EVALUATION OF SHEAR MODULUS OF HIGH DAMPING RUBBER BEARINGS AND LEAD RUBBER BEARING DURING LOW-RATE LOAD REVERSALS

Kazuhiko KAWASHIMA[1], Masahiro KOSHITOGE[2], Chiaki SUDO[3], Yutaka MAKIGUCHI[4] and Kazuo ENDO[5]

1) Head, Earthquake Engineering Division, Public Works Research Institute, Ministry of Construction, Tsukuba Science City, Japan
2) Engineer, Testing Division, MB Material Development Department, The Yokohama Rubber Co., Ltd, Hiratsuka City, Kanagawa-ken, Japan
3) Chief Engineer, New Products Department (Seismic Isolation), Bridgestone Corporation, Yokohama City, Kanagawa-ken, Japan
4) Staff Manager, Second Technical Development Department, Oiles Corporation, Fujisawa City, Kanagawa-ken, Japan
5) Chief Engineer, Technical Development Division, The Yokohama Rubber Co., Ltd, Hiratsuka City, Kanagawa-ken, Japan

ABSTRACT

Presented are two loading schemes proposed for evaluating the equivalent stiffness of Menshin devices against low rate loading developed due to the elongation and shrinkage of a bridge deck associated with the daily change of temperature. Although it is important for properly designing the Menshin devices against such deformation, it is generally difficult to evaluate it because the test requires a special loading facility which can produce the loading with extremely low frequency. Therefore the Extrapolation Method and the Relaxation Method are proposed for such purpose. The validity of the two methods is examined through the tests to two high damping rubber bearings and a lead rubber bearing.

INTRODUCTION

Menshin devices are subjected to various loadings developed by not only seismic effects but creep, shrinkage and temperature change effect. It is one of the main feature in bridge application that the elongation and shrinkage of a deck becomes important as the total deck length becomes long. Menshin devices are designed so that the lateral force developed in the devices by not only seismic effects but such temperature change, creep and shrinkage be properly distributed to as many piers as possible. For distributing the lateral force to piers, it is important to correctly evaluate the equivalent stiffness of the devices.

Some Menshin devices have the loading rate dependence of their equivalent stiffness. For example, some high damping rubber bearings (HDR) have lower equivalent stiffness against low rate loading such as the one developed due to the daily temperature change than the equivalent stiffness against seismic loading. Such characteristics are favorable for constructing super multi-span continuous bridge with the deck length over 1 km, because the lateral force developed due to shrinkage and elongation of the deck associated with temperature change becomes quite large in such bridge. Therefore, if the equivalent stiffness against the low rate loading is small, it is favorable to reduce the lateral force caused by the deformation of the deck associated with temperature change.

For studying the equivalent stiffness against the low rate loading, a special loading facility which can produce the loading with extremely low frequency is required. However because the loading rate required is very low, it is not always easy to produce such low rate loading. Therefore special loading procedures are required for studying the equivalent stiffness against the low rate loading.

Two methods are proposed for such purpose in this paper. The validity of the procedures is presented through the implementation of the methods to two high damping rubber bearings and a lead rubber bearings.

EVALUATION METHOD OF SHEAR MODULUS AGAINST LOW RATE LOADING

Low Loading Rate Expected due to Daily Temperature Change

Associated with the deck elongation and shrinkage due to the daily temperature change, the Menshin devices are subjected to cyclic loading reversals with very low loading rate. The deck elongation and shrinkage is evaluated as

$$\triangle L = \varepsilon \cdot \triangle t \cdot L \qquad (1)$$

where,

- $\triangle L$: elongation and shrinkage of deck (m)
- ε : coefficient of elongation per unit length and unit temperature (1/m/℃)
- $\triangle t$: increase of temperature (℃)
- L : effective length of deck (m) against temperature change

The coefficient ε of elongation per unit length and unit temperature is 1.0×10^{-5} in concrete.

It is required to design the devices against such temperature change effect as[1]

$$u_O \leq \gamma_{Oa} \cdot \Sigma t_e \qquad (2)$$

$$u_E \leq \gamma_{Ea} \cdot \Sigma t_e \qquad (3)$$

where,

- u_O : design displacement of Menshin device against normal load such as creep, shrinkage and temperature change effect (cm)
- γ_{Oa} : allowable shear strain of rubber against normal load (= 0.7)
- u_E : design displacement of Menshin device against normal load and seismic effects
- γ_{Ea} : allowable shear strain of rubber against normal load and seismic

effects, and shall be 1.5 in the Seismic Coefficient Method and 2.5 in the Bearing Capacity Method

Σt_e : total thickness of rubber (cm)

Because the Menshin devices are designed so that Eqs. (2) and (3) are satisfied, it can be considered that the shear strain induced in the Menshin devices due to the temperature change effect should be less than γ_{cs}, i.e., 70 %. There are other contribution by the creep and shrinkage in concrete bridges. Therefore the shear strain induced in the Menshin devices against the temperature change effect may be between 50 % and 70 %.

Assuming that the daily temperature changes in a harmonic way as shown in Fig. 1 with the period of 24 hours, the averaged shear strain rate may be approximated as

$$\dot{\gamma} = \frac{\gamma}{t'} - \frac{50\% \sim 70\%}{6 \text{ hours}} = 2.3 \times 10^{-5}/\text{sec} \sim 3.2 \times 10^{-5}/\text{sec} \quad (4)$$

in which γ and $\dot{\gamma}$ represent the shear strain and shear strain rate, and t' represents a quarter of a day (6hours).

