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ANALYSIS OF EXPERIMENTAL INVESTIGATIONS ON ELASTOMERIC SEISMIC ISOLATION BEARINGS

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ABSTRACT

In this paper the main results of some experimental investigations on laminated rubber bearings, reported in the international technical literature or carried out in the Laboratory of testing materials and structures of the University of Basilicata, are critically reviewed and compared. The trends of shear stiffness and damping properties with respect to axial load and shear strain are analysed. Whereas experimental results show that shear stiffness depends strongly on shear strain, a clear influence of axial load on shear stiffness does not come out. Shear stiffness also depends on the loading history which is carried out. This influence can mask the role of other parameters such as, for instance, the level of axial stress, and shall be adequately taken into account when carrying out tests and/or when evaluating results. Analysis of energy-dissipating properties on the basis of equivalent viscous damping ratio and of normalised dissipative energy confirms that the former one does not effectively represent damping characteristics for highly non linear behavior.

KEYWORDS

Base isolation; bearings; energy dissipation; rubber; seismic protection; shear stiffness; viscous damping.

INTRODUCTION

Base isolation is developing more and more as a design strategy for the seismic protection of civil structures. The design concept is to protect structures against seismic damage by limiting the level of earthquake attack rather than resisting it. This is obtained by increasing the flexibility of the system, that is by moving the period of the stucture away from the predominant period of the ground motion, and, in some cases, by providing appropriate damping.

Whereas its advantages are out of question, base isolation is not commonly employed because its behavior has not been thoroughly investigated, by experiment and by numerical analyses, yet. In fact, to date, most applications of base isolation have been in important facilities such as nuclear power plants, structures with high value content or with important historical-architectural value. Because of the increasing interest in applying this technology to ordinary buildings, many research centers are carrying out wide experimental programs in this field, aimed to study and improve the behavior of various typologies of isolation devices.

At present, laminated rubber bearings are the most commonly used type of device. They consist of a stack of rubber layers vulcanised to interleaved steel shims. Due to this layout, they have high vertical stiffness to carry the gravity loads, while providing small stiffness to large horizontal displacements. Vertical and horizontal stiffness properties may be simply varied by changing the number and/or the thickness of rubber layers.

In this paper the main results of some experimental investigations on laminated rubber bearings, reported in the international technical literature or carried out in Laboratory of testing materials and structures of University of Basilicata (LUB), are critically reviewed and compared.

OBJECT AND METHODS

Modeling rubber bearings in a base isolated structure requires modeling two crucial properties: shear stiffness and damping. Owing to the strongly non linear behavior of rubber, this is not easy, particularly, because of the dependence of the shear stiffness and of the damping properties on the levels of shear strain and of axial load. To answer the above questions, the behavior of elastomeric bearings tested in various experimental research programs is analysed.

The bearings are characterized by means of some parameters as type of compound (filled or unfilled, high or low damping), dimensions (diameter, number and thickness of rubber layers and steel shims), primary shape factor *S1*, secondary shape factor *S2*. The primary shape factor *S1* is defined as the ratio of the cross-sectional area of rubber to the free surface area of a single layer; for a circular bearing with diameter D and thickness of a single layer t, $S1 = D/4t$. The secondary shape factor *S2* is defined for a circular bearing as the ratio of the diameter D to the total thickness of rubber $n{\cdot}t$ (Mizukoshi *et al.*, 1992). A filler material is usually added to rubber to enhance the mechanical properties of rubber. Carbon black is the outstanding filler agent, because no compounding ingredient has been found to equal carbon black in imparting favourable properties to rubber, up to now. The rubber compound so obtained has properties well suited to base isolation applications, enhancing the material damping characteristics and producing a non linear shear modulus-shear strain relationship. The shear modulus G is high at small strains but rapidly decreases as strains increase. This provides a good behavior to the isolation system, because it is sufficiently stiff for wind and low seismic excitations while being flexible enough under large seismic excitations. Moreover, G becomes almost constant with shear strain in the 100-150% range, thus allowing simple models to be used in structural analysis.

