

Design of a building with 20% or greater damping

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ABSTRACT: To create highly safe and damage free buildings against very strong earthquake input a wall-shaped energy absorber called a "Viscous Damping Wall" was developed. Using these walls at each floors, a 78m high steel frame building was designed. 170 Viscous Damping Walls in total gave the building damping constants of 27.4% and 26.4% at 20°C for the first mode in X- and Y-directions, respectively. That all of the maximum responses remain in the elastic range of the frame without any damage against maximum credible earthquakes of level 2 with a maximum input velocity $V_{max}=50\text{cm/s}$, was confirmed by the time history analyses. Additionally, super-plastic rubber dampers used to attach precast curtain wall panels were developed and are used as sub-dampers for the building.

1 INTRODUCTION

The purpose of this study is to create highly safe and damage free buildings against very strong earthquake ground motions.

Conventional earthquake resistant design methods try to avoid collapse of buildings by absorbing vibration energy through plastic deformation of yielded beams and or columns. Since conventional structures cannot absorb enough energy in their elastic range of the frame before the yielding of members, damage will be inevitable during strong earthquakes.

On the other hand, Base Isolation is a very effective technique for buildings to safely resist very strong earthquake excitations,¹⁾ but it has some difficulties in application for tall buildings, especially those in soft soil conditions.

Therefore, the purpose of this paper is to show a solution for relatively tall buildings in soft ground, and to design in practice an actual building using the proposed method.

2 CONCEPT AND METHOD

The basic concept of the approach is to create a building which has a large energy absorbing capacity. The method used to realize this is to install powerful energy absorbers in each story of the building in parallel with the structural frame.

The target value for a damping constant aims at 20%~30% in the elastic range of the frame to decrease the dynamic response distinctly. As the energy absorbers, wall shaped "Viscous Damping Walls(VD-Walls)" developed by the author are used.^{2, 3)}

In order to satisfy the following conditions:

- effective from weak to strong input
- reliable and durable for a long time
- maintenance-free, or easily maintained
- economical

the author considers that the mechanism of the devices should be simple and tough, therefore a passive control approach is practical.



