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LATEST ADVANCES IN SEISMIC ISOLATION

WILLIAM H. ROBINSON

Penguin Engineering Ltd, PO Box 33-093 Petone, New Zealand

ABSTRACT

In New Zealand, Japan, Italy and the USA seismic isolaton, the technique in which the structure is decoupled from earthquake-induced ground motions, has now advanced to the point where it is often considered for the protection of both new and existing buildings, bridges, and industrial plant.

The seismically isolated buildings fall into two broard catogaries - fragile structures of historic significance and new structures with contents which need to be protected or continue to operate during and immediattely after the earthquake. The seismically isolated bridges include both new and old bridges in areas of seismic activity.

In this paper we briefly describe the principles of seismic isolation, discuss some of the isolation systems available before giving some examples of the application of seismic isolation to structures in New Zealand.

Very strong support for the principles of seismic isolation is given by the fact that of the ten hospitals affected by the Los Angeles (1994) earthquake, only the hospital seismically isolated by a lead-rubber bearing system was able to continue to operate. Further confirmation of these principals was provided by the excellent behaviour of isolated structures (two buildings and six bridges) in Kobe during the great Hanshin earthquake (1995).

INTRODUCTION

Seismic isolation is a technique in which a structure is decoupled from earthquake induced ground motions. In Italy, USA, Japan and New Zealand this technique has now advanced to the point where it is often considered for the protection of both new and existing buildings, bridges, and to a lesser extent, industrial plant. The use of seismic isolation in China and Indonesia has been supported with the recent openings (in May and October 1994) of the seismically isolated demonstration buildings in Shantou City and in Java, Indonesia. In these projects, supported by UNIDO, the buildings are mounted on high damping rubber bearings. With our collegues in Indonesia and Austria, Penguin Engineering is now investigating the feasibility of seismically isolating a number of hospitals in Indonesia. In Chile low cost seimsmically isolated apartment buildings have been constructed (Sarrazin et al 1993).

Our studies of seismic isolation began in 1968 as the cobination of two groups working in the fields of Materials Science and Engineering Seismology respectively. This research has had three main components: experiments, theoretical work and the application of seismic isolation devices (Skinner et al 1993).

Very strong support for the principles of seismic isolation is given by the fact that of the ten hospitals affected by the recent Los Angeles (Jan '94) earthquake only the hospital seismically isolated by a lead-rubber bearing system was able to continue to operate. This seven-storey hospital (the University of Southern California

Teaching Hospital) underwent ground accelerations of 0.49g, while the rooftop acceleration was 0.21g, that is an attenuation by a factor of 1.8. The Olive View Hospital, nearer to the epicentre of the earthquake, underwent a top floor acceleration of 2.31g compared with its base acceleration of 0.82g, a magnification by a factor of 2.8. The Olive View Hospital, designed to strength criterea, suffered no structural damage but had to be closed tempoarily because the high acceleraton caused a water pipe to burst on the top floor. One kilometer closer to the epicentre than the University Teaching Hospital, the Los Angeles County Hospital suffered severe damage causing the closure of a number of wings. Repair of this damage is estimated to cost US$400 million.

In the January 1995 Great Hanshin Earthquake a building isolated with lead-rubber bearing system in the affected zone survived with no damage or disruption to services. For this building, the Computor Center of the Ministry of Post and Telecommunications, preliminary results indicate a maximum ground acceleration of 0.40g while the sixth floor acceleration had a maximum of 0.13g, that is an attenuation by a factor of 3.

FLEXIBILITY AND DAMPING

Seismic isolation systems have two important functions:

- The period of the isolated structure is increased to a value beyond that which dominates in a typical earthquake
- The displacement is controlled (to 100-400 mm) by the addition of an appropriate amount of damping (usually 5 to 20 percent of critical).

The increased period (>1.5 seconds, usually 2 to 3 seconds) is achieved via a flexible support which provides a reduction in the 'stiffness' or 'spring constant' between the structure and the ground. Examples include flexible piles and rubber elastomeric bearings. The damping is usually hysteretic, provided by plastic deformation of either steel or lead or by 'viscous' damping of high-damping rubber. For these dampers strain amplitudes, in shear, often exceed 100 percent. The high damping has the effect of reducing the displacement by a factor of up to five from unmanageable values of ~ 1 metre to large but reasonable sizes of <300mm. Recently 'inverted friction pendulums' have been used.