The characteristics of the analysed elastomeric bearings are reported in table 1, where
LLB = Low primary shape factor, Low damping, Bolted bearings;
LHB = Low primary shape factor, High damping, Bolted bearings;
HHB = High primary shape factor, High damping, Bolted bearings;
MHB = Medium primary shape factor, High damping, Bolted bearings;
EB = Elongation-at-Break.

Table 1. Characteristics of the analysed elastomeric bearings

Type	Hardness	EB (%)	D (mm)	t (mm)	H_r (mm)	S1	S2
LLB	55	662	254	25.4	76.2	2.5	3.33
LHB	62	562	254	25.4	76.2	2.5	3.33
HHB	-	-	240	2.0	44.0	30	5.45
MHB	64	520	400	12.8	128	7.5	3.125

The analyses relevant to the LLB, LHB and HHB types have been carried out working on data taken from the technical literature; the tests were performed at the Earthquake Engineering Research Center (EERC) of the University of California at Berkeley. Major details about test modality, test setup and results are given in (Aiken *et al.*, 1989 and Kelly, 1991).

The tests on the MHB type were carried out at LUB. Twenty-four full-scale bearings, whose characteristics are reported in table 1, were tested. All the tests were performed in the test machine showed in Fig. 1, where four bearings can be simultaneously tested under vertical monotonic and horizontal cyclic loads. The maximum vertical capacity of the equipment is 4000 kN. A maximum horizontal load of 700 kN can be applied to the bearings, while producing horizontal displacements up to ±450 mm to each couple.

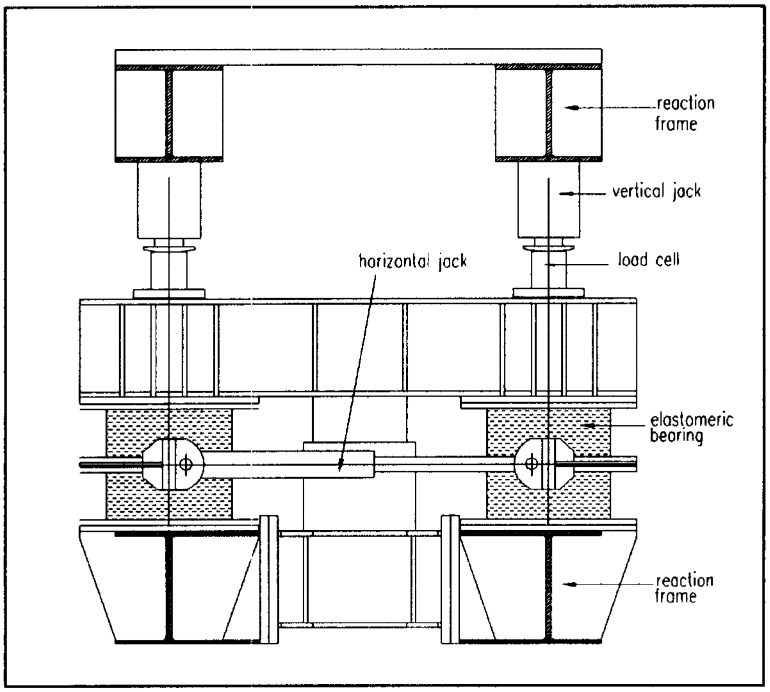

Fig. 1. Four Bearings Test Machine of the LUB

The behavior of the bearings is evaluated by means of typical tests where the specimens are subjected to static or dynamic cyclic horizontal displacements with constant axial load. The main behavioral parameters (shear modulus of rubber, dissipated energy, damping ratio) are evaluated and compared.

The shear modulus of bearing is given by

$$G = K_{eff} H_r / A_s \qquad (1)$$

where

$K_{eff} = (F_{max} - F_{min})/(d_{max} - d_{min})$ = effective shear stiffness;

A_s = shear area of bearing;

H_r = total rubber height;

F_{max}, d_{max} = maximum values of shear force and displacement in the hysteresis loop;

F_{min}, d_{min} = minimum values of shear force and displacement in the hysteresis loop.