Fig-1 Perspective View of the SUT-Building

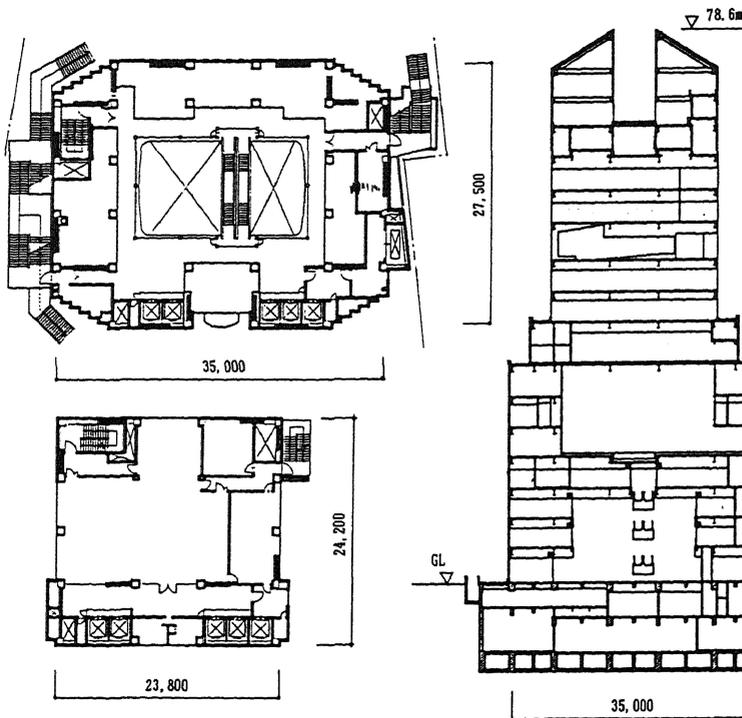


Fig-2 Plan and Sectional Views

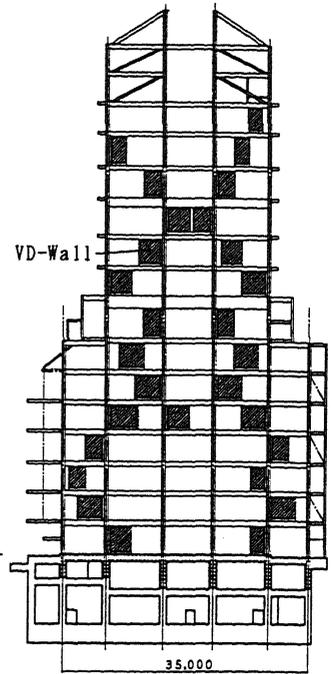


Fig-3 Structural Frame and VD-Wall Location

3 BUILDING DESCRIPTION

3.1 Location

The SUT-Building was planned at the center of Shizuoka city, 150km west of Tokyo. The city is located at the central area where a large scale "Tokai", or "Off the Suruga-Bay Earthquake" is expected to occur sometime in the future.

3.2 Outline

The building has two basement floors and 14 stories above the ground. The maximum height is 78.6m and total floor area is 11,521m². The building contains a 400-seats music hall, a high quality video theater, banquet rooms, shops and restaurants.

3.3 Structural planning

The structure is composed of a steel rigid frame above the ground, and the basements are composed of a rigid reinforced concrete body with strong peripheral shear walls. Four main steel frames are allocated to the four sides of the building in a # shape so as to surround the music hall and central public space of the building.

170 Viscous Damping Walls in total (80 in the X- and 90 in the Y-direction) are installed from the first floor to the roof. Basement floors do not have VD-Walls, but were designed with high rigidity and with high stability to avoid the building's rocking motion during an earthquake.

Figure-3 shows the allocation of VD-Walls in a main frame. The VD-Walls are installed in a checked pattern to avoid the accumulation of axial force in the columns caused by the VD-Walls, and also to prevent VD-Walls rotation, thereby keeping the movement in a horizontal shear mode.

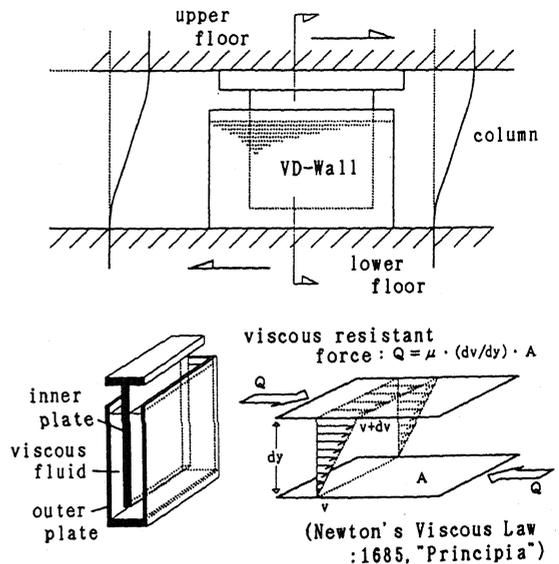


Fig-4 Diagram of VD-Wall Mechanism

4 ENERGY ABSORBER: "VISCOUS DAMPING WALL"

4.1 Basic mechanism

The basic mechanism of "Viscous Damping Walls (VD-Walls)" explained in Figure-3 is based on Newton's Viscous Law. It replaces a relative velocity between floors to relative movements between two wall plates facing each other with a small gap filled with a high viscous fluid.

The viscous resisting force Q_w and energy absorbing capacity E_w can be easily adjusted to a required value by changing three factors, i.e. viscosity of the fluid, gap distance and area of the wall plates.

