Proceedings of the Institute of Acoustics

EXPERIENCE IN DESIGN AND TESTING OF ELASTOMERIC SEISMIC BASE ISOLATORS

C J Derham Materials Engineering Research Laboratory, Tamworth Road, Hertford, UK.
R Shepherd Materials Engineering Research Laboratory, Tamworth Road, Hertford, UK.

1. INTRODUCTION

A number of passive devices have been proposed for the isolation of buildings and other structures from the ground movements caused by earthquakes. The most widely implemented system provides isolation by mounting the entire structure on a number of multi-layer elastomeric bearings comprising alternate horizontal layers of rubber and steel strongly bonded together. The bearings act as springs with a high vertical stiffness and a relatively low horizontal stiffness. They confer on the mounted structure vertical and horizontal natural frequencies which depend on these stiffnesses, and can therefore be chosen to de-tune the structure from the damaging ground vibrations. De-tuning, as a strategy, avoids the necessity for any particular strengthening of the structure, because much of the ground shaking energy is simply not transferred into the structure. A building on flexible supports moves translationally as a rigid body, instead of having to accommodate, within its ductile range, increasing forces which peak at roof level. Normally, the rigid body acceleration can be reduced to a level where the contents as well as the structure itself are protected from damage, whereas protection by strengthening may actually increase the forces experienced by the contents.

The first large building protected in this way in the United States was the Foothill Communities Law and Justice Center, San Bernardino, California, completed in 1985, with bearings designed by one of the authors of this paper (CJD). There have been no major earthquakes near this building since completion, but it is fully instrumented, and the effectiveness of the system has been demonstrated in smaller events. The attenuation of ground forces has been as predicted in the design.

In this paper we consider the design and testing of elastomeric base isolators and whether current practice has fully utilized their potential.

2. BASIC REQUIREMENTS FOR ISOLATORS

Seismic base isolators support the structure, and are designed to protect it from earthquake damage. However, there are other requirements for the isolators, some essential, some desirable. Eleven requirements are listed below which cover both categories.

a) Isolators are structural components. They must support the building with an adequate safety factor to both dead and live loads.

b) Isolator shear stiffness must be chosen to produce a translational natural frequency for the mounted structure which is well below the predominant horizontal earthquake frequencies predicted for that site.

c) It is impractical, and generally unnecessary, to attempt to isolate the vertical earthquake component. The vertical stiffness should be chosen to be high enough to avoid vertical amplification or rocking of the structure.

d) The isolators must be capable of deforming in shear, without damage, to the amplitudes predicted for the mounted structure in the Maximum Credible Earthquake.

e) The stability of the isolators, considered as columns or struts, must be adequate to avoid buckling at maximum shear displacement.

f) Isolation parameters must remain within specification over the temperature range of operation.

g) The system should be capable of full recovery after a Maximum Credible Earthquake event. It must remain effective against aftershocks or repeated major events.

h) It is convenient if all of the required damping can be provided by the bearings themselves, without introducing supplementary mechanical devices. This damping should be adequate to make the system conservative to the detail of the design spectrum.

i) Provision can be made for isolator replacement, but a good design should provide bearings with a lifetime at least equal to that of the structure they support, so that replacement is unnecessary.

j) It is convenient if the system has enhanced stiffness at low amplitude due to wind loading. This eliminates the necessity for mechanical fuses, and avoids harmless, but subjectively disturbing, movement of the structure in high winds.

k) It is convenient if the bearings are intrinsically fire resistant so that additional fire barriers are not required.

The basic design parameters for elastomeric base isolators have been widely covered elsewhere [1,2], and the requirements relating to them can be achieved, so that they will not be discussed here. Instead, we will concentrate on areas where choices are available.

3. DETAILED DESIGN CONSIDERATIONS

3.1 Vertical stiffness

Most structures, and their contents, are intrinsically strong vertically. Only some specialized power or public utility installations require protection from the vertical earthquake component. In normal structures, only the horizontal earthquake component is potentially damaging. It is sufficient to ensure that the vertical component is not amplified significantly.

