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TEMPERATURE DEPENDENCE OF HIGH DAMPING RUBBER IN BASE-ISOLATED STRUCTURES

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ABSTRACT

High damping rubber is used widely as base-isolator because of their simplicity in design. No oil dampers or no friction damper are needed additionally. However, temperature of high damping rubber rises quickly at the time of earthquake vibration. So the material properties of the rubber are changed. In this paper, the influence of temperature of high damping rubber on earthquake response is investigated. As a restoring curve of high damping rubber, the Double-Target Model (DTM) is adopted, which considers the first rigidity of hysteresis curve. In numerical simulations, a seven floors building subjected three kinds of earthquakes (El Centro-EW, Taft-EW and Hachinohe-EW) under three different initial temperatures is investigated. Coefficients concerning restoring curves of the rubber are determined by experimental results under different temperatures. Amount of rising temperature of the isolator is estimated from absorbed energy calculated from restoring curves at each time step. Both heat transfer effects and thermal conductivity effects are considered in it.

And it is appeared that the temperature raises about 10°C to 20 °C in 4 second, and maximum amplitude of displacement increase about 20%.

KEYWORDS

base isolator; high damping rubber; temperature dependence; Double target model; restoring model of isolator

1. INTRODUCTION

In recent years, it has been recognized that base-isolated structural system is effective to prevent the damage of buildings from stronger ground motions. The basic idea of this system is making the natural period longer to avoid resonance of structure with ground motion. As a kind of material of seismic isolator, high damping rubber is well applied. However, it remains following problems that should be resolved:

1) Hysteresis loop problem under cyclic loading
It has been found out by many experiments that the high damping rubber has a kind of peculiar nature that its hysteresis characteristics on maiden loading are different from that after that time.
2) The influence of temperature dependence of high damping rubber on earthquake response of base-isolated structure
Damping capacity and rigidity of the high damping rubber is influenced by variation of its temperature. While

its temperature rising, the damping capacity and rigidity will become lower.

The first problem is investigated in detail by Fujisawa et al.[1]. He showed a new restoring force model rules that is called as Double-Target Model (DTM). This model represents well actual behavior of high damping rubber, while the latter problem has not been clearly understood yet.

In this study, by using DTM, two aspects of the influence of temperature dependence of seismic isolator using high damping rubber on earthquake response of base-isolated structure is investigated, that is, the first, the influence of different surrounding temperature of high damping rubber seimsic isolator on earthquake response of base-isolated structures, and the second, when the ground motion is keeping, the influence of earthquake excitation on structures will be fallen by absorbing the energy of ground motion of high damping rubber seimsic isolator. The absorbed energy by seimsic isolator, namely the dissipated energy, will be transformed mainly into the internal heat energy of high damping rubber seimsic isolator. With the variation of temperature inside the seimsic isolator, the damping capacity and the rigidity of high damping rubber will also be varied. It is the second subject in this study to investigate the influence of the variation of damping capacity and rigidity of the high damping rubber seimsic isolator caused by the dissipated energy (as stated above) on the earthquake response of base-isolated structure.

2. DOUBLE-TARGET MODEL (DTM)

DTM was proposed in 1991 by Fujizawa and et al. of Sumitomo Rubber Industry Company. This model for high damping rubber and circumference binding rubber, is more reasonable than Bi-linear, Tri-linear which was applied to its before. It considers first variation of rigidity of seismic isolator due to hysteresis affectation and hysteresis loop problem under cyclic loading of high damping rubber. Three kinds of curve, that is, the initial skeleton curve, the steady skeleton curve and the hysteresis curve are combined in DTM for this purpose. The sketch of hysteresis characteristics of DTM is illustrated as Fig.1.

2.1 The main rules of hysteresis characteristics

a) The hysteresis characteristics is expressed by the skeleton curves, which are applicable to the initial and steady cases, and the independent hysteresis curve.

b) It is considered that the displacement and load, which experienced on positive or negative side, did on the other side as well.

c) If the absolute value of displacement and load exceeds its maximum value by that time, it will travel along the initial skeleton curve (line 1 in Fig.1). Except this case, it will travel along the hysteresis curve (line 2,3,4,5 in Fig.1).