4.2 Materials

The viscosity of the fluid is defined by its value at a temperature of 30°C, as the Design Standard Viscosity μ_{30} , and it can be selected in the range of $\mu_{30}=3,000\sim 100,000$ (poise). The wall plates are made of steel and usually the surface is covered by fire protection board, which also aims at thermal insulation in normal use conditions.

4.3 Dynamic characteristics

Photo-1 shows an actual VD-Wall set up on the dynamic testing machine. Figure-5 shows how to install VD-Walls to a structure frame.

Figure-6 shows a relationship between resisting force Q_w and displacement d , and Figure-7 shows Q_w vs velocity dv . Since the VD-Walls show dynamic characteristics like a visco-elastic material, it can be expressed by the Voigt model as follows;

$$Q_w = Q_o + Q_k$$

where Q_o : viscous resisting force
 Q_k : stiffness spring force

Figure-8 shows the relationship between Q_o and velocity dv , and it shows a non-Newtonian characteristics of VD-Walls.

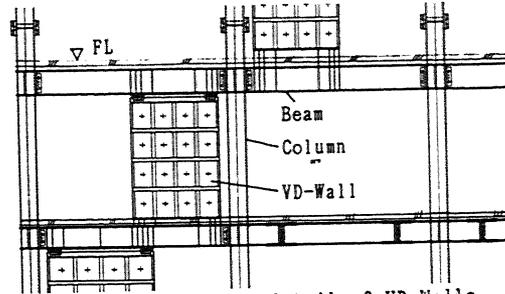


Fig-5 Installation detail of VD-Walls

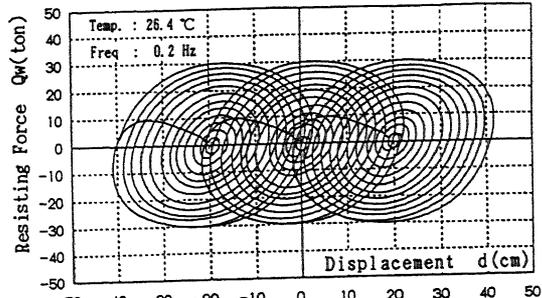


Fig-6 Force Q_w vs Displacement d

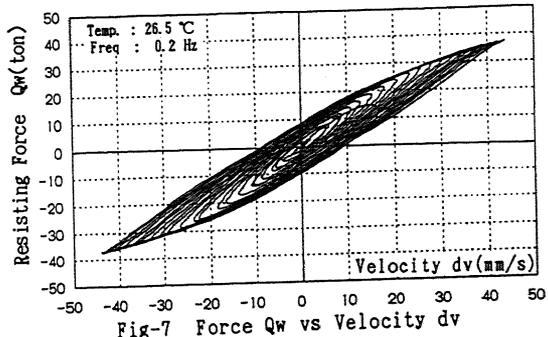


Fig-7 Force Q_w vs Velocity dv

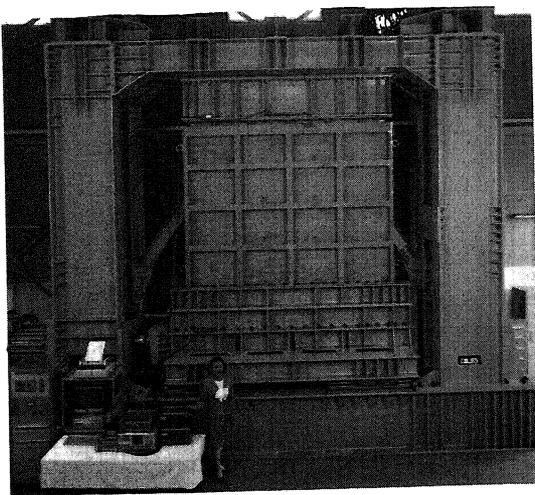


Photo-1 VD-Wall set up on testing machine

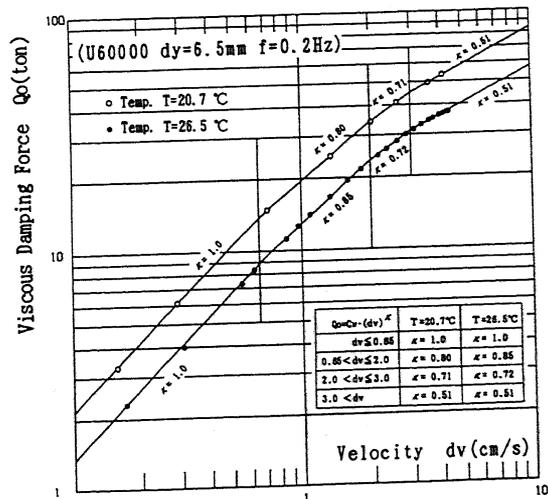