In general, the aim will be to make the isolators as stiff vertically as is practicable. Excessive stiffness, however, may lead to construction problems. In most construction methods isolators will be placed under the soffits of base beams. They must have sufficient compliance to allow the load to be spread evenly along a row of bearings without imposing too a high tolerance on dimensions.

The vertical natural frequency of a mass supported on a spring is a function of spring deflection only. Thus, for a vertical natural frequency of, say, 1.5 Hz, the isolators would have to compress by 110mm under load. Clearly, this would be unsatisfactory, and, far from producing isolation, would amplify the vertical component in most earthquakes, and introduce rocking. For a compression of 10mm, the vertical natural frequency will be about 5 Hz. This is just too low a frequency to avoid some amplification for typical earthquakes, so a somewhat smaller compliance is usually chosen.

In early tests carried out at the University of California, Berkeley [3], a vertical natural frequency of around 12 Hz was chosen. Large scale model tests on a shaking table showed, for a variety of different earthquake inputs, no significant amplification of the vertical earthquake component.

Combining horizontal and vertical components leads to some increase in structural accelerations compared with horizontal-only excitation, but the displacement response is hardly affected.

For structures in urban areas, it may be beneficial to combine earthquake protection with vibration isolation, for example from road traffic, or from surface or underground railways. This can be done by correct choice of the vertical mounting frequency and is discussed in detail elsewhere [4].

3.2 Acceptable shear displacement

As a multi-layer bearing shears, individual layers tilt with respect to one another about a horizontal axis (see Figure 2 below). The leading edge of a layer goes into tension and the trailing edge into compression. That part of the layer which is in tension experiences negative hydrostatic stress. Under such stress, rubber will fail by internal cavitation at a stress approximately equal to the Young's modulus. However, extreme conditions are required to cause failure. In practice, we have carried out tests on a range of bearings and found that, even at shearing distances up to 70% of the plan dimension, the bearings can sustain their normal compressive load, and, on subsequent sectioning, show no sign of cavitation damage.

For the San Bernardino building referred to above, the maximum anticipated horizontal displacement at the centre of rotation is 280mm. If there is any torsional movement of the structure, then peripheral bearings could experience higher displacements, and a maximum potential bearing displacement of 405 mm has been allowed for. As the plan diameter of the active portion of the bearing (ignoring the fire protection cover) is 608 mm, even this displacement is less than 70% of the plan dimension.

3.3 Temperature effects and damping.

These two topics are being treated together as temperature affects both stiffness and damping.

Stiffness is the main design parameter for the bearings, as it controls the horizontal and vertical natural frequencies which have been chosen with reference to the design earthquakes. If the design criteria are to be met, it is essential that the stiffness of the isolators does not change very much over the temperature range which they will experience in service. The stiffness of elastomers, however, changes with temperature. They become stiffer at low temperatures and softer at high temperatures. Below the characteristic 'Glass Transition Temperature (T_g)' (i.e. in the 'glassy' region), the stiffness of a rubber will be approximately one thousand times greater than it is above T_g (the 'rubbery' region). Although by far the biggest change in stiffness takes place close to T_g, the effects are significant for some tens of degrees C either side of T_g.

Broadly speaking, low damping rubbers such as natural rubber have very low T_g, (-70C for natural rubber), so that their stiffness does not change much over normal service temperatures, but higher damping rubbers such as nitriles and fluoroelastomers have higher T_g and the stiffness can change significantly in the working range.

For maximum de-tuning, which is the purpose of the isolators, the damping in the isolator would have to be as low as possible. However, for practical reasons, very low damping isolators would be dangerous. This is associated with the transmissibility (amplification of input frequency) at resonance. For low damping values the transmissibility at resonance is high (theoretically infinite for zero damping). As the damping in the isolator increases, the transmissibility for the resonant frequency decreases. Because earthquakes, although peaking at a frequency which can be predicted [5] from the soil and other conditions (see Table 1), contain a very broad spectrum of frequencies - there is likely always to be some component at the resonant frequency of the isolator system chosen. This component may be small, but if the isolators had low damping, it could be amplified to dangerous levels. It is therefore advisable to choose an elastomer with some damping for the isolator as this will avoid any possible resonance effects, and make the system less sensitive to the precise choice of design earthquake - which is always an area of some uncertainty.