Equation (1) assumes that lateral deformation of bearing is a result of shear deformation; i.e. that flexural deformation is negligible in comparison.

The simplest mathematical model of damping is provided by linear viscous damping, where the damping action is directly proportional to the velocity $f_D = -c\dot{d}$. Owing to an harmonic excitation $F(t) = F_0 \, sin(\Omega t)$, the energy dissipated per cycle by viscous damping is

$$W_d = \int_0^{2\pi/\Omega} f_D \, \dot{d} \, \mathrm{d}t = d_{\max}^2 \, c \, \Omega \, \pi \qquad (2)$$

Even when the energy dissipation is other than linear viscous, it may be possible to retain the simplicity of that model by introducing an equivalent viscous damping as

$$c_{eq} = \frac{W_d}{\pi \, \Omega \, d_{\max}^2} \qquad (3)$$

where, in this case, W_d is the energy dissipated by the nonviscous damping mechanism, evaluated as the hysteresis loop area in a plot of force against displacement. By considering resonance situation, one may obtain from Eq. (3) the equivalent viscous damping ratio ξ. In a bearing of rubber height H_r and effective shear stiffness K_{eff}, the equivalent viscous damping ratio ξ is given by

$$\xi = \frac{W_d}{2\pi \, K_{eff} \, \gamma_{\max}^2 \, H_r^2} \qquad (4)$$

where γ_{max} is the maximum value of shear strain in the hysteresis loop.

In reality rubber, as a usual viscoelastic material, responds to external forces in an intermediate way between an elastic solid and a viscous liquid. The total response to a shear stress $\tau(t) = \tau_0\, sin(\omega t)$ can be separated in an in-phase component of amplitude $\gamma_0 \cos\delta$, and in an out-of-phase component of amplitude $\gamma_0 sin\delta$, yielding to a shear strain $\gamma(t) = \gamma_0 \cos\delta\, sin(\omega t) + \gamma_0 sin\delta \cos(\omega t)$, where δ is the loss angle. In an analogous manner it is possible to define the in-phase or elastic modulus G' and the out-of-phase or loss modulus G'', given as

$$G' = \frac{\tau_0}{\gamma_0}\cos\delta \qquad G'' = \frac{\tau_0}{\gamma_0} sin\delta \tag{5}$$

from which follows $G = \dfrac{\tau}{\gamma} = \sqrt{(G')^2 + (G'')^2}$ and $\dfrac{G''}{G'} = \tan\delta$ (loss tangent).

One may calculate that the energy dissipated by the in-phase component is zero. On the contrary, the energy dissipated per unit volume by the out-of-phase strain in one cycle of strain (ωt goes from 0 to 2π) is

$$\frac{W_d}{V} = \int_0^{2\pi} \tau_0\, sin\omega t\, \gamma_0\, \mathrm{d}(\cos\omega t) = \gamma_0^2\, G''\, \pi \tag{6}$$

RESULTS

The trends of shear stiffness and damping properties with respect to axial load and shear strain are analysed. When possible, the relationships between these properties and the characteristics of the elastomeric bearings are evaluated.

Shear stiffness

The experimental results relevant to the LLB and LHB types of bearing confirms the positive role of filler. Fig. 2 shows as shear modulus G depends strongly on the maximum shear strain γ in the filled rubber bearing: G decreases considerably for γ increasing up to about 100 % and, for larger γ values, G remains almost constant showing a slightly hardening behaviour. On the contrary, G appears almost constant with γ in the unfilled rubber bearing.