Fig-8 Relationship on Q_o vs Velocity dv

4.4 Fire resistance and protection
Viscous fluid is a high polymer in room temperature, but above 200°C the polymer begins to decompose. Therefore, in this design VD-walls are protected by calcium silicate insulating board to keep the fluid below 200°C even during a fire.

Photo-2 shows a fire test using actual VD-Walls by JIS A 1304 heat-curve. Temperature was kept below 200°C in both the one-hour and two-hour tests shown in Figure-9, and there was no damage at all in the walls by fire.

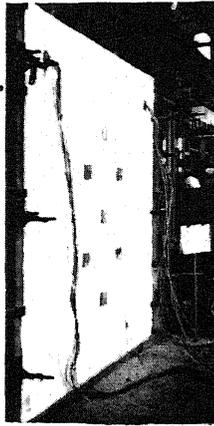


Photo-2 View of Fire Test

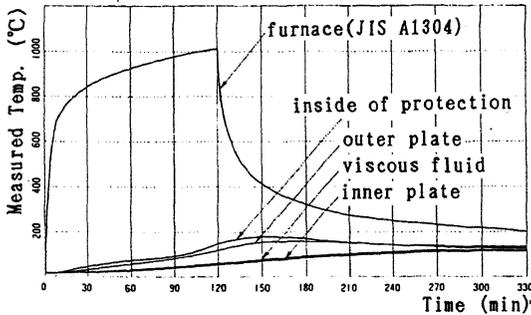


Fig-9 Temperature measured by Fire Test

5 SUB-DAMPER: SUPER-PLASTIC RUBBER DAMPER UTILIZING PRE-CAST(PC) WALL PANEL

Photo-3 shows an auxiliary energy absorber called "super-plastic rubber damper", using precast curtain wall panels. The main purpose of this device is to avoid the uncertain increase of stiffness by PC-wall panel caused by friction between PC-panels and the structure.

Figure-10 shows how to install the damper between a PC-panel and a beam of the building.

By this auxiliary dampers, damping constant of $\eta=3\% \sim 5\%$ can be added to the building, but its energy absorbing capacity is considered as a safety margin, and it is not accounted for in the design.

