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# A study of structural control using viscoelastic material

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ABSTRACT: The focus of this study is on the feasibility of acrylic viscoelastic material as an energy absorbing device. The dynamic material test of the acrylic viscoelastic material was carried out to obtain the dynamic characteristics. The experimental results show that the mechanical characteristics considerably vary with environmental temperature and excitation frequency. It was verified experimentally that degrading Maxwell model (five-element) can be used to describe the dependence upon excitation frequency in the time domain. The dynamic loading test on a 1/3 scaled frame model with a damper was performed. The result shows that the absorption of energy was influenced very little by the change of loading frequency. Seismic response analyses for the structure using dampers under various temperatures were performed.

## 1. INTRODUCTION

Recently, because huge super high rising buildings are going up and the development of micro electronics has rapidly come about, structural control and base isolation systems have been applied to many buildings. Structural control systems that reduce vibrations of tall buildings have many applications. Currently two types of passive structural control systems have been put into practical use. One method is called TMD (Tuned Mass Damper) in which a mass consisting of steel or liquid is placed at the top of a building. The other is an approach that uses a friction damper or a viscoelastic material that is incorporated into each floor. TMD is effective for stationary vibrations due to wind, but not for transient vibrations from earthquake excitation. We have been developing the latter type of passive structural control utilizing acrylic viscoelastic material.

The focus of this study is on the feasibility of acrylic viscoelastic material as an energy absorbing device. The dynamic characteristics of acrylic viscoelastic material greatly depends upon loading frequency, environmental temperature, amplitude of deformation etc. At first, we selected three of the above mentioned parameters. Dynamic loading tests were carried out and then the dynamic characteristics were modeled in accordance with the degrading Maxwell model. A dynamic loading test on a 1/3 scaled frame model with a damper was performed. Seismic response analyses for the structure using dampers under various temperatures level were carried out.

Table 1 Loading program

| cycle | Deformation amplitude | Strain amplitude | cycle | Deformation amplitude | Strain amplitude |
|---|---|---|---|---|---|
| 1 | 0.1mm | 5% | 6 | 3.0mm | 150% |
| 2 | 0.2mm | 10% | 7 | 4.0mm | 200% |
| 3 | 0.4mm | 20% | 8 | 6.0mm | 300% |
| 4 | 1.0mm | 50% | 9 | 10.0mm | 500% |
| 5 | 2.0mm | 100% | 10 | 14.0mm | 700% |

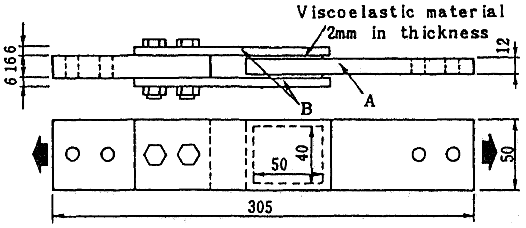
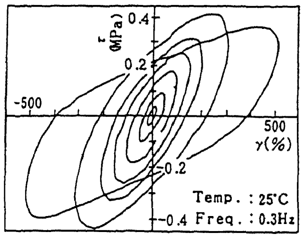


Fig.1 Specimen

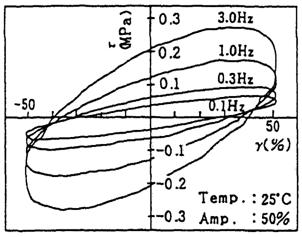
## 2. A DYNAMIC TEST OF VISCOELASTIC MATERIAL UNDER VARIOUS TEMPERATURES

### 2.1 *Outline of the test*

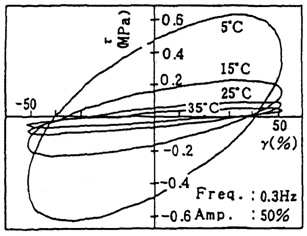
Acrylic viscoelastic material was provided for a dynamic test at various temperatures. The specimen is shown in Fig.1. Two acrylic viscoelastic material sheets, 40mm in width, 50mm in length and a thickness of 2mm were stuck to both side of a center steel plate A, and to both sides of the outer steel plates



(a)Dependency upon strain amplitude



(b)Dependency upon frequency



(c)Dependency upon temperature

Fig.2 Hysteresis loops of viscoelastic material

B. The specimen was loaded with a dynamic loading machine with a 9.8kN loading capacity , then layers of viscoelastic material were subjected to shear deformation.

