High Damping Natural Rubber for Seismic Isolation Bearings

H. R. AHMADI, V. A. COVENEY, K. N. G. FULLER
Malaysian Rubber Producers' Research Association Brickendonbury, Hertford, UK

1 INTRODUCTION

Base isolation of structures has been gaining worldwide acceptance as a strategy for earthquake protection over the past five years. Because it protects the contents as well as the structure itself, base isolation is particularly suitable for buildings which house important, vulnerable equipment. Many modern schemes are based on laminated natural rubber bearings. The most rapid recent uptake of base isolation has occurred in Japan (Kelly 1988).

To be most effective, practical base isolation schemes need to incorporate a certain amount of damping. Normal natural rubber formulations give low damping and in many base isolation systems energy dissipation is provided by devices external to the bearing. In contrast high damping natural rubber (HDNR) isolation bearings utilize specially-developed formulations to provide sufficient damping within the elastomer itself. This paper concentrates on HDNR isolation bearings.

2 ISOLATION AND DAMPING

The low horizontal stiffness of the isolators results in quite large relative displacements between the building and the ground during an earthquake. Moderately high levels of damping in the isolators can help to reduce the relative displacements and the peak acceleration experienced by the structure and its contents. It should be pointed out, however, that doubling the damping from 10 to 20% of critical generally results in only modest further reductions (Delfosse 1982).

3 SIMPLE MATERIAL MODELS

The Kelvin and the standard linear (SL) models are commonly used to represent materials with damping. A Kelvin model material has a loss factor ($\tan\delta$) which is proportional to the frequency (f) and a complex shear modulus (G^*) which increases roughly with f^2 over a limited range. The SL model also exhibits strong frequency dependence of G^* and $\tan\delta$. Both Kelvin and SL models (like all linear models) give sinusoidal force-time signals for sinusoidal displacements. The dynamic stiffness for such idealised representations is independent of amplitude and no harmonics are introduced. The behaviour of high damping elastomers differs from that predicted by these simple models in a number of respects.

4 DYNAMIC BEHAVIOUR OF HIGH DAMPING ELASTOMERIC MATERIALS

In some elastomeric materials (eg. nitrile or epoxidized natural rubber [ENR]) damping originates primarily from mechanisms associated with the elastomer-glass transition; this can result in strong dependence of G^* and δ on temperature and frequency. HDNR materials, however, derive their high level of damping primarily from interactions involving solid filler particles added to the elastomer formulation, and sensitivity to frequency and temperature is much less.

For HDNR-1 (a medium modulus HDNR) G^*, at shear strain amplitude $\gamma_a = 0.5$, increases by 8% in the frequency range 0.5-20Hz while the loss angle (δ) increases by 20%; the Kelvin model, in contrast, gives eight-fold increases in G^* and δ in the same frequency range. The similarly modest effect of temperature on modulus and damping of HDNR-1 is shown in Fig.1 along with data for: higher [HDNR-2] and lower modulus [HDNR-S] variants; heavily [ENR-HI] and less heavily filled [ENR-LO] ENR; and a material developed in Japan [HD-J] (Kojima and Fukahori, 1989).

In contrast to the insensitivity with frequency and temperature, G^* for HDNR materials is strongly dependent on the amplitude of sinusoidal deformation (Fig.2). It might be expected that such strong non-linearity would introduce substantial, higher harmonics into the force response to sinusoidal deformation. The data for the variation of the in-phase modulus G' with shear strain amplitude (γ_a) was applied to the spring element in the Kelvin model; the third harmonic level predicted by this modified Kelvin model was 12%. The out-of-phase modulus $G''(=G^* \sin\delta)$ was kept constant throughout each cycle; representative values in the range 0 to 0.3MPa were used. It is therefore perhaps surprising that when HDNR-1 is subjected to 0.5Hz sinusoidal shear deformations at strain amplitudes up to 1.0 the third harmonic level in the force signal is less than 4% (see Table 1).

5 EARTHQUAKE SIMULATION

Recently, experiments have been performed to study more closely the extent to which HDNR can be modelled linearly, and the degree to which such materials will introduce higher harmonics into the isolated structure during an earthquake. A test-piece of HDNR-1 was subjected to a 'representative' shear-displacement history and the resulting shear-force history was monitored. The chosen displacement history (EC) was calculated by applying the El Centro 1940 earthquake (SOOE horizontal component) to a single degree of freedom mass on a Kelvin model system with a natural frequency of 0.5Hz and damping 0.1 of critical and taking the difference between the ground and the mass displacements. The displacement history obtained had a very strong component at the isolation frequency and approximated to a modulated 0.5Hz sinusoidal signal (Fig.3). The experimental force signal (Fig.3) was first analysed by dividing the force level at peaks (and troughs) by the corresponding peak displacement. The resulting stiffness values are compared with 6th cycle stiffnesses obtained from standard sinusoidal tests in Fig.4. The two sets of values are remarkably similar and indicate that large shear strain cycles during an earthquake may exert only a minor effect on subsequent small strain amplitude cycles. In spite of this marked nonlinearity the form of the frequency spectrum of the force signal was almost indistinguishable from that of the applied displacement history (Fig.5); the force level at 1Hz was ~4% of that at 0.5Hz and the displacement level at 1Hz was ~3% of that at 0.5Hz.