It should be noted that the shear strain rate during an earthquake is much larger than those values. Because the Menshin devices are designed against normal load and seismic load so that Eq. (3) be satisfied, one can consider that the shear strain developed in the Menshin device during an earthquake is at maximum 150 % in the Seismic Coefficient Method. Therefore assuming that the first natural period of the bridge is 2 second, the shear strain rate during an earthquake may be estimated as

$$\dot{\gamma} = \frac{\gamma}{t'} = \frac{150\ \%}{1/4 \text{ second}} = 3\ /\text{sec} \quad (5)$$

Extrapolation Method

If the loading rate vs. the equivalent stiffness of the Menshin devices can be evaluated for a set of loading rates which can be produced by the testing machine available, the equivalent stiffness for the desired loading rate may be estimated by extrapolating the relation. This method is not special but may be used for most type of Menshin devices.

In the Manual for the Menshin Design of Highway Bridges, it is recommended to conduct the test for loading rate of 0.002 cm/sec, 0.005 cm/sec, 0.01 cm/sec, 0.05 cm/sec, 0.1 cm/sec, 0.5 cm/sec, 1.0 cm/sec and 5.0 cm/sec. The Menshin devices are subjected to a harmonic excitation with either strain amplitude of ±50% or displacement amplitude of ±7.5 cm under the vertical load equivalent to the dead weight of superstructure and at the temperature of 20℃.

Relaxation Method

Although the mechanism causing the loading rate dependence of the shear modulus of rubber (high damping rubber) is not well known, it may be related to the relaxation of the rubber. Therefore the loading rate dependence of the shear modulus of rubber may be evaluated by the relaxation method.

When a rubber specimen is subjected to a constant shear strain for a certain period, the stress induced in the specimen decreases as shown in Fig. 2 (a) and (b). Because shear modulus of the rubber is defined as

$$G_r = \frac{\tau}{\gamma} \tag{6}$$

where,

G_r : shear modulus of rubber (kgf/cm^2)
τ : shear stress (kgf/cm^2)
γ : shear strain

shear modulus G_r vs. period of relaxation t^* relation can be written as shown in Fig. 2(c). The averaged shear strain rate for a period of relaxation t^* may be evaluated from Eq. (4) as

$$\dot{\gamma} = \frac{\gamma}{t^*} \tag{7}$$

Therefore, the shear modulus G_r vs. shear strain rate $\dot{\gamma}$ relation may be written as shown in Fig. 2(d). It should be noted that this relation is similar in nature with the loading frequency dependence of the shear modulus of rubber subjected to a harmonic excitation. Therefore, by specifying an appropriate shear strain rate $\dot{\gamma}$, one can estimate the shear modulus for $\dot{\gamma}$. It should be noted that the equivalent stiffness of the Menshin devices can be obtained from the shear modulus of the rubber as

$$K_E = \frac{A_R \cdot G_r}{\Sigma t_r} \tag{8}$$

where,

K_E : Equivalent Stiffness of Menshin device (kgf/cm)
A_R : Sectional area of Menshin device (cm^2)
G_r : Shear modulus of rubber (kgf/cm^2)
Σt_r: Total thickness of rubber (cm)

This method is proposed hereinafter as the "Relaxation Method".

However various consideration has to be made for applying the Relaxation Method for evaluating the equivalent stiffness of the Menshin devices subjected to the daily temperature change, because the shear strain developed in the Menshin devices by the daily temperature effect changes with time as shown in Fig. 1.

As the first approximation for such change, a constant strain may be applied to the devices as shown in Fig. 3(a). But more accurate result may be obtained by applying the strain in several steps as shown in Fig. 3 (b) and (c). It is expected that the accuracy would be improved by increasing the number of load step.

In such a stepwise loading, the load need to be applied as follows. Consider the case where the shear strain is applied to the devices in three steps. The shear strain for which the low loading rate stiffness is required (target shear strain γ_T) is divided into three steps as shown in Fig. 4(a). The load needs to be applied to the specimen until the shear strain induced in the specimen reaches to 1/3 of the target shear strain. Then hold this shear strain for two hours so that relaxation be developed. The stress of the specimen decreases as shown in Fig. 4(b) due to relaxation. Then, apply the load until the shear strain induced in the specimen reaches to 2/3 of the target shear strain and hold it for two hours. Finally the same procedure needs to be repeated for the target shear strain. The stress developed in the specimen after the relaxation for two hours at this shear strain level is the shear stress required. This approximates the shear strain developed against a quarter cycle of harmonic loading with the period of 24 hours. Because actuator can be held for two hours after each stepwise loading, a special loading facility which is capable to produce the extremely low frequency loading is not required.

The shear stress vs. shear strain relation of Fig. 4 (a) and (b) can be obtained as shown in Fig. 4(c).

Although it was proposed to apply the shear strain as shown in Fig. 4 (a), it may be applied as shown in Fig. 5 (Loading Scheme B) as an alternative scheme. The Loading Scheme A which was proposed in Fig. 4 (a) would give higher equivalent stiffness than the Loading Scheme B, because relaxation time at the target shear strain is longer. Loading scheme for approximating the actual change of the daily temperature needs to be carefully set.

TEST MODELS

Three types of test specimens as shown in Table 1 were used to evaluate the stiffness of the devices against low strain rate load reversals. The HDR-A and LRB are specimens fabricated for this test. The HDR-B is the specimen with the same size and characteristics with the one adopted for the Yama-age Bridge[2]. Figs. 6,7 and 8 as well as photos 1, 2 and 3 show the specimens.

LOW LOADING RATE SHEAR MODULUS OF HDR-A

Extrapolation Method

In the Extrapolation Method, the HDR-A was subjected to a harmonic loading with the displacement amplitude equivalent to 50% shear strain of the rubber. The loading frequency was varied as 0.05 Hz, 0.1 Hz, 0.05 Hz, 0.01 Hz, 0.005 Hz, 0.001 Hz and 0.00025 Hz. Because the strain rate may be evaluated as

$$\dot{\gamma} \fallingdotseq 4 \cdot \gamma \cdot f \quad (9)$$

where,

$\dot{\gamma}$: strain rate (1/sec)

γ : shear strain

f : frequency (Hz = 1/sec)

the strain rate in the tests was from 1/sec to 0.00041/sec.