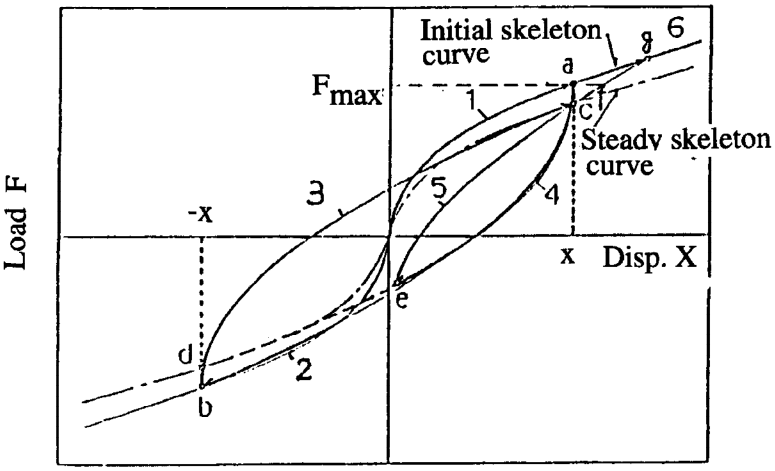

Fig.1 The main rules of hysteresis characteristics

But, once reversed, when the displacement (or load) approaches the definite point on the initial or steady skeleton curve (which is obtained on the skeleton curves by the maximum value of displacement by that time, point *c* in Fig.1), passing through point *c* and *f*, it will travel along the hysteresis curve as it is; however, it will travel along the initial skeleton curve after crossing it (line 6 in Fig.1).

d) When the displacement (or load) reverses at point (X_i, F_i) in the case of hysteresis curve, if this point is over the range of both the displacement and the load by that time $[(X_i < X_{\min}$ and $F_i < F_{\min})$, or, $(X_i > X_{\max}$ and $F_i > F_{\max})]$, it will approach the point $(-X_i, F_{so}(-X_i))$ on the initial skeleton curve.
Except this case $[(X_{\min} \leq X_i \leq X_{\max})$, or, $(F_{\min} \leq F_i \leq F_{\max})]$, if the displacement (or load) reverses from decrease to increase, the directing point will be on the steady skeleton curve $(X_{\max}, F_s(X_{\max}))$. And, if it reverses from increase to decrease, the directing point will also be on the steady skeleton curve $(X_{\min}, F_s(X_{\min}))$.

e) The coefficients which decide the shape of hysteresis curve are determined by the damping constants which have been obtained by the results of the sinusoidal wave inputting experiment used the displacement between the reversing point and the directing point as amplitude. (For example: in Fig.1, if it starts from *0* and reverses on point *a*, hysteresis curve 2 will be determined by the damping coefficient when the displacement between point *a* and *b* is used as amplitude. And then, if it starts from point *b*, passing through point *c*, and reverses at point *e* on the way to point *d*, hysteresis curve 5 will be determined by the damping coefficient when the displacement between point *e* and point *c* is used).

2.2 The expressions of hysteresis characteristics

a) The skeleton curves:

[Steady skeleton curve]: $F_s = A \cdot \gamma \cdot G_e(\gamma)$

[Initial skeleton curve]: $F_{so} = A \cdot \gamma \cdot G_e(\gamma) \cdot \alpha$

$$\mathrm{G_e} = \mathrm{a_1}\gamma^{-0.5} + \mathrm{a_2} + \mathrm{a_3}\gamma\,, \quad \gamma = x / H$$

b) The hysteresis curve:

$$\mathrm{F(X)} = \mathrm{sgn}\,(\mathrm{X}) \cdot \left|\mathrm{F_T} - \mathrm{F_R}\right| \times \left\{\mathrm{b_1}\left|\mathrm{X}\right|^{0.5} + (1 - \mathrm{b_1})\mathrm{X}^2\right\} + \mathrm{F_R}$$

$$X = (x - x_R) / \left|x_T - x_R\right|$$

$$b_1 = (2 + 3\pi h) / \left\{4 + (4\sqrt{2} - 5)\pi h\right\}$$

$$h = c_1 + c_2\sqrt{\gamma_H} + c_3\gamma_H + c_4 \exp\,(-c_5\gamma_H)$$

$$\gamma_H = \left|x_T - x_R\right| / (2H)$$

where

F_{so} : initial shearing force (kgf).
F_s : shearing force (kgf).
A : sectional area of seimsic isolator (cm^2).
G_e : appearance shearing elasticity coefficient of high damping rubber (steady) (kgf/cm^2).
α : maximum shearing force in the 1st wave stage / the maximum shearing force in the 3rd wave stage (=1.2).
H : total thickness of high damping rubber (cm).
γ : shear strain of seimsic isolator (=x / H, x: horizontal displacement).
γ_H : shear strain for deciding hysteresis curve ($=\left|x_T - x_R\right| / (2H)$).
a_i : coefficients of shearing elasticity coefficient depended by strain.
X : non-dimensional displacement ($=(\mathrm{x} - x_R) / \left|x_T - x_R\right|$).
x : horizontal displacement.
x_T : displacement as the object (the maximum or minimum value of displacement by that time).
x_R : displacement of reversing point just before.
F : shearing force of hysteresis curve.
$\mathrm{F_T}$: force as the object (shearing force obtained on the skeleton curve by displacement x_T.)