Site conditions	**Frequency peak**	**Note**
Rock	6.1 Hz	Narrow peak
Stiff soil (< 45 m)	4.0 Hz	Narrow peak
Deep cohesionless soil (> 75 m)	3.2 Hz	Broader peak with considerable energy to 1 Hz.
Soft to medium clay	3 Hz to 0.9 Hz	Very broad peak

Table 1

How high, then, should the damping be? This is not an easy question to answer. To the best of our knowledge it is not a topic on which systematic research has been carried out. The tendency has been to choose available materials, rather than to develop a material which would optimize response. Natural rubber is usually chosen for isolators because it is, a) strong, b) fairly constant in stiffness over most service temperature ranges, and c) can have its damping increased by additives without sacrificing point b. Typical earthquake isolators have around 10% to 11% of critical damping at large excursions. This represents the upper limit of what can relatively easily be achieved with natural rubber. In some installations, requiring higher damping, this is supplied by supplementary mechanical dampers, either hydraulic or metal-deforming. This greatly complicates construction, compared with having all of the damping supplied by the elastomer of the isolator. Table 2 gives some shaking table results on 20 and 40 tonne models carried out at EERC Berkeley [5].

Earthquake	**Peak input acceln.**	**Peak acceln. of model**
El Centro N-S (1940)	0.30g	0.09g
Parkfield N65E (1966)	0.20g	0.12g
Pacoima Dam S16E (1971)	1.10g	0.39g
Bucharest NS (1977)	0.20g	0.50g
Bucharest EW (1977)	0.18g	0.20g

Table 2

These tests were carried out on bearings having about 11% of critical damping, and conferring on the model a natural frequency of 0.5Hz. For the first three earthquakes representing rock or stiff soil conditions, there is a factor of two or three attenuation of input acceleration. The importance of internal damping in the isolators is illustrated by the Bucharest result, with a peak in the frequency response spectrum at 0.64Hz, apparently dangerously close to the mounting frequency, but which, even so, has not led to disastrously high amplification of the ground vibration.

Although base isolation may not be the obvious option for earthquake protection in softer soil conditions, such as Bucharest, it should be remembered that one of the major advantages of isolation over strengthening is the virtual elimination of P-Δ effects, or inter-storey drift. Provided the structure is moving as a rigid body, quite high accelerations can be tolerated without damage.

If isolators having higher internal damping can be developed it may increase the range of soil conditions where isolation is a viable option for protection. For a discussion on the potential for higher damping bearings, see Section 5.2 below.

3.4 Wind restraint

Even the highest wind loadings on structures are well below the levels associated with damaging earthquakes. Wind loadings would not produce any damage in a base isolated structure. However, because the structure is mounted on isolators which are necessarily soft in shear, the movement of the building under high wind loadings, while in no way dangerous, could be subjectively disturbing.

As an example, the effect of a typical peak wind loading of 0.03g will be considered. If the structure is mounted to have a horizontal natural frequency of 0.5Hz, then the corresponding movement of the structure under this wind loading will be about 30mm. In fact, all engineering rubbers are stiffer at small amplitude and this would, typically, reduce the movement by about a factor of 2, down to 15mm. Even at such a low frequency this movement could be felt by the occupants, and if they could see a fixed object through a window, they might well be alarmed.

The original solution to this problem was to incorporate mechanical fuses in the system (see for example Ref 3). Such fuses would hold the system rigid under all normal conditions, but break, leaving the building free to move, under earthquake loading. In practice, it is difficult to design such a system because the fuses must not break under the normal thermal movements of the structure, and a shock loading is found to occur when the fuses do break.

The special rubber compounds used in isolators are designed to have higher damping than normal engineering rubbers. It has also been possible to 'tailor' the compounds to exaggerate the increase in stiffness at small amplitude. Figure 1 compares shear modulus vs. shear strain for a normal engineering rubber, with that for the specially developed seismic isolator compound.