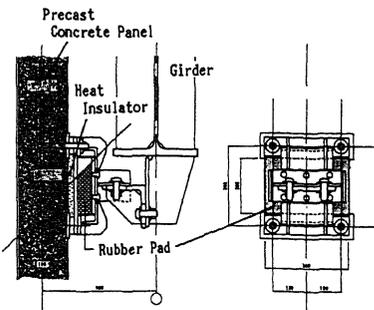


Fig-10 Installation of Rubber-Damper

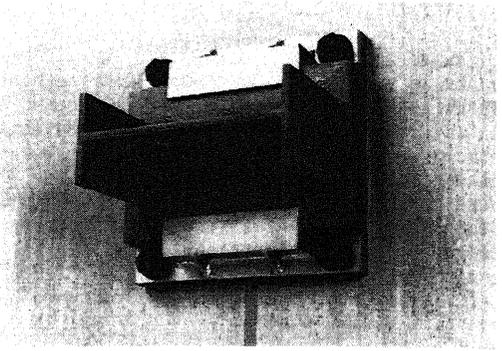


Photo-3 Super-Plastic Rubber Damper

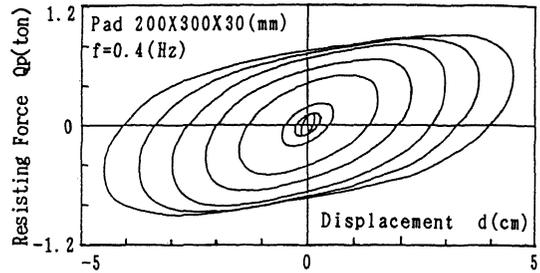


Fig-11 Performance of Rubber-Damper

6 DESIGN OF DAMPING CAPACITY BY VD-WALLS

Based on temperature data for 30 years in Shizuoka-city and FEM heat transfer analyses considering the building and VD-Wall conditions, the annual design temperature was set at 15°C ~ 26°C.

Figure-12 shows an example of designed restoring force characteristics of the 8th floor. It shows VD-Walls' hysteresis loops coupled with skelton curve of the structural frame.

The damping constant of each floor is in the 23%~39% range in the X-direction and in the 20%~49% range in the Y-direction at 20°C. The modal damping constants of the first mode are 27.4% and 26.4% in X- and Y-directions, respectively.

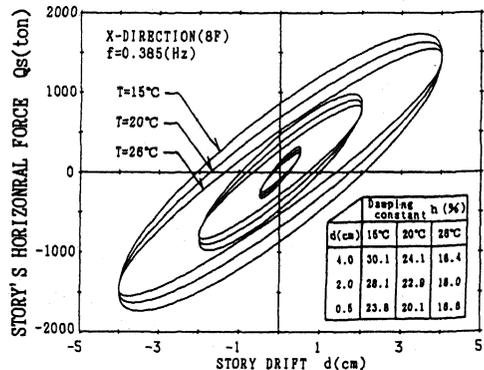


Fig-12 Designed Characteristics(8th Floor)

7 DYNAMIC BEHAVIOUR OF SUT-BUILDING
WITH DAMPING CONSTANT $h \geq 20\%$

7.1 Analysis model

Figure-13 shows a dynamic time-history analysis model. Structural frame, VD-Walls & also rubber dampers are expressed by a stiffness element and a dash-pot, respectively. So each story is composed of 4 or 6 elements.

Each story's restoring characteristics of the frame is determined based on the elasto-plastic step by step analysis by applying the incremental horizontal force, and idealized to a tri-linear curve.

7.2 Analysis method

In the time history analysis, the damping matrix of VD-Walls [Cw] is added to the ordinary equation of motions, and the non-Newtonian effect ($\alpha < 1.0$) is taken into account.

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [Cw]\{\dot{x}^\alpha\} + [K]\{x\} = -[M]\{\ddot{z}\}$$

7.3 Earthquake input condition

The intensity of the input earthquake motions is defined by the maximum velocity value of the input waves. The maximum velocity value of Level 1 is 25(cm/s), and that of Level 2 is 50(cm/s). Level 2 is the input for a maximum credible earthquake. Table-1 shows the maximum acceleration value of each input wave.

Table-1 Max.Input Acceleration(cm/s²)

Earthquake input wave	Level 1 (V=25cm/s)	Level 2 (V=50cm/s)
EL CENTRO NS(1940)	255.4	510.8
TAFT EW(1952)	248.4	496.8
HACHINOHE NS(1968)	165.1	330.2
HACHINOHE EW(1968)	127.7	255.4
OKITU EW(1978)	135.9	271.8

7.4 Analysis results

Figure-14 shows the first mode of the building by three dimensional frame analysis, and its period is 2.595(sec).

Figure-15 is the response hysteresis loops for the 8th-floor in X-direction, and Figure-16 is a time history of shear force Qc of the frame and damping force Qw of VD-Walls. Both forces are almost equal, and they are working together with phase lag to effectively reduce the dynamic response.