Figure 1 shows the principles underlying seismic isolation. Note the rapid decrease in the acceleration transmitted to the isolated structure as the isolated period increases. This effect is equivalent to the building approaching the state where it remains fixed in space while the earth moves back and forth under it. The effect of damping for controlling displacement is shown in Figure 1 also, with increased damping reducing both the displacement of and the accelerations to the structure.

Table 1 lists the various passive isolation systems being used at present, passive isolation systems being systems which do not require any power or external energy source as opposed to active systems. These isolation systems are grouped according to whether they are linear or nonlinear. An example of a system which behaves in a linear manner for restoring force and damping is the laminated rubber bearing while, both the high-damping rubber bearing and the lead-rubber bearing are nonlinear in restoring force and damping.

The rubber bearing consists of layers of rubber, 5 to 20mm thick, placed between sheets of steel. The rubber layers give the bearing its relatively low shear stiffness in the horizontal plane while the steel plates control the vertical stiffness and also determines the maximum vertical load which can be applied safely. Before the introduction of vulcanised rubber bearings in the 1970's, problems of delamination occured with the failure of the glued joints between the rubber and steel plates. It would be expected that the delaminated bearings would display decreased performance but tests we conducted in 1974-6 illustrated clearly that normal vertical loads were sufficient to hold the delaminated bearing together. The only way for the delamination to be detected was to place the bearing under a vertical tension of someting like 20% of the design vertical load.

The high-damping rubber bearing has a damping in the range of 8 to 20% of critical. At present the higher value of damping introduces problems such as 'scragging', that is, the force-displacement loop for the first cycle being makedly larger than subsequent cycles.

DEVICES BASED ON THE PLASTICITY OF LEAD

High-damping hysteretic devices which rely on the plastic deformation of steel or lead have many engineering and industrial applications, such as the seismic isolation of buildings, bridges and delicate or hazardous

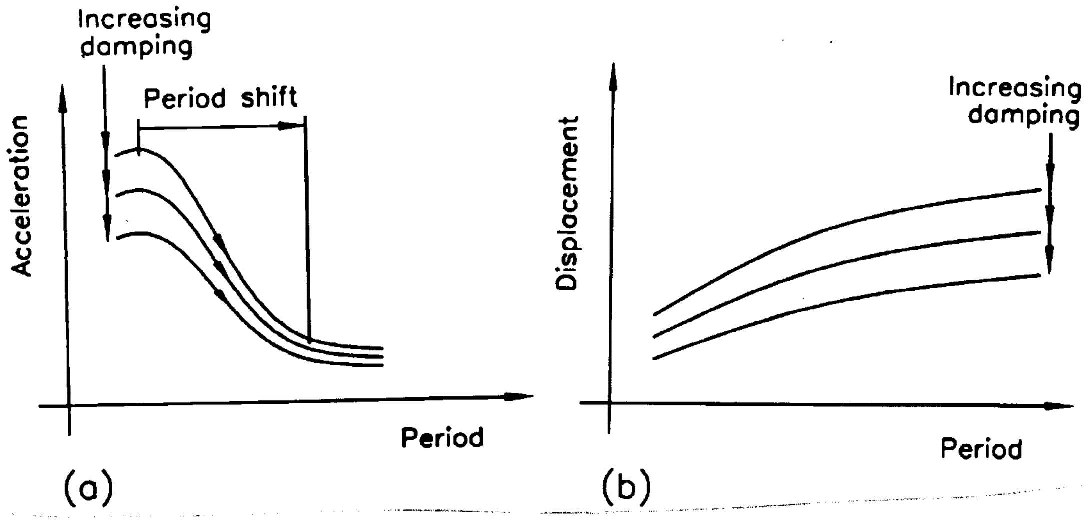

Figure 1 Effect of period and damping on (a) acceleration and (b) total displacement for the isolated system.