F_R : shearing force of reversing point just before.
b_i : coefficients which provide hysteresis curve.
c_i : coefficients of equivalent damping constant depended by strain.

3. RESTORING FORCE PARAMETER OF HIGH DAMPING RUBBER

To investigate the influence of temperature dependence of high damping rubber on earthquake response of base-isolated structures, it is necessary to understand the relation between the temperature and the damping capacity and the rigidity of high damping rubber. In Table 1, we provide data about the relation between the temperature and the coefficients a_i of shearing elasticity coefficient G_e, and the coefficients c_i of equivalent damping constant h. These data were obtained by the experiment in which high damping rubber ϕ 180 was tested. The experiment condition was frequence f = 0.5 Hz, surface pressure intensity σ = 50 kgf/cm^2, and the shearing strain γ = 2.5 - 200%.

Table 1 Coefficients of shearing elasticity coefficient G_e and equivalent damping constant h of high damping rubber.

Temperature °C	coefficients of G_e a_1	a_2	a_3	coefficients of h c_1	c_2	c_3	c_4	c_5
-10	15.0	-7.08	2.97	-0.122	0.363	-0.118	0.325	2.00
0	11.8	-5.57	2.34	-0.109	0.324	-0.105	0.290	2.00
20	8.40	-3.98	1.67	-0.094	0.279	-0.091	0.250	2.00
35	7.22	-3.42	1.44	-0.087	0.259	-0.084	0.233	2.00

4. ANALYTICAL MODEL AND METHOD

In numerical simulations, a 7 floors structural system as Table 2 using the high damping rubber as seismic isolator is adopted, where the 1st floor is considered as base-isolated floor. The Newmark β method is used to analyse it. And the value of β, time interval and the total of time duration is assigned as 1/6, 0.02sec and 20sec, respectively. The inputting seismic waves are three ones based on El Centro (1940) EW, Taft (1952) EW and Hachinohe (1968) EW, of which the maximum velocities have been adjusted to 40cm/s. The surrounding temperature is set as 20°C and -10°C.

Table 2 Analysis model

Floor	1	2	3	4	5	6	7
Weight (tonf)	1010	810	810	610	610	610	600
Stiffness (tonf/cm)	*	870	870	760	700	680	640

* The 1st floor is based-isolated floor, the total area and thickness of the seismic isolator is 10200(cm^2) and 500(cm), respectively.

And the analysing method to investigate the influence of temperature independence of high damping rubber on earthquake response of base-isolated structure is showed as follows:

1) Potential energy of deformation:

$$d_k = \frac{1}{2}(F_{k+1} + F_k)(D_{k+1} - D_k) \tag{1}$$

where d_k : potential energy of deformation absorbed by the rubber at K step.
F_{k+1} , F_k : restoring force of the rubber at K+1 or K step.
D_{k+1} , D_k : deformation of the rubber at K+1 or K step.

2) Amount of rising temperature inside the rubber (not considering the amount dissipated)

$$T_k = d_k \times 2.343\times 10^{-5} / (c_p \times 2.389\times 10^{-4} \times P) \tag{2}$$

where T_k : amount of rising temperature inside the rubber (not considering the dissipated).
c_p : specific heat of rubber. P : weight of the rubber.
the others are conversion coefficients of units.

3) Dissipated quantity of heat, dissipated amount of temperature:

$$Q_{1k} = h \times 2\pi R \times H \times 10^{-4} \times (T_{1k} - T_0) / 3600 \times \Delta t$$

$$T_{1K} = Q_{1k} \times 980.0 / (c_p \times 2.389 \times 10^{-4} \times P)$$

$$Q_{2k} = 2.0 \times \lambda \times \pi R^2 \times 10^{-3} \times (T_{2k} - T_0) / L / 3600 \times \Delta t$$

$$T_{2k} = Q_{2k} \times 980.0 / (c_p \times 2.389 \times 10^{-4} \times P)$$

where Q_{1k} , Q_{2k} : quantity of heat dissipated from the circumference or up-down side of the rubber.
R,H : radius or thickness of the rubber.
L : thickness of steel plates on up-down side of the rubber.
T_{1K} , T_{2k} : amount of temperature dissipated from the circumference or up-down side of the rubber.
T_0 : surrounding temperature.
Δt : time interval.
h : heat transfer coefficient of air.
λ : thermal conductivity of steel plates on up-down side of the rubber.