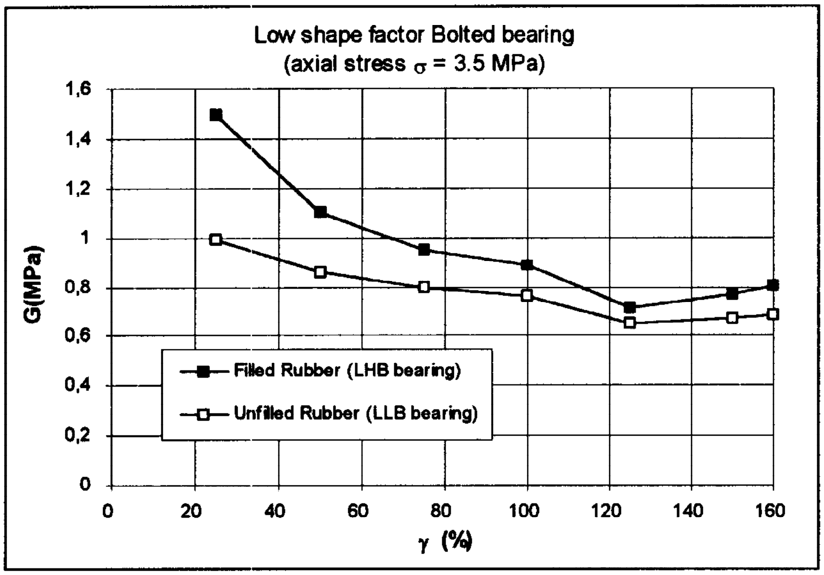

Fig. 2. Variation of G with γ in filled and unfilled rubber bearing (data taken from Aiken *et al.*, 1989).

The relationship between G and γ also depends on the axial stress σ, but the effects of increasing axial stress on shear stiffness are not so clear. The variation of G with σ, relevant to both the LHB and LLB bearings (see Fig. 3 for LLB type), does not provide a general trend. Where it is expected that shear stiffness decreases as the compression load on bearing increases, an anomalous variation of G with σ is apparent in Fig. 3. G decreases when σ going from 3.5 to 5.25 MPa; after it shows a hardening behavior, which is unexpected if one considers that the buckling stress according to Gent (1964) is about 8 MPa. It has to be noted that all the cyclic shear tests at different levels of σ were carried out on the same specimen. Thus, a significant role on the above bearing performances is probably played by the test sequence.

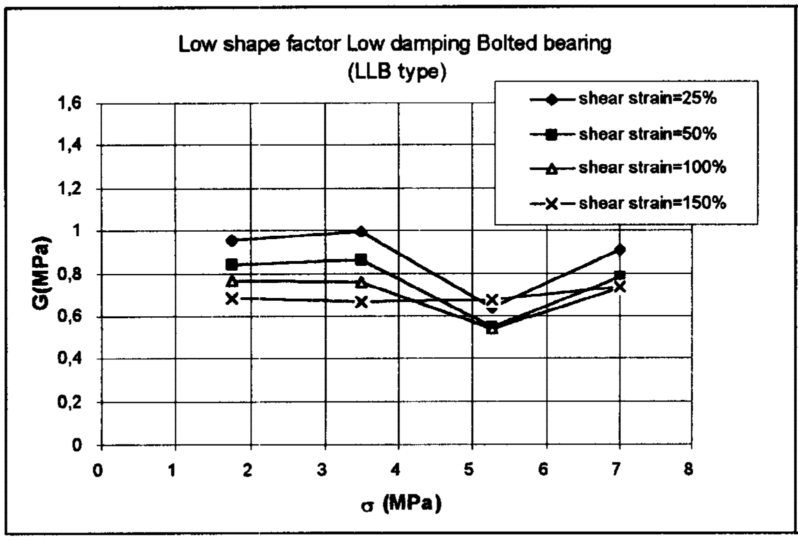

Fig. 3. Variation of G with σ at different γ levels in LLB bearing type (data taken from Aiken *et al.*, 1989).

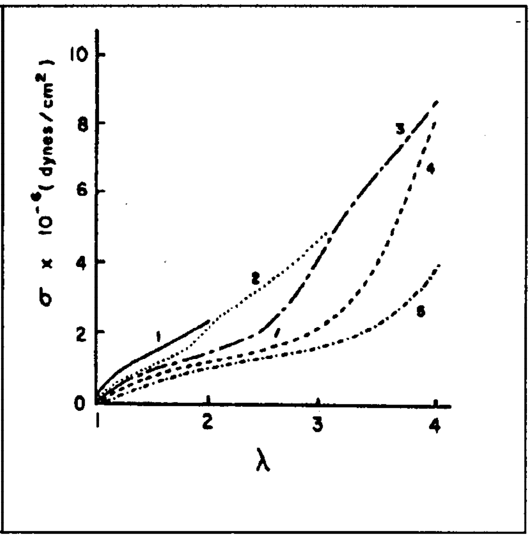

Fig. 4. Effects of loading history on filled rubber behavior (Aklonis *et al.*, 1983).