The experiment was repeated with the timescale of the displacement history reduced by factors of 2 and 2.82. The results showed similar nonlinear behaviour regarding amplitude-dependent stiffness, in all cases. This suggests that many aspects of the behaviour of HDNR observed in shaking table tests, at linear scaling factors up to 8, are valid for full-scale performance.

The force response history of the elastomer to the above displacement history was compared with that predicted by a Kelvin and by an SL model (Fig.3). The parameters for the two models were chosen in the following way. The loss angles (δ) and the complex shear moduli (G^*) given by the models were matched to those of the real material when subjected to steady sinusoidal deformation at 0.5Hz and at a strain amplitude equal to half the peak strain amplitude produced by the displacement history. The SL model required an additional parameter and this was found by matching the (log-log) frequency dependence of the loss angle predicted by the model with that observed for the material at 0.5Hz.

Both the Kelvin and the SL models represent many of the gross features of the real material behaviour - the SL offering no significant improvement over the Kelvin model; the linear models do, however, underestimate the peak force levels during small strain cycles. More accurate predictions of the peak force levels are given by the Kelvin model modified to have strain-dependent stiffness, however, unrealistically high levels at frequencies above 0.5Hz are predicted in the force signal.

6 CREEP

All elastomers exhibit creep under constant load so that the settlement of elastomeric bearing pads may have to be taken into account. Creep comprises a 'physical' component which increases approximately linearly with log time and a 'chemical' component which increases roughly linearly with time. For HDNR materials, physical creep is likely to dominate over chemical creep for the first few years. A typical value for chemical creep rate in natural rubber formulations is ~0.5% of initial displacement per year. Physical creep rate depends quite significantly on details of the natural rubber formulation, mode of deformation and strain. But in shear at ~50% strain, typical physical creep rates of HDNR-2 and HDNR-S are ~7% per tenfold increase in time. Creep rates in HDNR bearings may be significantly lower if the shape factor is more than about 10 (diameter 40 times an elastomer layer thickness) since in this case a significant proportion of the vertical displacement will be due to dilatational rather than deviatoric deformation of the elastomer.

7 CONCLUSIONS

The dependences of modulus and damping on temperature and frequency have been described for various elastomeric materials. HDNR materials offer attractions over other options in terms of their insensitivity to temperature and frequency. The stiffness of HDNR is greater for low strain amplitude cycling than for high amplitude cycling but this nonlinearity does not produce substantial higher harmonics. Components within the isolated structure are therefore likely to be well protected. Many important aspects of the behaviour of HDNRs to earthquake-related deformation histories can be predicted by simple linear models. Indeed, somewhat surprisingly, the Kelvin model modified to take account of the observed non-linearity gave generally poorer predictions. Isolation bearings based on HDNR can be devised to have very low settlement rates.

TABLE 1. Harmonics in force signal (% of fundamental, for 0.5Hz sinusoidal test on HDNR-1 (* indicates < 1%)

	Shear strain amplitude					
Harmonic	0.02	0.05	0.2	0.5	0.8	1
1(Fund.)	100	100	100	100	100	100
2	*	*	*	*	*	*
3	3	3	1.5	1.5	2.5	3.5
4	*	*	*	*	*	*
5	*	*	1	1.5	2.5	3

8 REFERENCES

Delfosse,G.C. (1982). Wood-Framed Individual Houses on Seismic Isolators, Proc. Internat. Conf. on Natural Rubber for Earthquake Protection of Buildings and Vibration Isolation, MRRDB, Kuala Lumpur.

Kelly,J.M. (1988). Base Isolation in Japan, UCB/EERC-88/20, University of California, Berkeley.

Kojima,H. and Fukahori,Y. (1989). Performance and Durability of High Damping Rubber Bearings For Earthquake Protection, ACS Rubber Division Fall Meeting, Detroit.