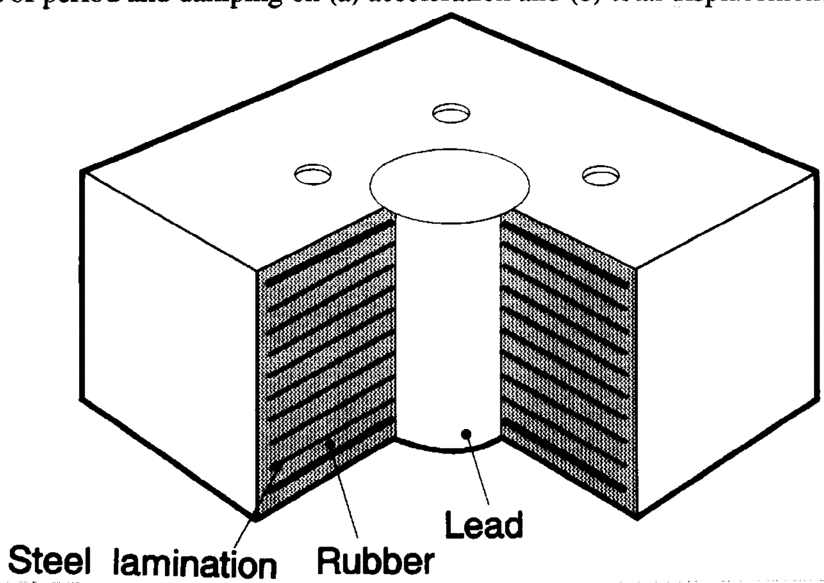

Figure 3 Schematic diagram showing the laminated layers of rubber and steel and the lead insert.

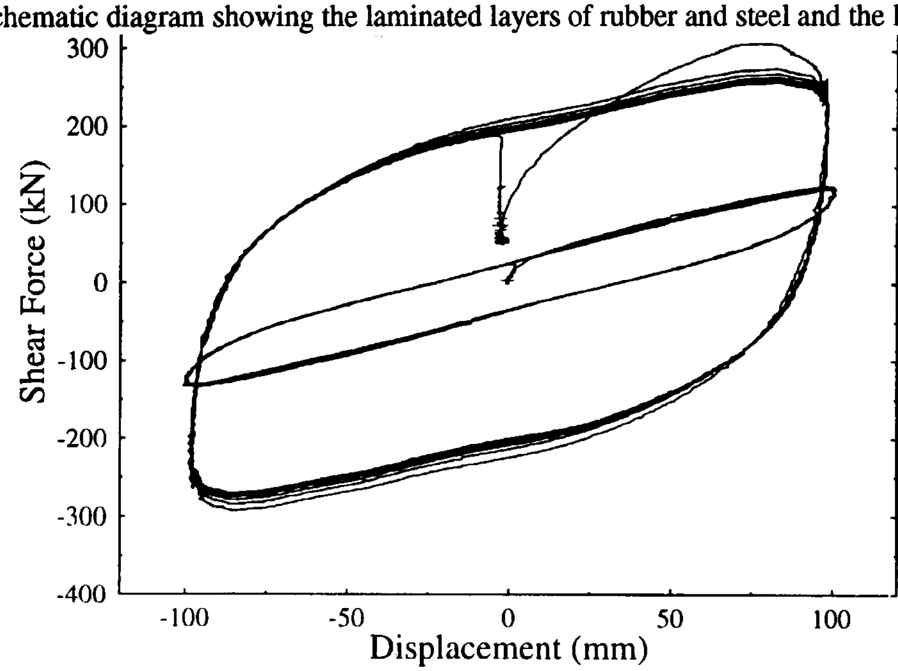

Figure 4 Hysteresis loops for high-damping rubber bearing (inside loops) and lead-rubber bearing (outside loop)

Table 1: Flexibility and Damping of Common Seismic Isolators

Property	Linear	Nonlinear
Restoring Force-> (providing spring constant and flexibility)	*Laminated rubber bearings *Flexible piles or columns *Springs *Spheres between curved surfaces (gravity)	*High-damping rubber bearings *Lead-rubber bearings *Buffers *Stepping (gravity) *Friction pendulum
Damping ------>	*Laminated rubber bearings *Viscous dampers	*High-damping rubber bearings *Lead-rubber bearings *Lead extrusion dampers *Steel dampers *Friction (eg PTFE) *Friction pendulum