It is known that loading history influences strongly the rubber behavior. If a rubber sample is deformed up to a tensile strain λ_1 and, after the strain has been removed, it is re-deformed up to $\lambda_2 > \lambda_1$, it will be found that its properties are changed (see Fig. 4). The rubber will be found softer and more deformable up to λ_1, after which it continues following the curve showed by a virgin specimen (Aklonis *et al.*, 1983). This change in properties, caused by the foregoing deformation, is known as Mullins effect and is typical of filled rubber. The filler produces a structure which is broken down by deformation, although sustantial recovery may occur in about 24 hours (recovery time) at room temperature, or by annealing.

To overcome the Mullins effect, Kelly (1991) carried out some cyclic shear tests making use of a new bearing for each different level of pressure. Some results of these tests on four HHB bearings are showed in Fig. 5: while the typical variation of G with γ is confirmed, no contribution comes out concerning the effect of pressure on shear stiffness.

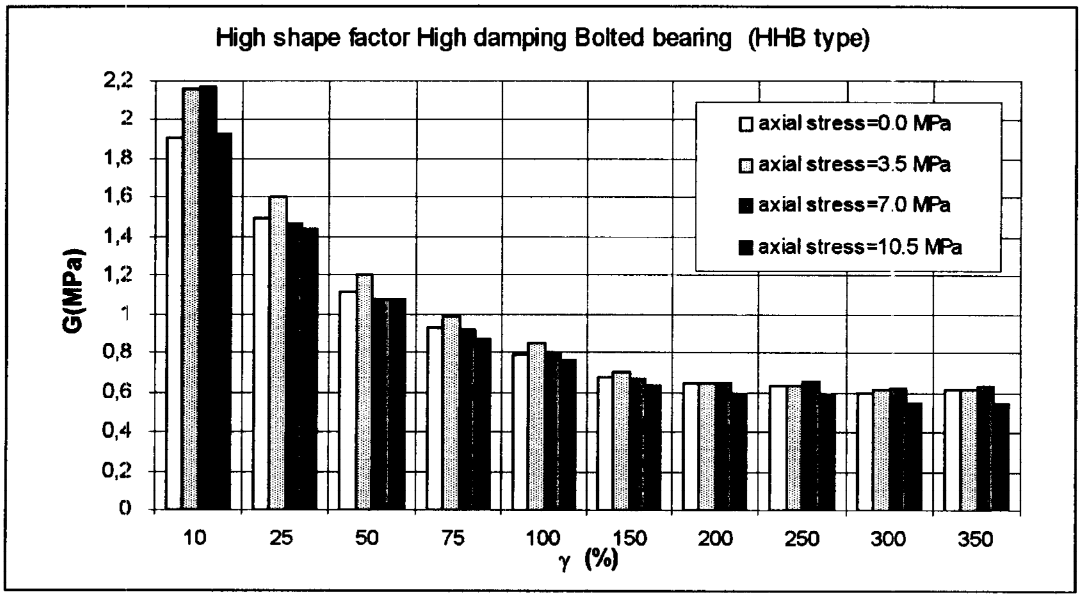

Fig. 5. Variation of G with γ at different axial stress σ in HHB bearing type (data taken from Kelly, 1991).

The role of Mullins effect on the behavior of filled rubber was also investigated at LUB, carrying out two different sequences of cyclic shear tests on MHB bearing. Whereas, in the first sequence, six bearings were subjected to tests at increasing level of strain, in the second a decreasing strain sequence was imposed on six other bearings of the same type (see Fig. 6).