The loading was controlled by the deformation indicated by using an inner deformation meter. With every ten sinusoidal displacement wave, the amplitude of deformation was increased from 0.1mm (shear strain = 5%) to 14mm (700%) as shown in Table 1. The loading condition was change at six different temperatures (-5,5,15,25,35,45℃ ) and four different loading frequencies (0.1,0.3,1.0,3.0Hz). But in consideration of the machine's loading velocity limitation, the deformation amplitude at 3.0Hz reached 3mm (shear strain = 150%).

As discrete time sampling was about one-hundredth of the period of sinusoidal deformation, measurement was done by digital value using an A/D converter. Shear deformation was measured by neglecting the elongation of the steel plates. Shear stress was the amount of force applied divided by the shear area of viscoelastic material.

## 2.2 *Results of the test*

The relationship between shear stress and shear strain at the 5th cycle is shown in Fig.2. Hysteresis loops showing the amplitude of shear strain ($\gamma_0$) is 20 ~ 500% at 25℃ ,0.3Hz are shown in Fig.2(a). The shape of the hysteresis loop is almost same ellipse in the range $\gamma_0 < 300\%$. When $\gamma_0$ exceeds 500%, the relationship of shear stress and shear strain turns into a bi-linear hysteresis loop. The maximum stress of the 5th cycle at 150% is about 97 percent of the maximum stress of the first cycle, but the ratio at 500% was about 30 percent. Under repeated loading at a greater amplitude, maximum shear stress of each cycle decreases. This behavior becomes more clear under low temperatures or at high frequencies.

The relationship between shear stress and shear strain at the 5th cycle is shown in Fig.2(b) (c) under each frequency at 25℃ and under each temperature at 0.3Hz. Under higher frequency or lower temperature, the stiffness shows a high value. Acrylic viscoelastic material greatly depends upon loading frequency and environmental temperature.

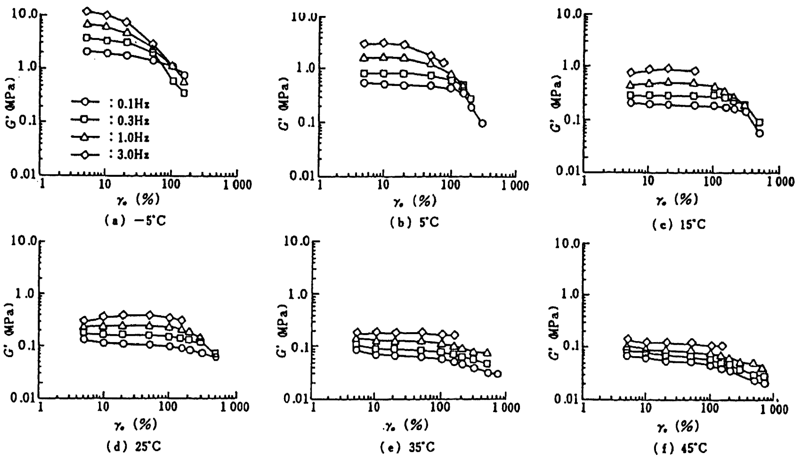
The relationship of shear strain amplitude and storage modulus (G') and the loss factor (tan$\delta$ ) under several environmental temperatures are shown in Fig.3 and Fig.4 respectively. G' was reduced by the increase of $\gamma$ 0, but G' remained almost the same value in part of the range of $\gamma$ 0. This showed a wide range under higher temperature or lower frequency.

The experimental results show that acrylic viscoelastic material has a large damping capacity. The mechanical properties are significantly influenced by environmental temperature and excitation frequency. The shear strain amplitude has little influence on the dynamic characteristics.