The vertical load of 14.7 tf, which corresponds to the vertical stress of 60 kgf/cm^2, was applied to the specimen for representing the dead weight of the deck. A special loading facility at the Yokohama Rubber Co. was used for the test.

Fig. 9 shows the hysteresis of shear strain vs. shear stress relation for the shear strain rate of 1/sec, 0.021/sec and 0.00041 /sec. It is apparent that the equivalent stiffness decreases as the shear strain rate decreases. Fig. 10 and Table 2 show how the equivalent stiffness in terms of shear modulus decreases as the shear strain rate decreases. Because the test results for various strain rates are consistent, they may be approximated as

$$G_E = 5.83\, \dot{\gamma}^{0.204} + 7.0 \quad (10)$$

where,

G_E : shear modulus of HDR-A (kgf/cm^2)

$\dot{\gamma}$: shear strain rate (1/sec)

By substituting γ = 2.3 x 10^{-5}/sec from Eq. (4), one can estimates the shear modulus of 7.7 kgf/cm^2. Because the shear strain during an earthquake is about 3/sec by Eq. (5), the shear modulus at the shear strain rate of 3/sec is evaluated by Eq. (10) as 14.3. The 7.7 kgf/cm^2 is about 46 % smaller than 14.3.

Relaxation Method

After the Extrapolation Method was made, the same specimen was used for the Relaxation Method. In the Relaxation Method, the target shear strain of 50 % was applied in the period of 6 hours. The loading step was set as 1, 2 and 4. In case of loading step of 1, the specimen was subjected to a load with the loading rate of 1 mm/sec (shear strain rate of 2.1 x 10^{-2}/sec) until 50 % shear strain. Then holding of the shear strain was made for 6 hours to have the relaxation. In the case of loading step of 4, the specimen was firstly loaded until 12.5 % shear strain, and the the shear strain was kept constant for 1.5 hour. The load was then increased so that 25% shear strain was developed, and the holding of the shear strain was made for 1.5 hour. Similarly, the load was stepwisely increased until the shear strain reached to 50%. It should be noted that because the shear strain was increased from 0 to 50% for 6 hours, the shear strain rate is 2.3 x 10^{-5}/sec for all the three tests.

Fig. 11(a) shows the shear strain vs. relaxation time relation thus used for the three types of loading steps. The relaxation of shear force of the specimen was developed as shown in Fig. 11(b). It is seen that the shear force at the shear strain of 50% slightly increases as the number of load step increases from 1 to 4. It is expected that the case of 4 loading step would give more accurate result. Fig. 11 (c) shows the shear force vs. shear strain relation.

From those results, the shear modulus of the HDR-A was evaluated as shown in Table 3. The shear modulus was 7.0 kgf/cm^2 in case of 4 load step. Reminding that for the shear strain rate of 2.3 x 10^{-5}/sec the shear modulus of the HDR-A evaluated by the Extrapolation Method was 7.7 kgf/cm^2, the shear modulus evaluated by the Relaxation Method is very close with that evaluated by the Extrapolation Method.

LOW LOADING RATE SHEAR MODULUS OF LRB

Extrapolation Method

The specimen was subjected to a harmonic loading with the displacement amplitude equivalent to 70% shear strain of the rubber. The loading frequency was varied as 1 Hz, 0.023 Hz, 0.0023 Hz, 0.00023 Hz and 0.000012 Hz. Because a specially designed facility which is capable for evaluating the low rate loading at Oiles Corporation was used, loading test could be made for the target shear strain (70 % / 6 hours = 3.2 x 10^{-5}/sec). The shear strain rate by Eq. (9) is from 4.4/sec to 0.00005/sec in this series of tests. The vertical load of 30.2 tf, which corresponds to the vertical stress of 60 kgf/cm^2, was applied to the specimen.

Fig. 12 shows the hysteresis of shear strain vs. shear force relation for the shear strain rate of 4.4/sec, 0.01/sec and 0.0002/sec. From these results, shear strain rate dependence of the shear modulus was obtained as shown in Fig. 13 and Table 4. The shear modulus G_s vs. shear strain rate $\dot{\gamma}$ relation may be approximated as

$$G_s = 12.1\,\dot{\gamma}^{0.0406} \qquad (11)$$

From Eq. (11) the shear modulus for the shear strain rate of 3.2 x 10^{-5} /sec is estimated as 7.9 kgf/cm^2. On the other hand, the shear strain rate developed during an earthquake is estimated by Eq. (5) as 3/sec. The shear modulus corresponding to this shear strain rate is evaluated by Eq. (11) as 12.7 kgf/cm^2. Therefore the above shear modulus for the daily temperature change is approximately 38 % smaller than the one developed during an earthquake.

Relaxation Method

The same specimen was used for the Relaxation Method. The target shear strain was assumed as 70 %, and the number of load step was 1. Therefore the load was increased until the shear strain of the specimen reached 70 %, and then holding of this shear strain was made for 6 hours.

Fig. 14 shows the decrease of stress developed in the specimen and the shear force vs. shear strain relation. From these results, the shear modulus of the specimen was obtained as 7.7 kgf/cm^2 for the loading rate of 3.2 x 10^{-5}/sec. Because the shear modulus evaluated from the Extrapolation Method is 7.9 kgf/cm^2, this value is quite close with the one evaluated by the Extrapolation Method.