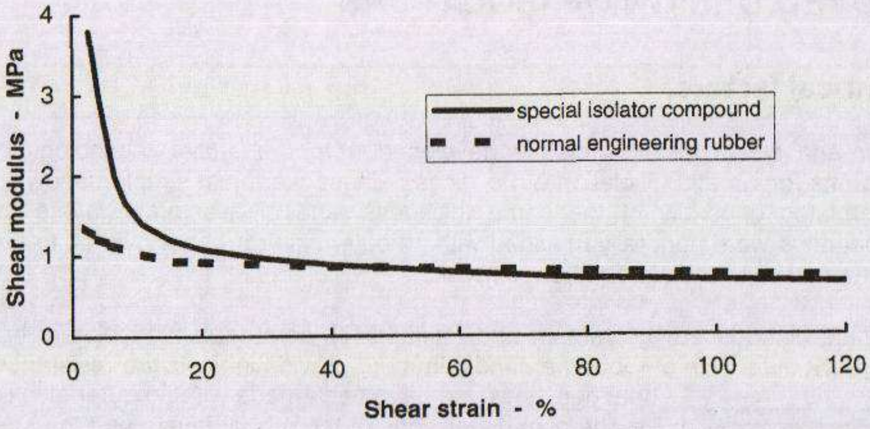

Figure 1 Shear modulus at 1 Hz

The special compound is about 5 times at stiff at wind amplitude as at large amplitudes. This reduces movement at maximum wind force down to about 6mm, barely detectable at this frequency.

4 ISOLATOR TESTING

Because of the critical nature of the components, it is usual for every isolator for use in construction to be tested fully before supply. As each isolator will, typically, carry a load of 100 tonnes or more, it is not usually possible to test isolators under the dynamic conditions which they will see in service during an earthquake. This is not a problem, although it is often perceived as such, due to a lack of understanding of the dynamic properties of elastomers.

The matter of dynamic vs. static properties has been examined in detail elsewhere [6], so that only a brief outline will be given here.

The properties of elastomers do change with frequency, but the effect is very small over the range of frequencies with which we are concerned in earthquake protection, and in particular between static and 0.5Hz. Frequency differences of kilocycles are required to produce large changes in, for example, shear modulus. A quantity referred to as the static/dynamic ratio is often cited. This ratio is real enough, and arises because stress vs. strain characteristics of elastomers are not usually linear, but it is not a function of frequency in the range with which we are concerned.

The main parameter affecting the stiffness of an elastomer under dynamic testing is the amplitude of the strain. As seen in Figure 1 above, there can be a difference in shear modulus of a factor of about 4 between tests at 5% strain and tests at 100% strain. Measurements of modulus or damping from quasi-static or from 0.5Hz testing will be negligibly different by comparison.

It is found, however, that the damping in an isolator tested by either technique will exceed the damping predicted by damping measurements on the elastomer alone. This is because there are at least two mechanisms which increase damping in a real bearing. The first of these is deformation of the metal interplates, and the second is due to the change in height of the bearing when it is cycled to large displacements under a constant compressive load [5]. This means that a prediction of the overall damping based on the properties of the elastomer alone will be conservative.

5 IMPROVED DESIGN OF ISOLATORS

5.1 Geometrical factors.

Multi-layer rubber and steel seismic isolators developed from the earlier technology of bridge bearings, and mounts for vibration isolation of buildings. These were just simple sandwiches, with all the steel interplates generally of the same thickness, and all elastomer layers the same thickness. The bearings were generally moulded with an outer skin of rubber overall, to protect the steel plates and the rubber-to-metal bond from corrosion.

Following a technique introduced by Derham and Plunkett [7], some seismic isolators have been made with a very thick outer skin of rubber, around 50mm, to provide intrinsic fire resistance. Some bearings, however, have been made with no outer skin of rubber, i.e. the plan dimensions of the rubber layers and the steel plates are the same. This is bad practice. When the bearing is sheared, the most vulnerable site for failure is usually the bond edges where the relevant strains are highest. If these edges are exposed to mechanical or environmental damage, they can provide an initial flaw site from which failure could occur in a large event.