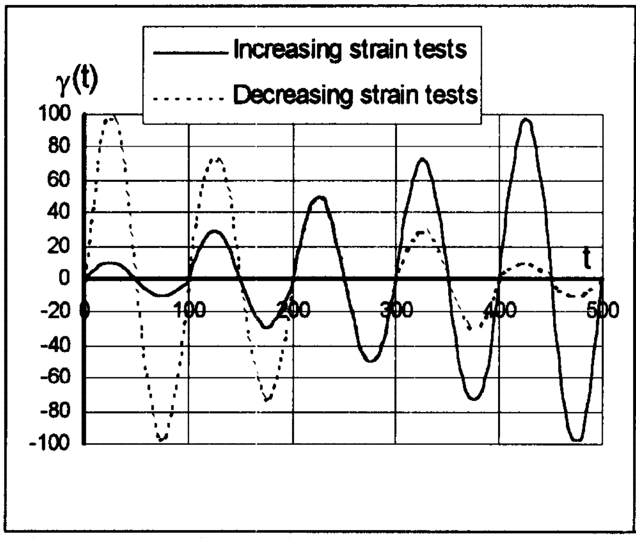

Fig. 6. Increasing and decreasing test sequences at LUB.

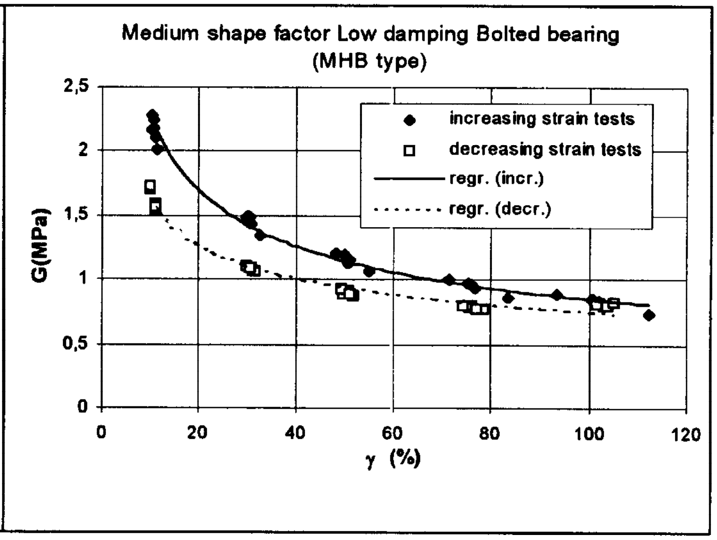

Fig. 7. Variation of G with γ increasing or decreasing.

The results clearly show the stress softening effect due to the previous deformation: there is a significant difference between the results obtained at increasing or decreasing strain (see Fig. 7); for instance, when $\gamma = 50\%$, the mean value of G evaluated from increasing strain tests is about 30% larger than the value from decreasing ones. The dependence of the elastomeric bearings behavior on the prior load-history makes difficult evaluating the role of single parameters, such as the level of axial stress. Because loading history can influence the experimental results obtained from consecutive tests on the same specimen, this effect shall be adequately taken into account in carrying out tests and/or in evaluating results. It should be noted that, as said before, the apparent stiffness degradation can be eliminated carrying out each following sequence of tests after the recovery time.