4) Amount of rising temperature inside the rubber and the parameters of hysteresis characteristics of the rubber at K step (considering the amount dissipated):

$$T_{sk} = T_0 + T_k - T_{1K} - T_{2k} \tag{3}$$

where

T_{sk} : temperature inside the rubber at K step (considering the amount dissipated).

When T_{sk} is given, the restoring force parameters at K step of the rubber will be calculated by the temperature of the rubber at that time from the Table of section 3. And the data will be applied when we calculate the earthquake response at K+1 step of the structure.

5. NUMERICAL RESULTS

Next, by using Eq.(3), numerical simulations are executed for the case of the seven floors building subjected three kinds of earthquakes (El Centro-EW, Taft-EW and Hachinohe-EW) under three different initial temperatures is investigated. Coefficients concerning restoring curves of the rubber are determined by experimental results under different temperatures. Amount of rising temperature of the isolator is estimated from absorbed energy calculated from restoring curves at each time step. Both heat transfer effects and thermal conductivity effects are considered in it. Table 3 shows maximum values of responses and the amount of rising temperature.

Table 3 Maximum values of structural response

		Surrounding temperature (°C)	Displacement (cm)	Velocity (cm/s)	Acceleration (cm/s^2)	Inter-story displacement (cm)	Amount of rising temperature (°C)
EL CENTRO	CASE-1	20	38.07	66.07	236.83	0.194	16
	CASE-2	-10	42.35	61.41	239.79	0.255	20
	CASE-3	-10	35.79	57.58	265.57	0.390	—
TAFT	CASE-1	20	21.30	50.07	447.77	0.176	7
	CASE-2	-10	19.78	52.01	467.89	0.234	13
	CASE-3	-10	19.56	49.99	478.75	0.290	—
HACHINOHE	CASE-1	20	19.95	43.01	253.96	0.156	7
	CASE-2	-10	18.10	48.69	276.55	0.226	15
	CASE-3	-10	20.73	50.90	286.87	0.273	-

Where in case1 and case2, considering the temperature rising in high damping rubber;
in case3, not considering it.

As can be seen from this table, temperature is up about 10°C to 20°C. The values of acceleration are not so reliable in this Table 3. Because very high stiffness is appeared near the turning point of hysteresis curve (Fig.1), and numerical ill conditions or singularity affect the peak acceleration. However, those are occurred in very short time, so the singularity do not affect displacements or velocity. Fig.2 and Fig.3 show displacement responses at 1-7 floors in the CASE2 and CASE3 of El Centro in Table 3.

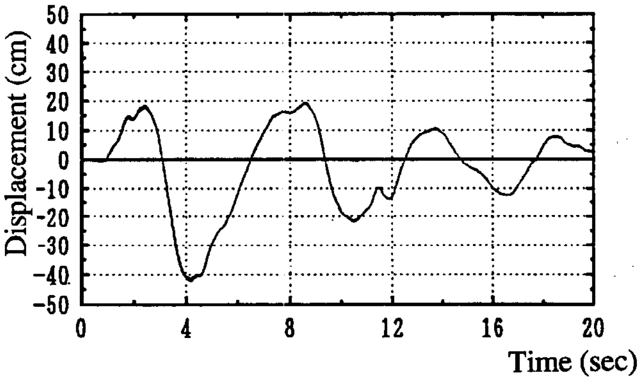

Fig.2 Displacement response at 1-7 floors (EL CENTRO-EW, -10°C, Considering the rising temperature of rubber)

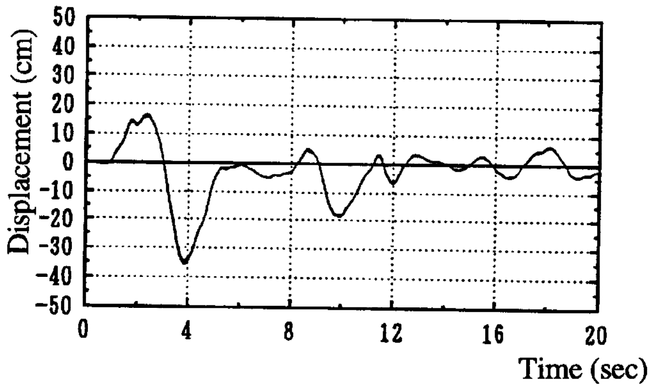

Fig.3 Displacement response at 1-7 floors (EL CENTRO-EW, -10°C, Not considering the rising temperature of rubber)

From these figures, no differences can be observed at every floor. This means whole structures move as rigid bodies.