LOW LOADING RATE SHEAR MODULUS OF HDR-B

Only Extrapolation Method was applied to the HDR-B. The specimen was subjected to a harmonic loading with the displacement amplitude of 70 % of the shear strain of the rubber. The loading frequency was varied as 0.005 Hz, 0.0011 Hz, 0.00011 Hz and 0.000012 Hz. The vertical load of 238 tf, which corresponds to the vertical stress of 40 kgf/cm^2, was applied to the specimen beside the lateral loading.

Fig. 15 shows the hysteresis of shear force vs. shear strain. From these results, the shear strain rate dependence of the shear modulus was evaluated as shown in Fig. 16 and Table 5. This can be approximated as

$$G_{eq} = 11.1 \cdot \dot{\gamma}^{0.0416} \qquad (12)$$

Based on Eq. (12), the shear modulus corresponding to the shear strain rate of 3.2 x 10^{-5}/sec and 3/sec is evaluated as 7.2 kgf/cm^2 and 11.6 kgf/cm^2. Therefore, the shear modulus developed during the daily temperature change is 38 % smaller than that developed during an earthquake.

CONCLUSIONS

For evaluating the equivalent stiffness of the Menshin devices subjected to low shear strain rate loading, two methods were proposed. In both the Extrapolation Method and the Relaxation Method, the test can be made even if a loading facility which is capable for producing extremely low frequency loading is not available. A series of loading tests were made for verifying the test methods proposed with use of two high damping rubber bearings and a lead rubber bearing. From the results presented in, the following conclusions may be deduced :

1) The shear modulus of HDR-A evaluated by the Extrapolation Method for the shear strain rate of 2.3 x 10^{-5}/sec (= 50 % / 6 hours) is 7.7 kgf/cm^2, while the value evaluated by the Relaxation Method is 7.0 kgf/cm^2.

2) The shear modulus of LRB evaluated by the Extrapolation Method for the shear strain rate of 3.2 x 10^{-5}/sec (= 70 % / 6 hours) is 7.9 kgf/cm^2, while the value evaluated by the Relaxation Method is 7.7 kgf/cm^2.

3) Based on 1) and 2), it can be said that the Relaxation Method gives the close shear modulus by the Extrapolation Method. Therefore, the Relaxation Method can be used as well as the Extrapolation Method for estimating the equivalent stiffness of Menshin devices for low rate loading developed by the temperature change.

4) Based on the Extrapolation Method, the shear strain rate dependence of the shear modulus is given by Eq. (10) for HDR-A and by Eq. (11) for LRB.

5) Assuming that the shear strain rate developed during an earthquake is 3/sec and that the shear strain rate due to the daily temperature change is 2.3×10^{-5} for HDR-A and 3.2×10^{-5} for LRB and HDR-B, the shear modulus against the daily temperature change is 46 % (HDR-A), 38 % (HDR-B) and 38 % (LRB) smaller that the one developed during an earthquake.

REFERENCES

1) Public Works research Institute and 28 Private Firms : Manual for Menshin Design of Highway Bridges, Bulletin of PWRI, Vol. 59, Public Works research Institute, March 1992

2) Ikeda, T., Kumakura, K, Oozeki, K. and Abe, N. : Design of Karasuyama (Yama-Age), Bridge, Bridges and Foundation, Vol. 91-6, 1991

Table 1 Specimens Used for Loading Tests

Specimen	Natural Period in Design (sec)	Dead Weight with Live Load		Design Displacement of Menshin Device (cm)
		Vertical Load (tf)	Vertical Stress (kgf/cm^2)	
HDR-A	1.2	15	60	7
HDR-B	1.4	328	56	33
LRB	0.9	30	60	6

Table 2 Shear Strain Rate Dependence of Shear Modulus of HDR-A evaluated by Relaxation Method

Frequency Hz	Strain Rate (1/sec)	Shear Modulus (kgf/cm^2)
2.5×10^{-4}	4.1×10^{-4}	8.3
1.0×10^{-3}	2.1×10^{-3}	8.5
5.0×10^{-3}	1.1×10^{-2}	9.3
1.0×10^{-2}	2.1×10^{-2}	9.7
5.0×10^{-2}	1.1×10^{-1}	10.6
1.0×10^{-1}	2.1×10^{-1}	11.2
5.0×10^{-1}	1.0	12.9

Table 3 Effect of Number of Load Step by Relaxation Method (HDR-A)

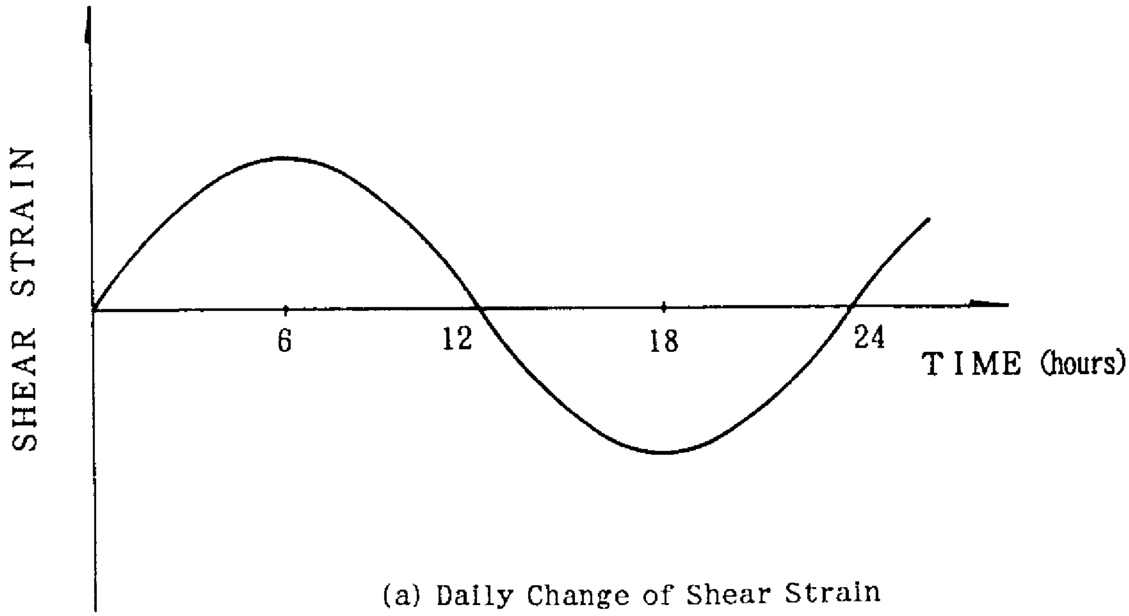
Number of Load Step	Shear Modulus G_s (kgf/cm^2)
1	6.1
2	6.5
4	7.0