Energy dissipation

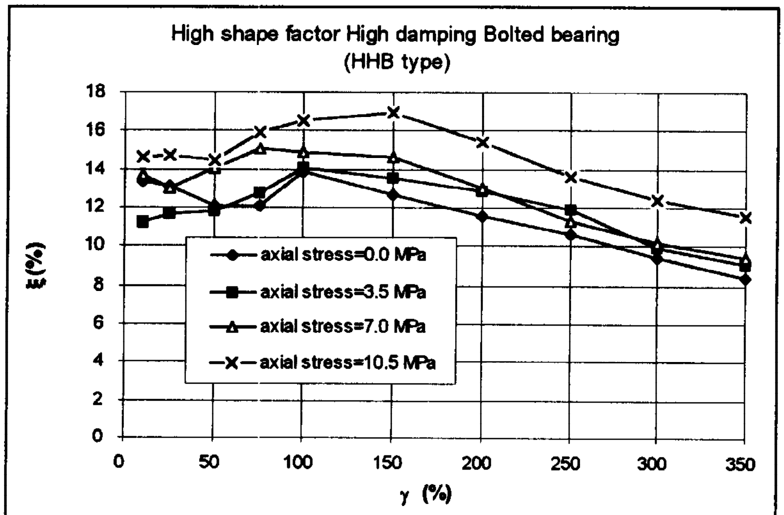

Fig. 8. Variation of ξ with γ in HHB bearing type (data taken from Kelly, 1991).

The positive role of filler is also confirmed by the damping behavior. The equivalent viscous damping ratio ξ in filled rubber is 1.5÷2.0 larger than one in the unfilled rubber. The variation of ξ with γ and σ is similar in all the types of bearing. A typical trend relevant to the HHB bearing is shown in Fig. 8. The level of maximum shear strain γ has not a clear influence on ξ: after a slight increase up to about $\gamma = 100\%$, ξ decreases considerably as γ increases. On the other hand, the dependence of ξ on σ clearly appears, that is ξ always increases with σ.

Because of non linear characteristics of elastomeric bearings, the evaluation of the damping behavior through ξ cannot lead to good results, particularly when the shear strain is high. For this reason, the damping properties are also analysed by means of the normalised dissipated energy W_d/V_r, where W_d is the hysteresis loop area.

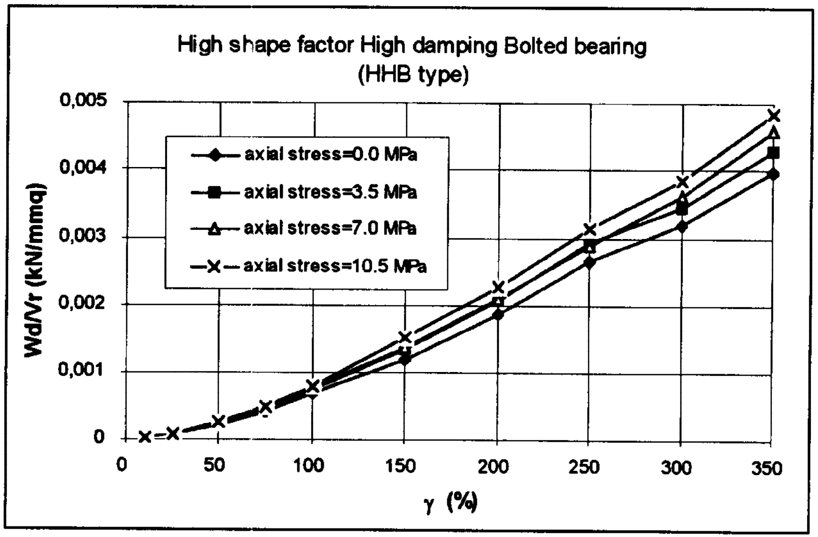

Fig. 9. Variation of W_d/V_r with γ in HHB bearing type (data taken from Kelly, 1991).

In Fig. 9 the variation of W_d/V_r with γ in HHB bearings, for four σ values, is showed; it confirms the increase of dissipated energy with σ. Particularly, damping increases about linearly with axial load over the range of loads considered. It has to be noted as the energy dissipation is always increasing with γ; the different trend showed by ξ in Fig. 8 emphasizes that, for highly non linear behavior, ξ is not a good measure of the damping properties of the bearings.

Eqs. (2) and (6) show as energy dissipation W_d is proportional to the square of maximum displacement, in the case of viscous behavior. While, energy dissipation can be considered linearly proportional to displacement, in the case of hysteretic behavior. The dependence of energy dissipated W_d on γ is analysed in (Aiken *et al.*, 1989 and Kelly, 1991) to evaluate the contribution of the two types of damping behavior; W_d is assumed as a function of the maximum strain raised to an unknown power α. It is found that α varies over the range 1.4÷2.0 for LLB and LHB bearings, with larger values for the former one (low-damping unfilled rubber), while α is about 1.6 for the HHB bearings.