Fig.4 shows the amount of rising temperature of rubber for the CASE-2 of El Centro in Table 3. The bold line and plain line represent the case of considering the dissipated energy or not in Eq.(3) , respectively.

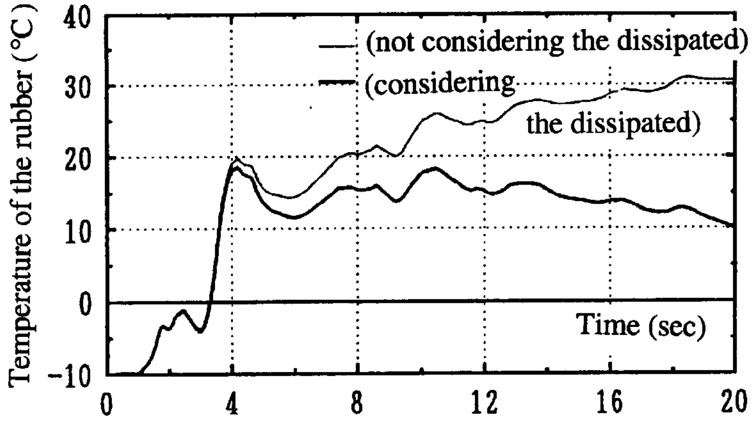

Fig.4 The amount of rising temperature of rubber (EL CENTRO-EW, -10°C)

Fig.5 and Fig.6 show the difference of hysteresis curves of high damping base isolator considering rising temperature or not. Much difference can be observed from these figures.

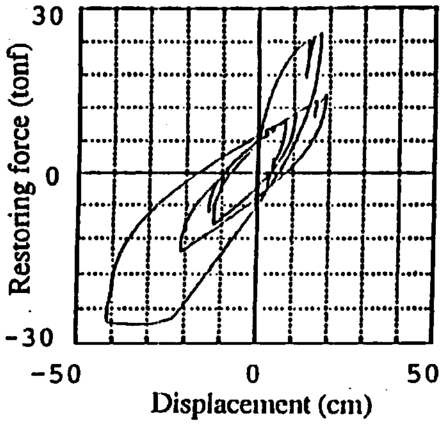

Fig.5 Hysteresis characteristics of high damping rubber (EL CENTRO-EW, -10°C , Considering the rising temperature of rubber)

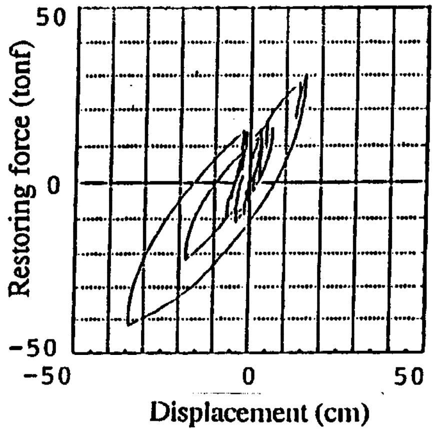

Fig.6 Hysteresis characteristics of high damping rubber (EL CENTRO-EW, -10°C , Not Considering the rising temperature of rubber)

6. CONSIDERATION AND CONCLUDING REMARKS

From the numerical results of CASE-1 and 2 in Table 3, we can see how the different surrounding temperature influenced the structural responses, each of the maximums of structural responses varies to about 10% extent between the cases of 20°C and -10°C. And from the results of CASE-2 and 3 in Table 3, if the same ground motion works in the same surround temperature, the structural responses will be influenced by the temperature dependence of high damping rubber to a great extent. In the numerical simulation here, the amount of rising temperature caused by the absorbed energy of the high damping rubber (dissipated energy) is 20°C, 13°C and 15°C in the case of El Centro-EW, Taft-EW and Hachinohe-EW, respectively (under the condition of -10°C surrounding temperature).

Because of this influence, the maximums of the earthquake responses have about 10% difference, the maximum of inter-story displacement has about 20% difference.

From the figures above, we also can see a great difference of the shapes of earthquake response, especially the shape of hysteresis characteristics between the case of considering the influence of the rising temperature of the rubber and the one of not considering it. And when the surrounding temperature becomes lower, there will be a tendency that the difference of earthquake responses in the two cases above becomes larger.

In this study, the influence of temperature dependence of high damping rubber on earthquake response of base-isolated structure has been investigated. By the numerical simulation above, following conclusion can be gained:

When the high damping rubber is used as seismic base isolator, the influence of temperature cannot be ignored that is caused of energy absorption. Especially, when the base-isolated structure in cold area is designed, the structural design should be done while considering the influence of temperature dependence of high damping rubber on earthquake response of the structure.

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