Table 4 Shear Strain Dependence of Shear Modulus of LRB by Extrapolation Method

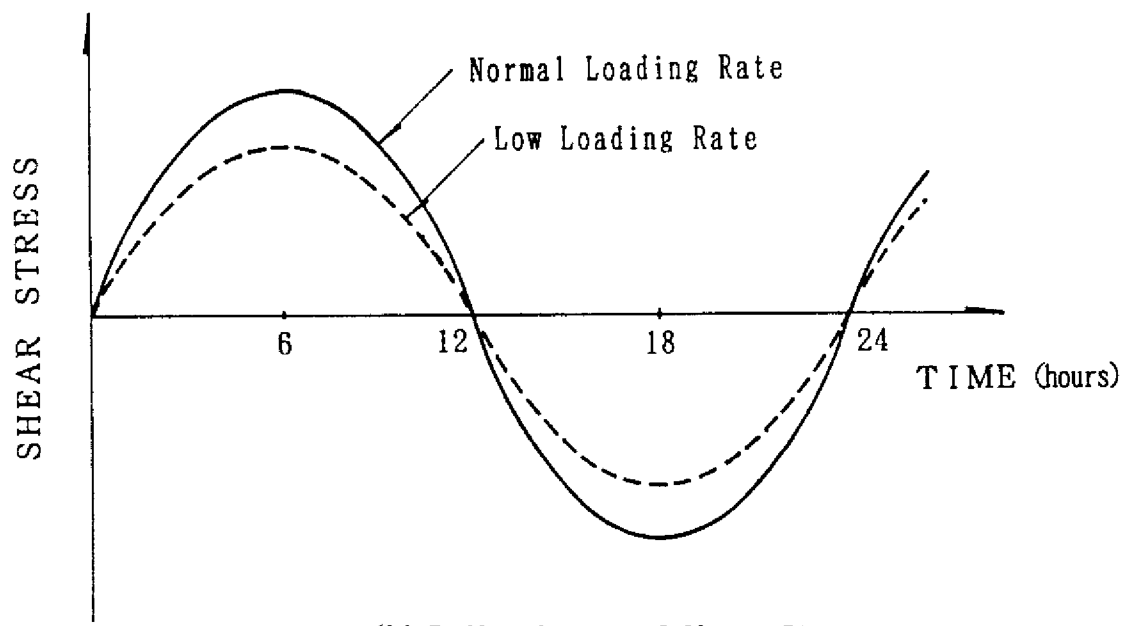
Frequency Hz	Strain Rate (1/sec)	Shear Modulus (kgf/cm^2) No.1 Facilities	No.2 Facilities
4.6×10^{-5}	2.0×10^{-4}	–	8.7
2.0×10^{-4}	8.8×10^{-4}	9.0	9.2
2.0×10^{-3}	8.8×10^{-3}	9.8	10.1
2.0×10^{-2}	8.8×10^{-2}	10.7	–
1.0	4.4	13.1	–

Table 5 Shear Strain Dependence of Shear Modulus of HDR-B by Extrapolation Method

Frequency Hz	Strain Rate (1/sec)	Shear Modulus (kgf/cm^2)
1.2×10^{-5}	3.3×10^{-5}	7.2
1.1×10^{-4}	3.2×10^{-4}	7.9
1.1×10^{-3}	3.2×10^{-3}	8.8
5.0×10^{-3}	1.4×10^{-2}	9.3



(a) Daily Change of Shear Strain



(b) Daily Change of Shear Stress

Fig. 1 Change of Shear Stress Shear Strain Induced in Menshin devices by Daily Change of Temperature