Figure-17~19 show the maximum response of each story in the Level 1 input (Vmax=25cm/s), in case of a model with and without VD-Walls.

Figure-20 and 21 show the maximum values of Level 2 input (Vmax=50cm/s).

These results show that the VD-Walls reduce the dynamic responses by 70%~80%, and all of the maximum responses remain in the elastic range of the structural frame without producing any yield hinges even against a level 2 maximum credible earthquakes.

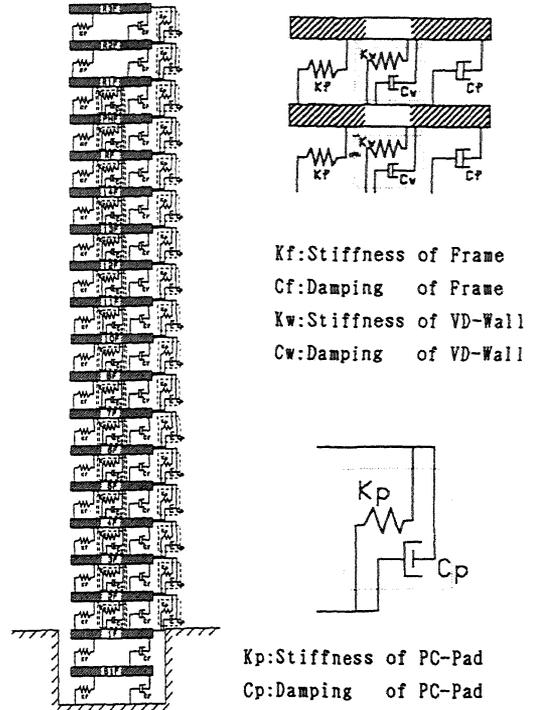


Fig-13 Dynamic Analysis Model

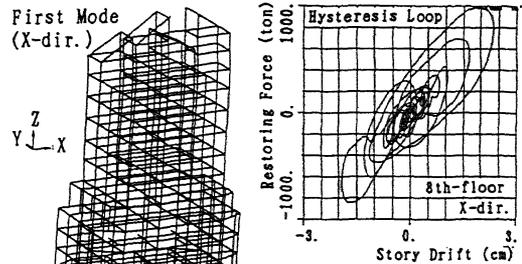


Fig-15 Response Hysteresis Loops (EL CENTRO NS Vmax=50cm/s)