## 3. NUMERICAL MODEL OF VISCOELASTIC MATERIAL

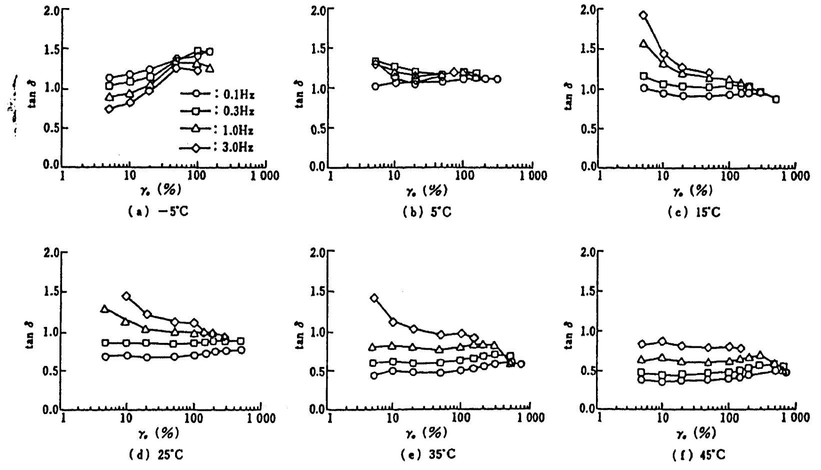
## 3.1 *Degrading Maxwell model*

The dynamic characteristics of viscoelastic material is generally expressed by the complex modulus dependent upon frequency and temperature. Under certain temperature conditions, it is relatively easy to setup a mathematical model of the dynamic characteristics of viscoelastic material in the frequency domain. When a damper utilizing viscoelastic material is incorporated into a structure, a part of the structure or the steel brace supporting the damper may become



(a) −5°C (b) 5°C (c) 15°C (d) 25°C (e) 35°C (f) 45°C

Fig.3 Dependency of G' upon shear strain



(a) −5°C (b) 5°C (c) 15°C (d) 25°C (e) 35°C (f) 45°C

Fig.4 Dependency of tan$\delta$ upon shear strain

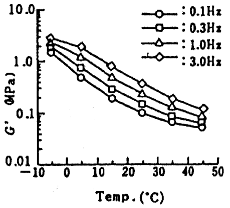


Fig.5 Dependency of G' upon temperature

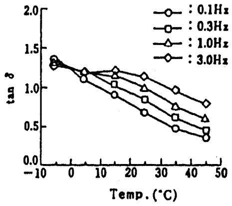
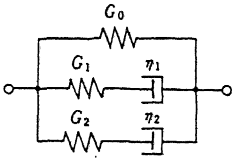


Fig.6 Dependency of tan$\delta$ upon temperature

non-elastically deformed under a larger earthquake. In this case, the mathematical model must be set in the time domain for analysis of earthquake response.

Considering the object frequency range used in the design, the reduced Maxwell model has been adopted as a base where one out of three Maxwell elements connected in parallel is replaced by the spring element (5-element model:Fig.7) Test results and the calculations with the 5 element model of storage modulus G', and loss factor tan$\delta$ are shown in Fig.8.



$$G(\omega) = G'(\omega) + iG''(\omega)$$

$$\tan\delta(\omega) = G''(\omega)/G'(\omega)$$

$$G'(\omega) = G_0 + \frac{G_1\eta_1^2\omega^2}{G_1^2 + \eta_1^2\omega^2} + \frac{G_2\eta_2^2\omega^2}{G_2^2 + \eta_2^2\omega^2}$$

$$G''(\omega) = \frac{G_1^2\eta_1\omega}{G_1^2 + \eta_1^2\omega^2} + \frac{G_2^2\eta_2\omega}{G_2^2 + \eta_2^2\omega^2}$$

Fig.7 Degrading Maxwell model (5 element)