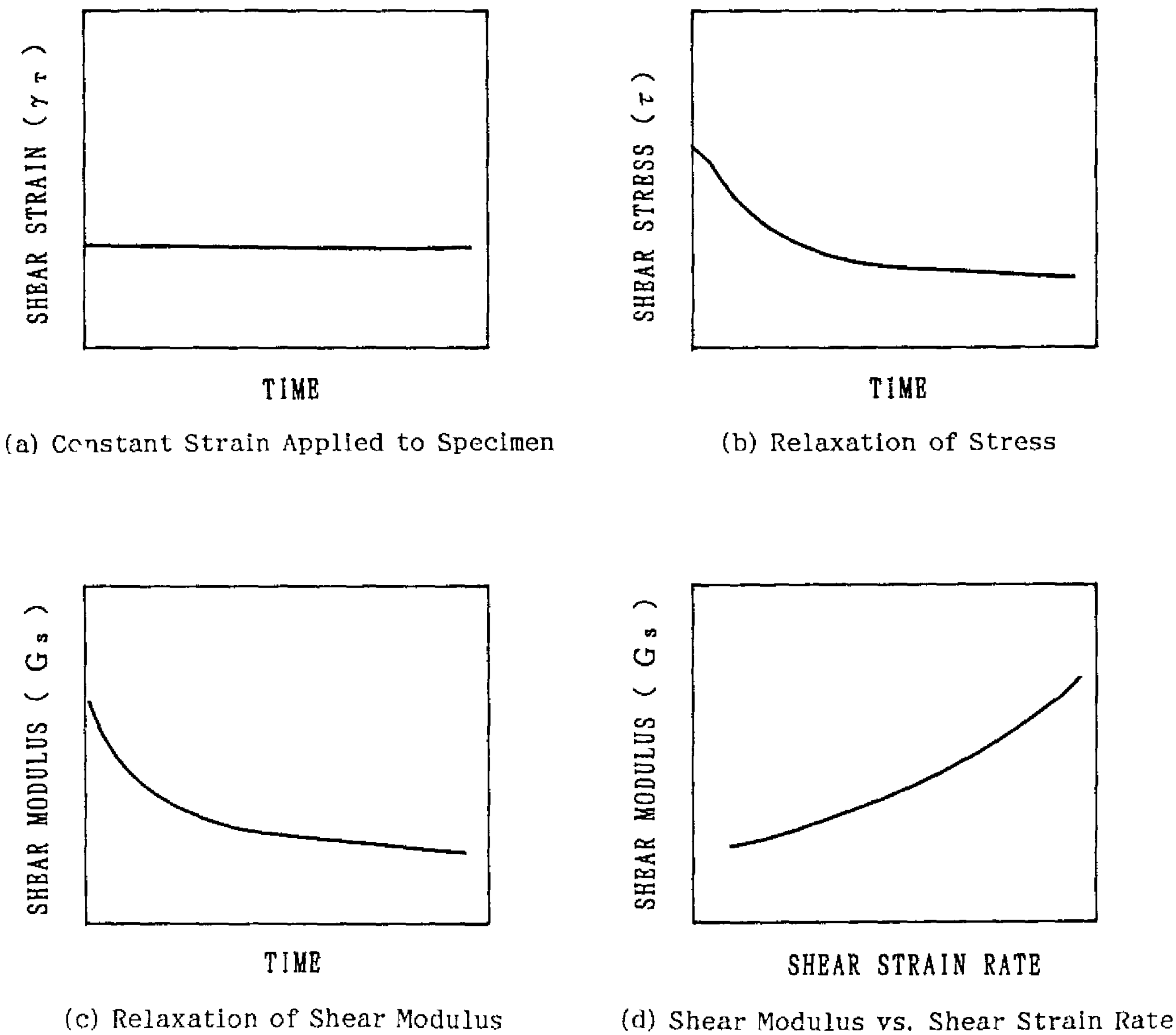
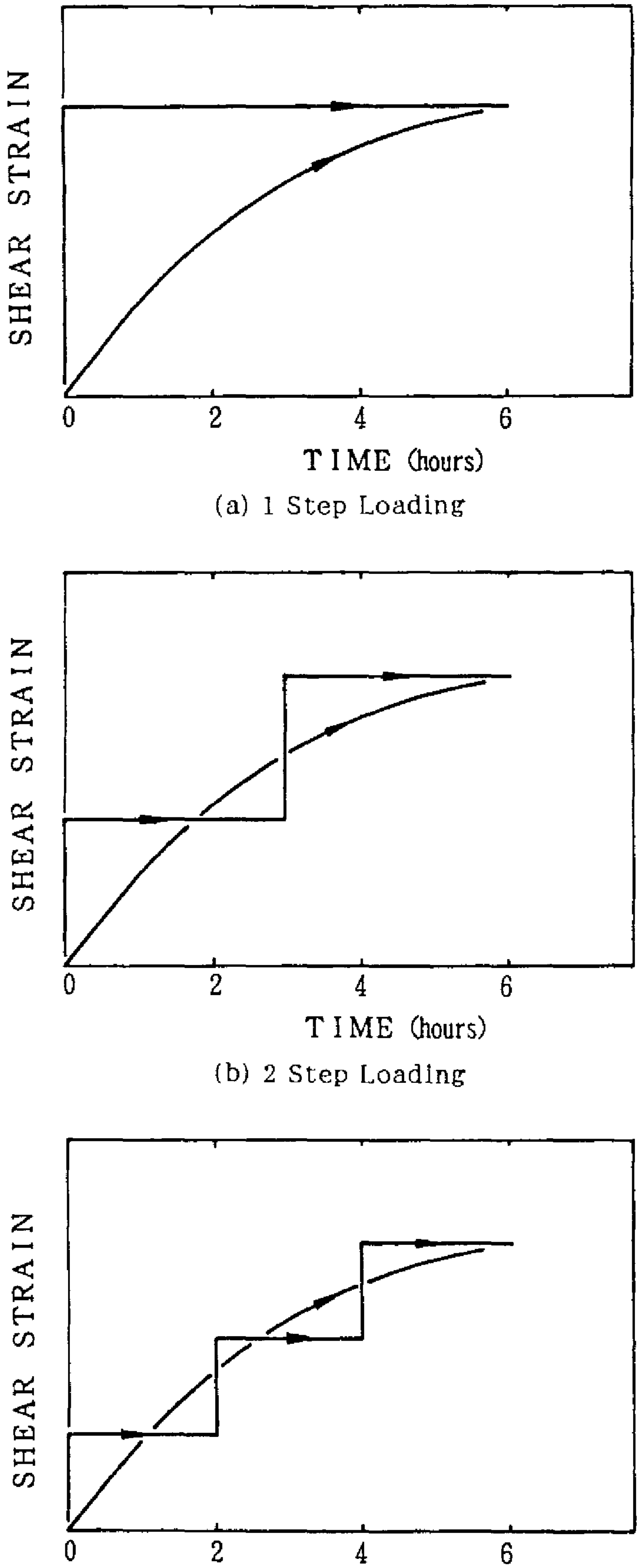