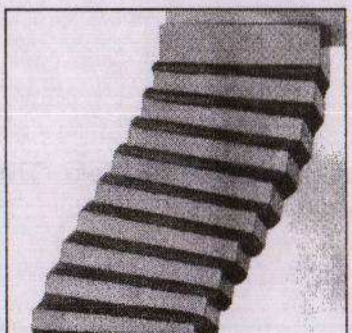

Figure 2

Figure 2 shows a model bearing under shear. The bearing is loaded in compression and the upper and lower loading surfaces are constrained to remain parallel as they would be in service. (This is done by reacting four bearings against one another, of which only one is shown.) The metal plates in the bearing are not to scale, and have been made deliberately very much thicker than usual, so that plate bending does not occur, and the deformation of the rubber can be studied.

The tensile strains on the bond at the trailing edge can be seen (top right), and the high compression at the leading edge (top left). This effect is greatest in the end layers, with the deformation of the mid-height layer being perfectly symmetrical. Rubber deforms at constant volume, and, if negative hydrostatic stresses, such as will clearly be generated in the tilted end layers, cannot be accommodated by changes in the surface geometry, then the rubber will fail internally by cavitation at very modest negative stresses. Such failure could be catastrophic.

That this does not occur very much in practice is probably largely fortuitous. Steel plates used in bearings are quite thin. Under shear as shown in Figure 2, thin plates would bend so as to relieve the negative stresses. However, the effectiveness of plate bending in relieving potentially dangerous negative stresses should not be relied on to provide a solution in all cases. For a bearing of different geometry, how can we know that it will not fail, or deduce in testing how close it is to failure?

What is required is a finite element analysis study of the deformation. The effect of plate thickness and rubber layer thickness can then be studied systematically. It may be that the end layers of the bearing should be made slightly thicker (i.e. with lower shape factors) to reduce potential for cavitation. The study is not a simple exercise, because elastomers used in seismic isolators are more non-linear than normal engineering rubbers. The material model chosen needs careful consideration - but the exercise is essential if the geometry of deformation is to be understood.

5.2 Increasing damping.

As discussed above, reduction in transmitted forces is only one of the advantages of base isolation. Constraint of the structure to move as a rigid body is equally important. For some soil conditions it may be that even higher damping than currently found in isolators would be advantageous in areas where somewhat lower frequency components are expected in the earthquake spectrum.

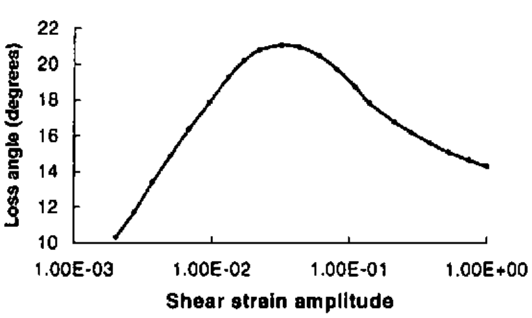

Figure 3

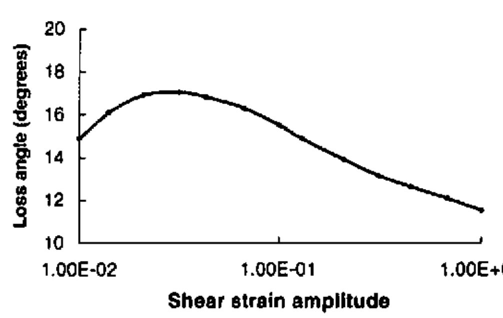

Figure 4

To date, almost all isolators have been based on natural rubber, specially compounded to give considerably higher damping than is usual for the polymer, up to around 11% of critical damping. It is possible to achieve even higher levels of damping using natural rubber. Figure 3 shows a plot of damping vs. strain amplitude for a natural rubber compound we have developed. Here the damping peaks at a loss angle of 21 degrees, corresponding to a critical damping of around 19%. At 100% shear strain the loss angle is 15 degrees, corresponding to a critical damping of over 13%.

Another approach is to employ synthetic rubbers with higher inherent damping. This would require a systematic study, but, as a first step, we have investigated the properties of a 75/25 blend of Neoprene and chlorobutyl rubbers. Figure 4 shows the damping of this material. The damping peaks at about 15% of critical damping, with the level at 100% shear strain being about 12%. In terms of amplitude, frequency, and temperature dependence, the material is similar to the natural rubber compound. There is no doubt that judicious blending of other synthetic elastomers could produce compounds with even higher damping, and possibly extend the types of location in which base isolation is appropriate.

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