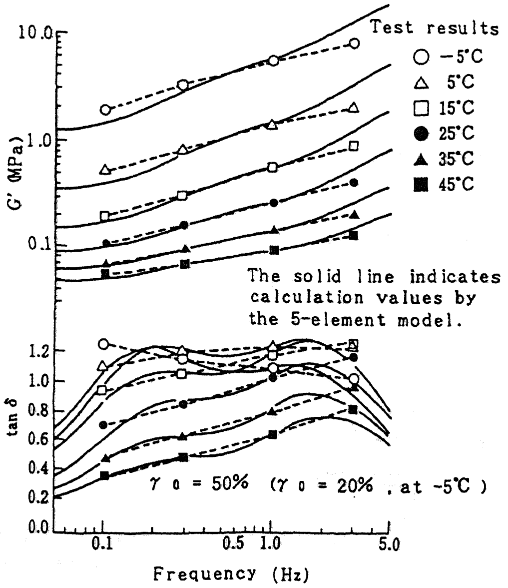


Fig.8 G' and tan$\delta$ of viscoelastic material

Table 2 Coefficients of 5 element model

| Temp. | $G_0$ | $G_1$ | $G_2$ | $\eta_1$ | $\eta_2$ |
|---|---|---|---|---|---|
| | MPa | | | MPa·sec | |
| -5°C | 1.08 | 3.43 | 20.6 | 1.67 | 0.784 |
| 5°C | 0.314 | 0.872 | 7.35 | 0.392 | 0.225 |
| 15°C | 0.137 | 0.304 | 2.74 | 0.157 | 0.0833 |
| 25°C | 0.0853 | 0.127 | 1.08 | 0.0637 | 0.0343 |
| 35°C | 0.0559 | 0.0549 | 0.402 | 0.0343 | 0.0147 |
| 45°C | 0.0441 | 0.0323 | 0.206 | 0.0216 | 0.00735 |

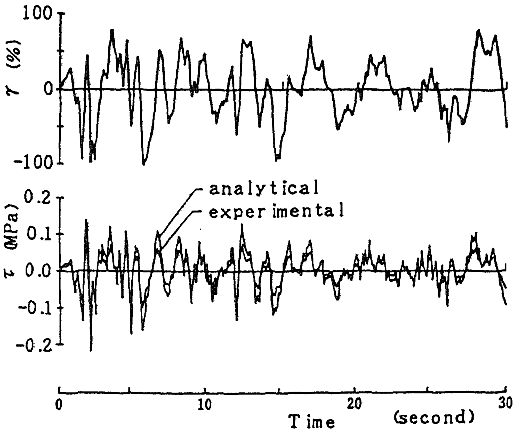


Fig.9 Shear stress and shear strain time history

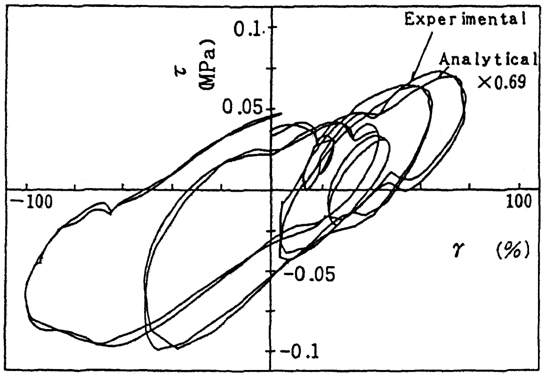


Fig.10 Hysteresis loops of viscoelastic material

Calculated values were mainly set in the range from 0.3Hz to 1.0Hz.

These calculations accurately represent the trend of the test results under each temperature, particularly in the range from 0.3Hz to 1.0Hz. To represent a wider range of frequency, a model with more elements is necessary.

### 3.2 *Outline of verification test and the results*

To clarify the degrading Maxwell model (5-element), damper response was applied to a viscoelastic material specimen. When the model described in Sec.5 undergoes El Centro 1940, the deformation response of the damper on the first floor normalized the maximum deformation amplitude to 2mm (shear strain:100%). The data time interval was decreased to 2 milliseconds from 20 milliseconds by spline interpolation.