Fig. 2 Stress and Strain developed due to Relaxation

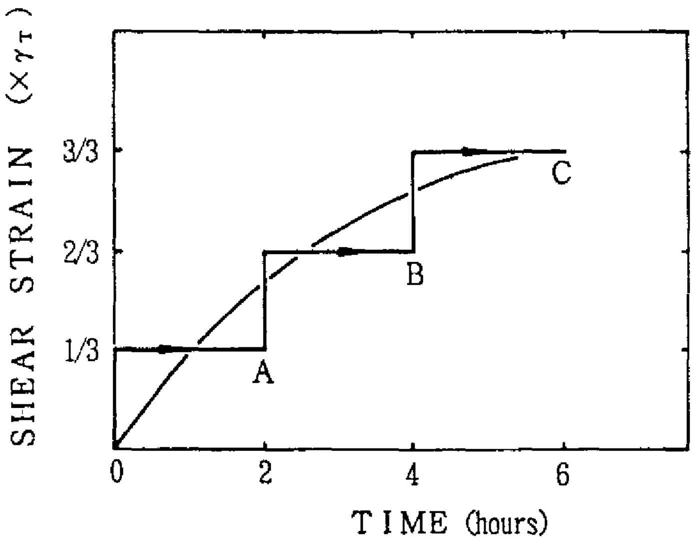


(a) 1 Step Loading

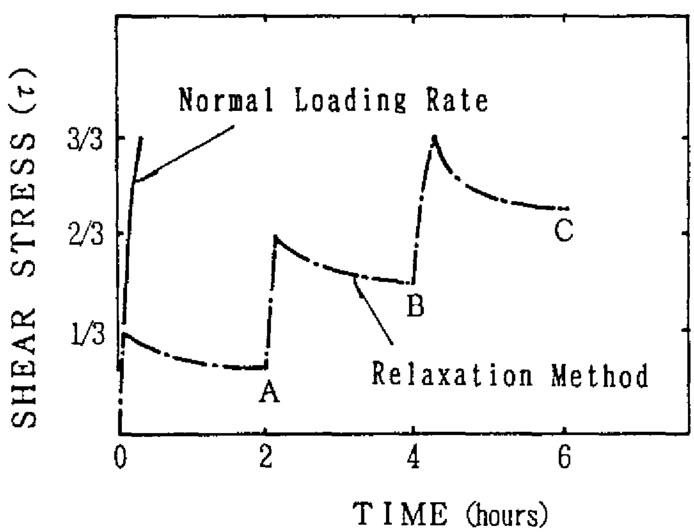
(b) 2 Step Loading

(c) 3 Step Loading

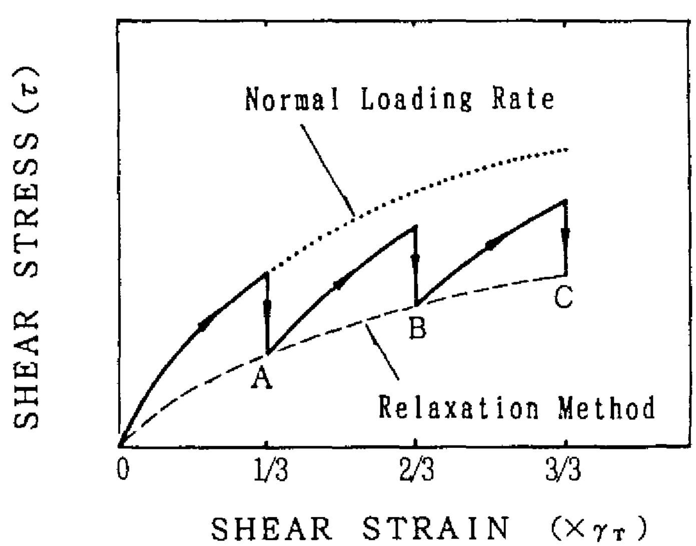
Fig. 3 Approximation by Stepwise Loading in Relaxation Method



(a) Shear Strain Applied to Specimen



(b) Shear Stress Hysteresis



(c) Shear Stress vs. Shear Strain Rate Relation

Fig. 4 Relaxation of Shear Stress vs. Shear Strain Rate in Relaxation Method for 3 Step Loading