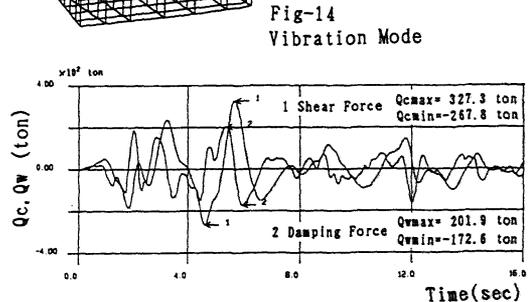


Fig-16 Time History of Shear force Qc and Damping Force Qw

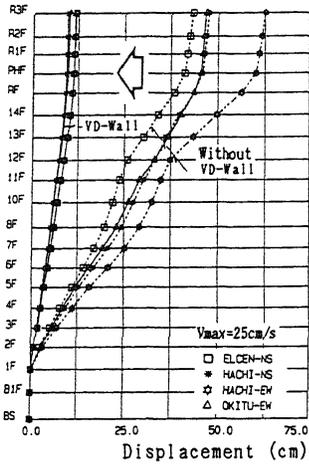


Fig-17 Max. Displacement

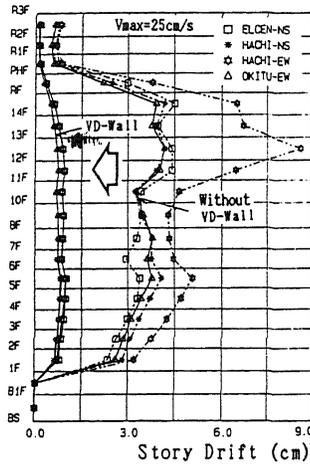


Fig-18 Max. Story Drift

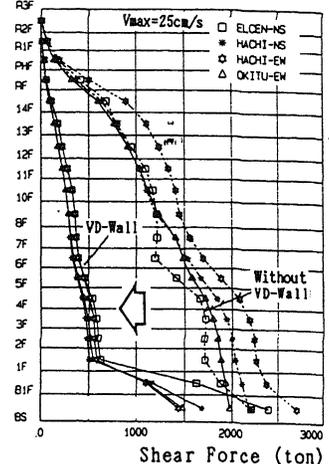


Fig-19 Max. Shear Force

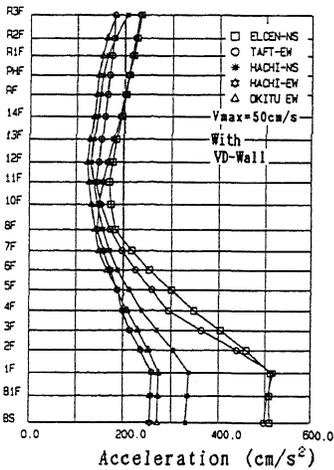


Fig-20 Max. Acceleration

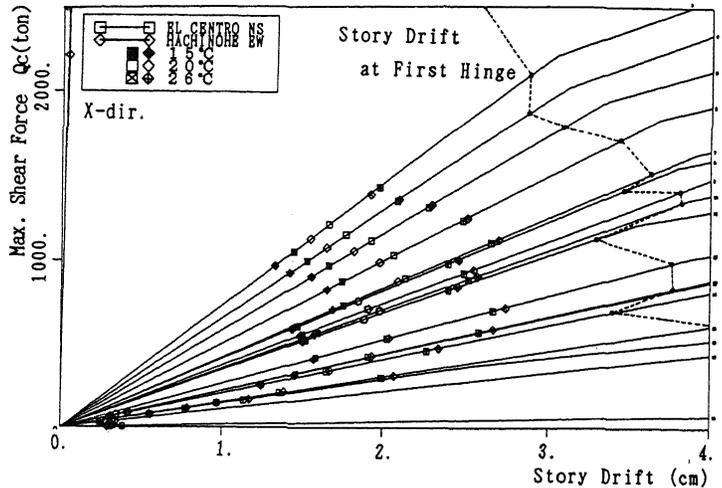


Fig-21 Max. Drift on Skelton Curves (Vmax=50cm/s)

8 CONCLUSION

The SUT-Building which has a damping constant of 27% at 20°C, and 20%~35% during a year in the elastic range of the structure was designed by using 170 Viscous Damping Walls.

Due to the effect of VD-Walls, the dynamic responses were reduced by 70%~80%, and the high safety with no damage even against level-2 earthquakes was confirmed by time history dynamic analyses.

Full-sized VD-walls for this building were manufactured at the factory. Full-sized dynamic tests were carried out and designed performance was confirmed.

Furthermore, super-plastic rubber dampers utilizing precast curtain wall panels were developed and used as auxiliary sub-dampers.

The building is now under construction in Shizuoka city, Japan, and the installation of the VD-Walls will begin in autumn 1992. And this building will be completed at the end of 1993 as the world's first building with such a large energy absorbing capacity.

REFERENCES

- 1) M.Miyazaki et al., "Design and its performance verification of a base-isolated building using Lead Rubber Bearings in Japan", 1988 9WCEE 7-9-18, Vol.V-p717
- 2) M.Miyazaki, "Earthquake response control design of buildings using Viscous Damping Walls", 1986, EASEC-1 Vol-3 p1882
- 3) Arima and Miyazaki, "A study on buildings with large damping using viscous damping walls", 1988, 9WCEE 7-10-11, Vol.V-p821