For the preliminary test, the sinusoidal wave amplitude of 50%, the frequency 0.3Hz

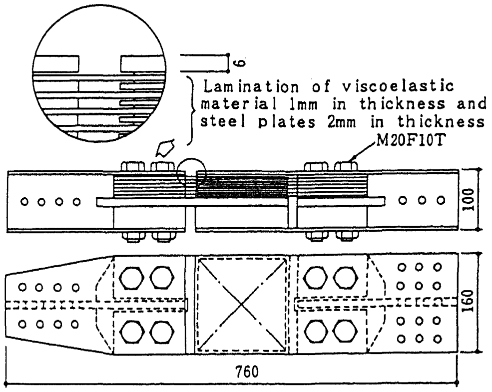


Fig.11 Damper using viscoelastic material

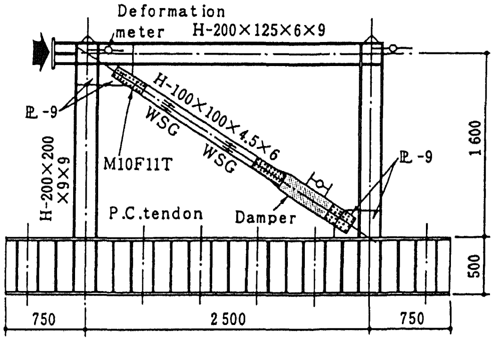
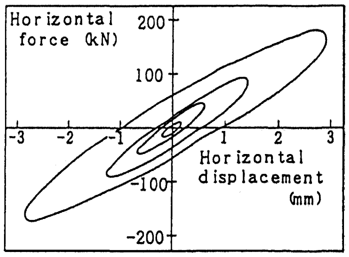
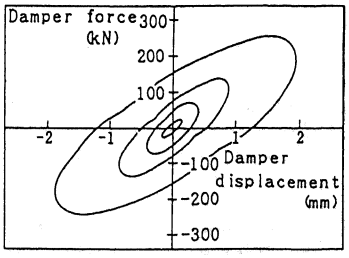


Fig.12 Test setup

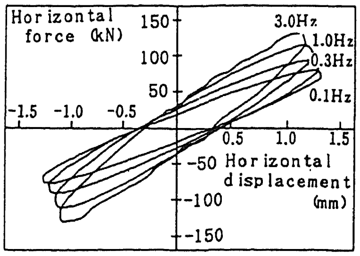


(a)Frame

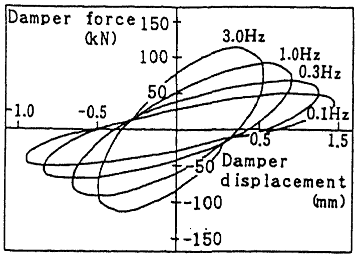


(b)Damper

Fig.13 Hysteresis loops dependency upon displacement



(a)Frame



(b)Damper

Fig.14 Hysteresis loops dependency upon frequency

and temperature 25℃ were loaded on the same specimen.

The loading procedure used was the same as that mentioned in the dynamic test. The environmental temperature was 25℃ .

The time history of shear strain and shear stress are shown in Fig.9. Experimental results of the shear stress was considerably less than the analytical result. However analytical stress waveform was coincidental with the experimental waveform within the region from primary natural frequency to higher frequency.

Results of the preliminary experiment shows that G' was 100 kPa. This value was about 69% of the modulus made numerical model 152 kPa. The reason considered was that a different manufacturing lot of viscoelastic material was used for this verification test.

The two hysteresis loops of comparatively large damper amplitude are shown in Fig.10. Analytical hysteresis loop shear stress was multiplied by 0.69. There is a problem of stiffness, but the degrading Maxwell model describes the behavior of the viscoelastic material.