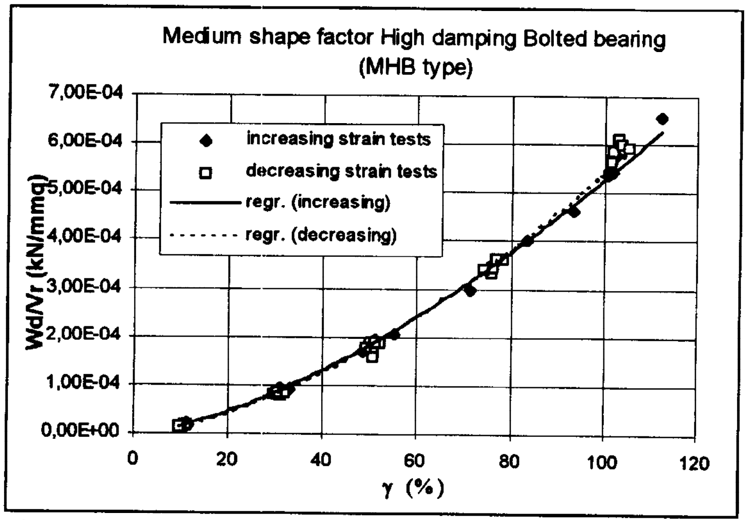

Fig. 10. Variation of W_d/V_r with γ in MHB bearing type.

A similar dependence of W_d on γ has been obtained in the tests on MHB bearings type at LUB (see Fig. 10). The best fit regression curves of the experimental results (increasing and decreasing strain tests) are as follows

$$W_d/V_r = 5E\text{-}07\gamma^{1.51} \text{ (increasing strain)}$$

$$W_d/V_r = 4E\text{-}07\gamma^{1.57} \text{ (decreasing strain)}$$

The above relationships (see also Fig. 10) suggest two observations:

a) the energy dissipating properties cannot be modelled neither as linear viscous nor as hysteretic;

b) whereas load-history has considerable effects on shear stiffness of rubber bearings, the effects on energy dissipation properties appear negligible.

Further analyses, where the energy dissipation is evaluated on the basis of the loss angle δ and Eq. (6), show as the viscous component is prevailing in comparison to the hysteretic one. Moreover, the contribution of the viscous component increases as the shear strain increases.

CONCLUSIONS

The experimental investigations analysed in this paper show as the restoring force and damping properties of laminated rubber bearings are influenced by the levels of shear strain and of axial load. In the bearings with filled rubber, the results show that the shear modulus G is high at small strains but rapidly decreases as strains increase. On the contrary, G appears almost constant with γ in the unfilled rubber bearings. The relationship between G and γ also depends on the axial stress σ, but the effects of increasing σ on shear stiffness does not appear very clear.

The positive role of filler is confirmed by the damping behavior: the equivalent viscous damping ratio ξ of filled rubber is 1.5÷2.0 larger than in unfilled rubber. The energy dissipated W_d monotonically increases with the level of maximum shear strain γ, this trend compared with the dependence of ξ on γ show as ξ does not effectively represents damping characteristics for highly non linear behaviour. Moreover, by examining the function $W_d = f(\gamma^{\alpha})$ it appears that the energy dissipating properties cannot be modelled neither as linear viscous nor as hysteretic. On the other hand, the dependence of both W_d and ξ on σ clearly appears, that is they always increase with σ.

Also, the experimental results emphasize the influence of loading history on the shear stiffness: previous deformation leads to a stress softening behavior. Such an effect shall be adequately taken into account in carrying out tests and/or in evaluating the shear stiffness. On the contrary, the effects of loading history on energy dissipation properties appear negligible.

Finally, the results of the various experimental investigations show that laminated filled rubber bearings possess good stiffness and damping properties to be used effectively like seismic isolation system, but there is still a further research work to make in completely understanding their behavior.

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