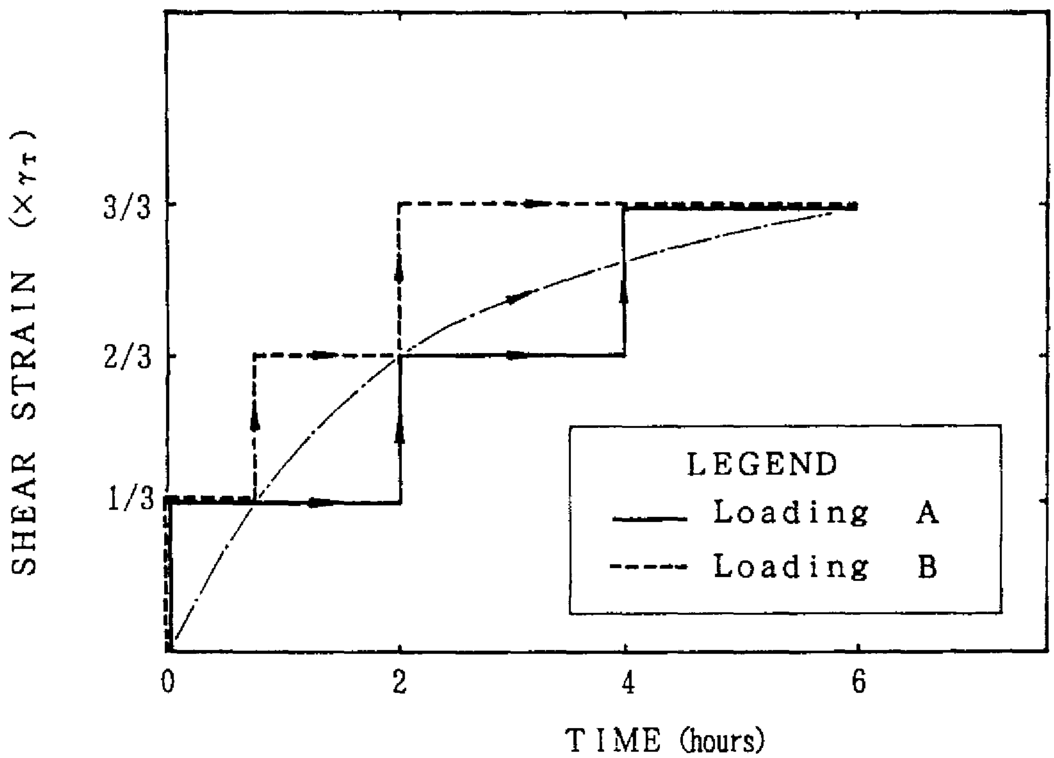
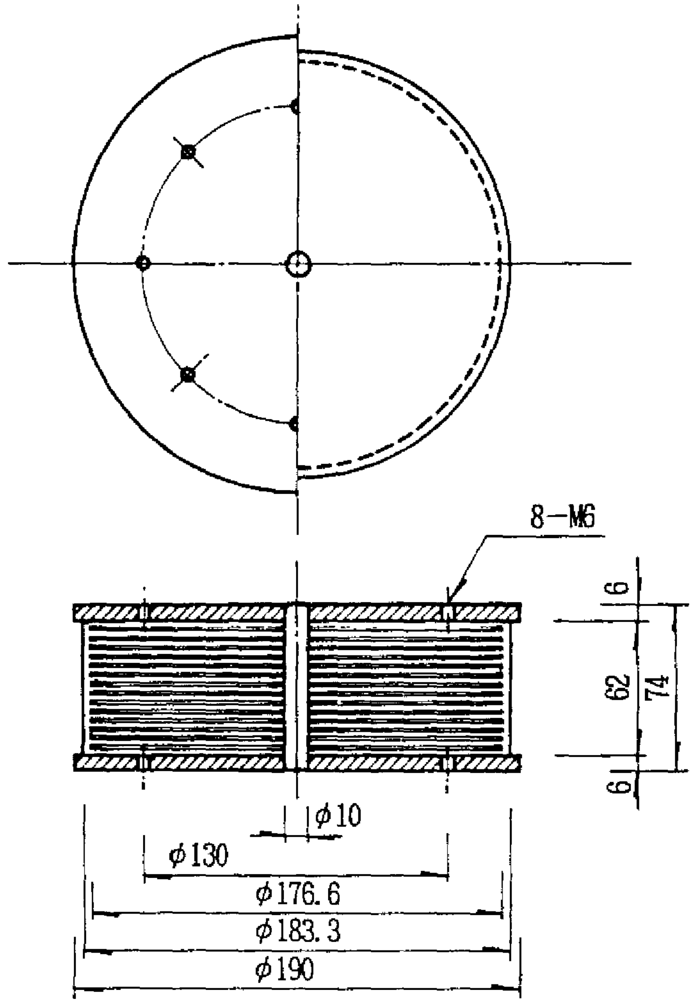


Fig. 5 Two Loading Schemes for Controlling Shear Strain



Rubber Layer 3.17mm×15=47.5mm

Steel Plate 1.0 mm×14=14.0mm

Fig. 6 Test Specimen of HDR-A

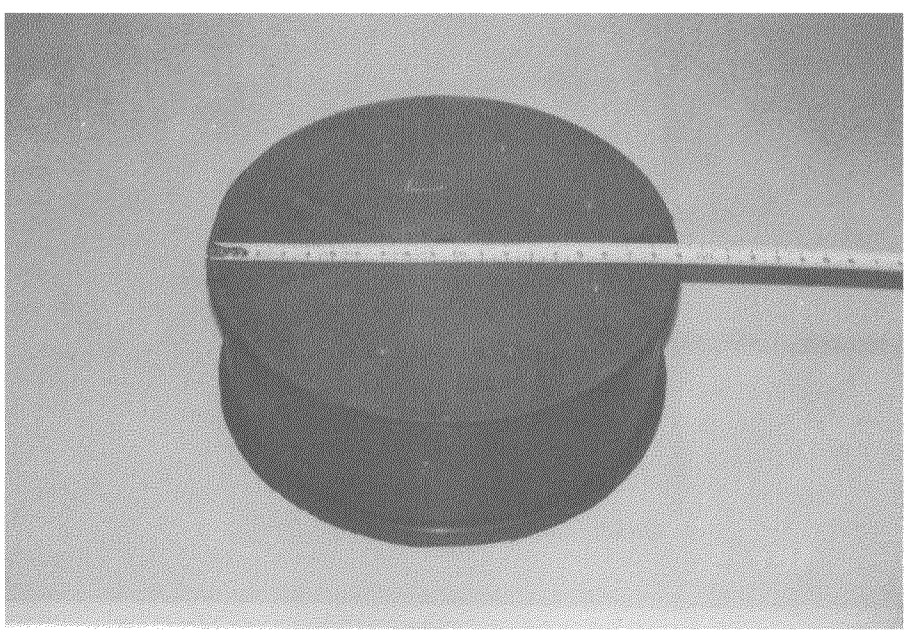


Photo 1 Test Specimen of HDR-A