## 4. DYNAMIC LOADING TEST ON STEEL FRAME WITH A DAMPER

### 4.1 *Setup*

Dynamic loading tests on a 1/3 scaled frame model with a viscoelastic material damper were carried out. The damper using the viscoelastic material is shown in Fig.11. The

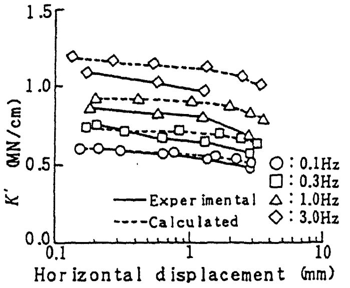


Fig.15 Dependency of frame stiffness upon displacement

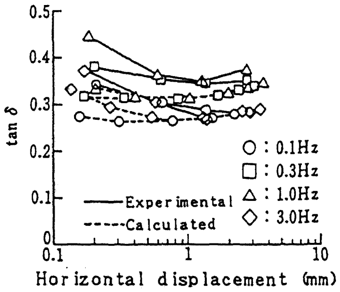


Fig.16 Dependency of frame loss, factor upon displacement

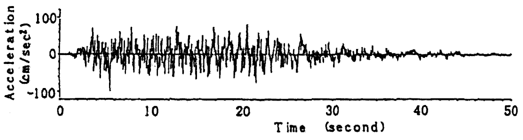


Fig.18 Time history of simulated earthquake

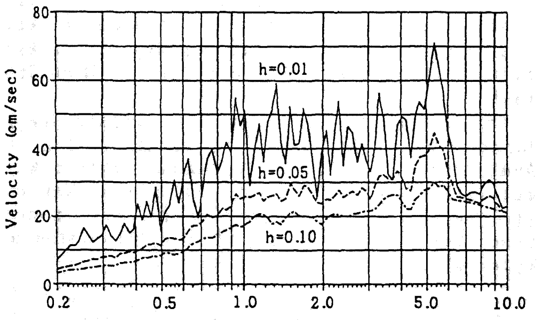


Fig.19 Velocity response spectrum of simulated earthquake

damper is composed of a lamination of steel plates 2mm thick and sheets of viscoelastic material 150mm by 150mm, 1mm thick. Each steel plate is alternately connected to either end of the device. This damper is supported by a

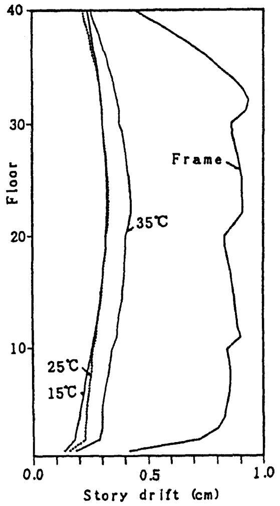


Fig.20 Story drift response

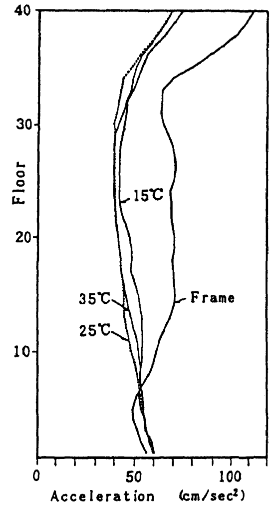


Fig.21 Absolute acceleration response

brace made of steel. The test setup is shown in Fig.12. The axial stiffness of the brace is two times the stiffness of the damper at 27℃, 0.3Hz. Horizontal force was applied by means of a 0.98MN dynamic hydraulic actuator.

The horizontal load simulates the horizontal shear that would arise under seismic excitations or during a strong wind. The displacement program consisted of cycles of sinusoidal displacement with incrementally increasing values of the peak displacements. The amplitude of the horizontal displacement was established as the angle of story drift becomes about 1/5000, 1/2000, 1/1000, 1/500 respectively. The loading frequency took on a higher value from 0.1Hz to 3.0Hz at a particular displacement level. Twenty cycles were made at each particular displacement level and each loading frequency. After every twenty cycles, the damper was allowed to cool and then retested at the next stage. The environmental temperature was 25~ 28℃ during the test.

