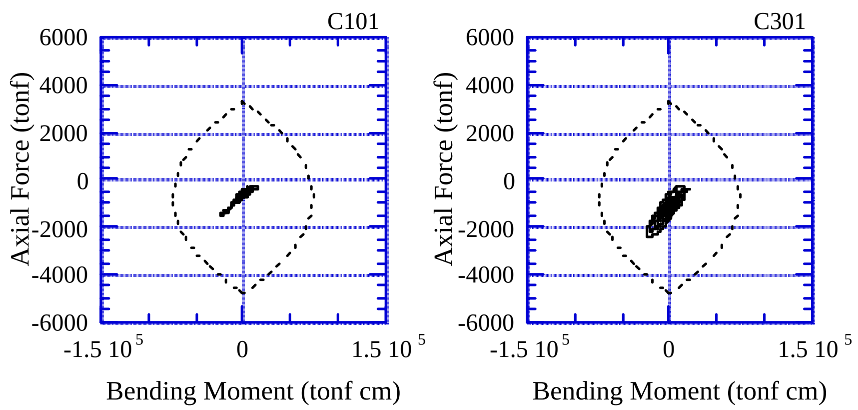

Fig.5-10 NM interaction

CONCLUSIONC

A method for evaluating the required quantity of dampers in conformity with the allowable displacement, and axial forces in columns which are generated by the dampers was studied, and the findings as stated in 1) to 12) in section 4 were obtained.

Furthermore, a 20-story VE-frame with slender columns were designed based on the above-mentioned results: conventional frame and VE-frame with non-slender columns were also designed for comparison. It was found through the dynamic analysis that both types of VE-frames are able to retain the elasticity even when exposed to seismic forces. It was also found that VE-frame with slender columns enables the diameter and mass of steel of column to be reduced to two-thirds and 60%, respectively.

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Appendix[2)]

Kasai 1) proposed the equations below for expressing the characteristics of the single-mass system shown in Figure A.1. Here, stiffness of the joint between the damper and the frame is assumed to be infinite for simplicity.

$$Teq=\sqrt{[1/(1+Kd/Kf)]}\ To \quad (A\text{-}1)$$

$$heq=ho+0.5*Nd/(1+Kf/Kd) \quad (A\text{-}2)$$

where

Teq and heq are equivalent natural period and equivalent damping factor.

Kd, Kf, T0, heq, and Nd are stiffness of the damper, stiffness of the frame, natural period of the VE-system, structural damping factor, and loss factor of the damper, respectively.

The ratio of response reduction Dh is given by the equation below:

$$Dh=\sqrt{[(1+25ho)/(1+25heq)]} \quad (A\text{-}3)$$

Where the velocity response spectrum is constant, the ratio of displacement reduction by damper and stiffness is expressed as follows:

$$Re=DhTeq/To \quad (A\text{-}4)$$

Furthermore, forces of the VE-system are expressed as follows:

$$V=\sqrt{[(1+4heq^2)/(1+4ho^2)]}\ Veq \quad (A\text{-}5)$$

$$Veq=Dh(To/Teq)\ Vo \quad (A\text{-}6)$$

$$Vf=Dh(Teq/To)\ Vo \quad (A\text{-}7)$$

$$Vd=\sqrt{[1+Nd^2]}/(1+Kf/Kd)\ Veq \quad (A\text{-}8)$$

where V, Veq, Vf ,Vd and V0 are maximum shear force, shear force of the point with maximum displacement, maximum frame force, damper force and maximum shear force of the non-damper system, respectively.

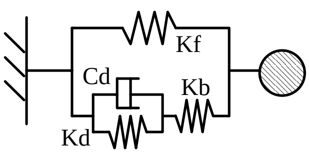

Fig.A-1 VE-system