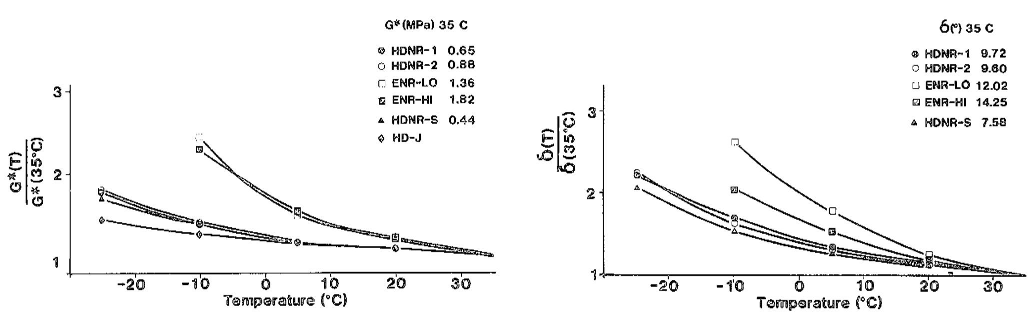

Fig.1 Temperature dependance

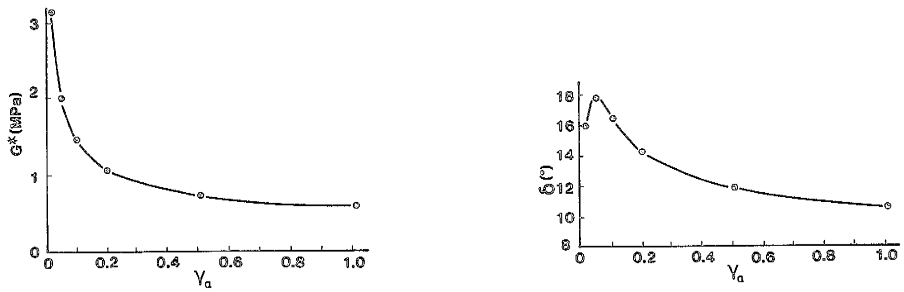

Fig.2 Shear modulus(G*) and phase angle(δ) against shear strain amplitude (γ_a)

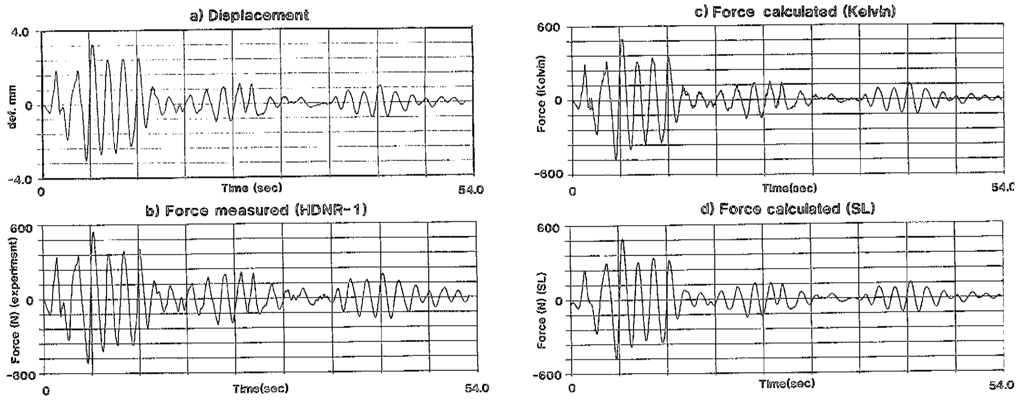

Fig.3 Displacement and force histories(EC)

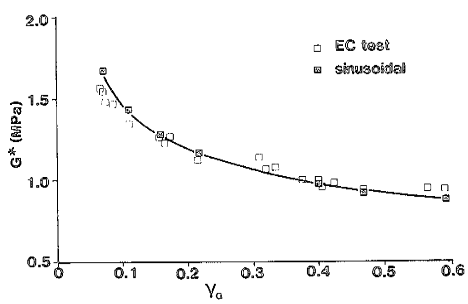

Fig.4 Shear modulus G* against shear strain amplitide

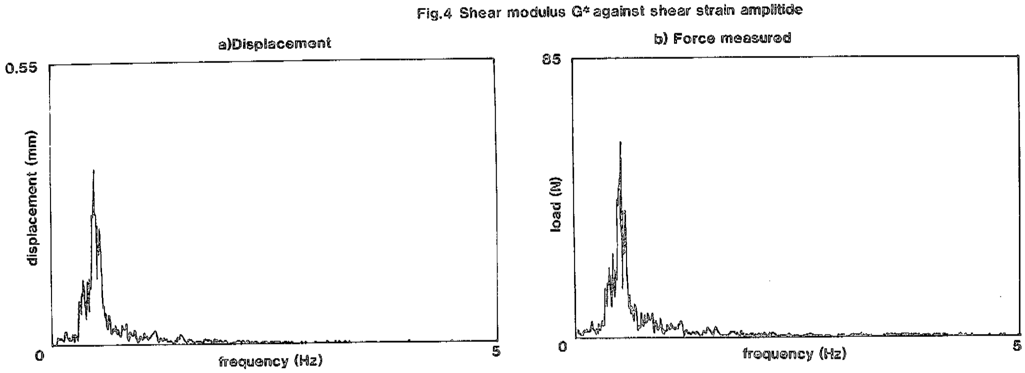

Fig.5 FFT's (EC)