### 4.2 *Results of the test*

Fig.13(a) and Fig.14(a) show the relationship of the horizontal force versus the horizontal displacement that was obtained under the same frequency 0.3Hz and the same displacement amplitude respectively. With the addition of the damper utilizing the viscoelastic material, hysteresis loops of the frame with the damper show a very smooth ellipse illustrating high energy absorption capabilities. The relationship of the damper force versus the damper displacement is shown in Fig.13(b) and Fig.14(b) under corresponding loading

Table 3 Characteristics of original frame

| | |
|---|---|
| First natural period | 4.41sec |
| Participation factor | 1.41 |
| Second natural period | 1.53sec |
| Participation factor | -0.59 |

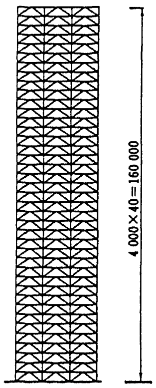


Fig.17 Frame model

cases in Fig.13(a) and Fig.14(a), respectively. The damper force was calculated from the strain measured by wire strain gauges on the brace. The change in the deformation amplitude exerts a small influence on the shape of hysteresis loops. as the loading frequency rises, the stiffness of the damper shows a high value and the shape of the hysteresis loops become a broad ellipse. The deformation peak of the damper became less because the steel brace was elongated. Consequently, the frequency of excitation significantly influences the damping factor of the viscoelastic material, but the area of the hysteresis loop that shows the absorption of energy was influenced very little by the change of loading frequency.

The relationship of frame storage stiffness versus the horizontal displacement is shown in Fig.15 and the relationship of the frame loss factor versus the horizontal displacement is shown in Fig.16. The value at the 5th cycle was adopted. Loss factor at 1.0Hz shows the highest value and 0.1Hz and 3.0Hz were almost same.

The characteristics of viscoelastic material at 27℃ was obtained by interpolation of the characteristic of 25℃ and 35℃ . The storage stiffness and loss factor that were calculated from the frame stiffness and the brace stiffness and the viscoelastic material characteristics was shown by the broken line in Fig.15 and Fig.16. Calculated storage stiffness of 0.1Hz was in accordance with the experimental results. But other calculations show higher a value than the corresponding experimental results. Loss factor was lower than the experiment results, the maximum loss factor 1.0 Hz was anticipated by the calculation.

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## 5. EARTHQUAKE RESPONSE ANALYSIS

An analytical model frame that is a 40 story steel structure is shown in Fig.17 and the characteristics of the frame without a damper are indicated in Table 3. Each floor with a horizontal rigidity of about 0.57MN/cm (at the top story) ~ 5.02MN/cm (at the first story) is equipped with a damper with a horizontal rigidity of 0.83 MN/cm (at 25℃ ,0.227Hz) and has a 5.88 MN/cm supporting steel brace at each floor. Three temperature levels of 15℃ , 25℃ and 35℃ were pre-set to conform to the characteristics of the viscoelastic material that are temperature dependent.

Th damping factor of the original frame was 0.01 to the primary natural frequency . An additional damping factor of the frame with the dampers were 0.11, 0.10, 0.07 to the primary natural frequency at 15℃ , 25℃ , 35 ℃ respectively. The primary frequencies were 0.330, 0.305, 0.285Hz respectively. These characteristics were calculated so that the viscoelastic material would have proportional damping to strain energy at the primary natural frequency of original frame for each temperature.

Simulated earthquake motion (Max. acc. : 100gal) corresponding to the acceleration spectrum (h=0.05) to the dynamic coefficient;Rt for intermediate soil conditions is in accordance with "Japanese Structural Calculation Guidance". The time history of the simulated seismic wave is shown in Fig.18 and the velocity response spectrum is shown in Fig.19. The viscoelastic material was modeled by the previously mentioned degrading Maxwell model for response analysis.

The response of the angle of story drift and absolute acceleration is shown in Fig.20 and Fig.21. At each temperature, maximum response decreased compared with the time when the devices were not provided, the effectiveness of the damper is in the region 15℃ ~ 35 ℃ .

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## 6. CONCLUSION

The experimental results shows that acrylic viscoelastic material has a great energy absorbing capacity and the 5-element degrading Maxwell model can be used to describe the behavior of the acrylic viscoelastic material in the time domain. The frame test result shows that the damping ratio of the frame incorporating the damper was relatively small with regard to dependency on excitation frequency. The analysis results shows that devices utilizing acrylic viscoelastic material are effective in reducing the response of seismic excitation under various temperatures.

## REFERENCE

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