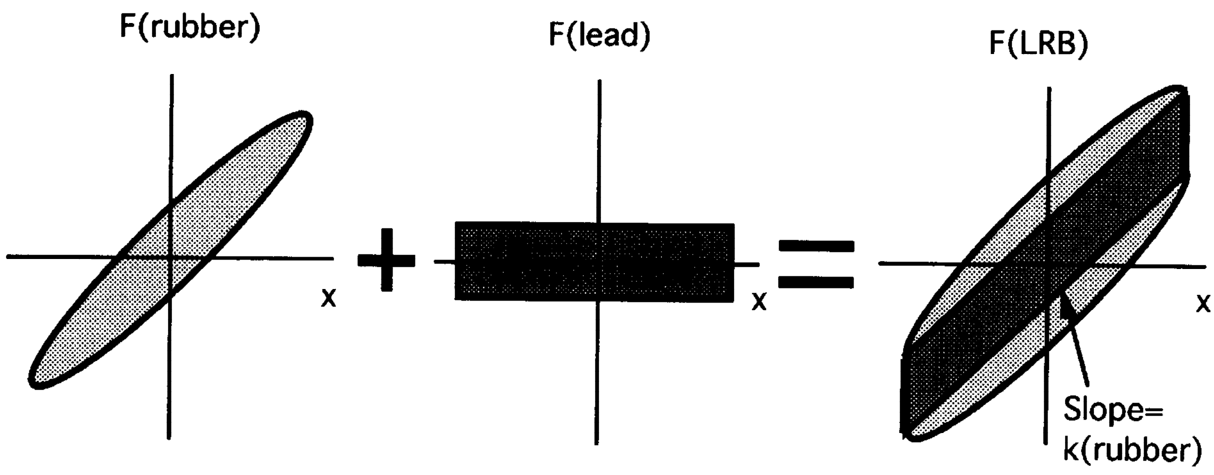

Figure 2 Force, F, versus displacement, x, for Lead-rubber Bearing (LRB); F(rubber) + F(lead) = F(LRB)

equipment. Another use is in the control of vibration such as in the 'rail' of the magnetically levitated train, presently undergoing tests in Japan.

Devices invented and developed at the Physics and Engineering Laboratory (PEL), and successfully applied in real seismic isolation systems, include various designs of steel damper, the lead-extrusion damper and the lead-rubber bearing. It is the lead devices which have received most application in New Zealand while throughout the rest of the world the lead-rubber bearing is often used for the seismic isolation of bridges and buildings. For example for isolated bridges in the USA (>80) and Japan (>20) more than 90% use lead-rubber bearings. For isolated buildings in these two countries the relative use of high damping rubber and lead-rubber bearing systems is more or less equal with a smaller number of other systems such as rubber isolation plus steel dampers, sliding devices and friction pendulums. The friction pendulum has been found to be particularly applicable to storage tanks where the mass of the isolated structure is varable (Zayas, 1995).

The lead-rubber bearing (LRB) consists essentially of a laminated elastomeric bearing of the type commonly found in bridges (to accomodate thermal expansion), with a lead insert. In all lead based devices the process of recovery of mechanical properties after and during plastic deformation is rapid (ca. 1ms) via the interrelated processes of recovery, recrystallisation and grain growth. These processes are particularly efficient at ambient temperatures because of the low melting point of lead (327°C). The almost rectangular elastic-plastic force-displacement hyteresis loop typical of such dampers is shown schematically in Figure 2(b). Figure 3 shows schematically a typical lead-rubber bearing while Figure 4 is a superposition of hysteresis loops obtained when testing the bearings manufactured by DIS Pacific Limited for the NZ Parliament Building described below. For these tests the axial load was 1.6MN (160tonnes) and a cycling rate of 0.1 Hz. The inside loops are for a high-damping rubber bearing, damping ~10% of critical, while the outside loops are for a lead-rubber bearing, damping ~50%.

Figures 2 and 4 can be understood by the following: It has been found that to a good approximation the total force required to shear a lead-rubber bearing, F(LRB), is given by

$$F(rubber) + F(lead) \quad = \quad F(LRB)$$

The reason for this approach is that the elastic stiffness of the rubber is the only mechanism by which the LRB is able to store elastic energy. Thus both the resonant frequency of the isolated structure and the decay of any oscillation is determined by '$k(r)$', the elastic stiffness of the rubber in shear.

The damping parameter, h, is defined as the energy absorbed in one cycle, ΔW, divided by 2π times the maximum elastic energy, $k(r)\, x^2(max)/2$. Thus $h = \Delta W / \pi\,(k(r)\, x^2(max))$, where for the lead-rubber bearing, ΔW is due mainly to the plastic deformation of the lead and is given by the area of the hysteresis loop in the figure. The incorrect 'diagonal', from opposite corners of the force-displacement hysteresis loop, has been used instead of the correct equation illustrated in Figure 2. This approach results in an overestimate of the shear stiffness by ~1.9 resulting in values for the damping which are low by factors of 1.3 to 1.9.

The lead-shear damper, a device suitable for providing 'added damping', is a very compact damper with a dynamic range of ~four orders of magnitude which behaves as a 'coulomb damper'. The lead-shear damper can be used to provide additional damping for isolation systems or to increase the damping capacity of a tall structure (Monti and Robinson, 1996).

DESIGN, TESTING AND COST

To date seismic isolation systems have been specially designed for particular applications. This has meant that often the designs are of a prototype nature and extensive prototype testing is required. Furthermore in some countries (for example the USA) every device is required to be tested. This excessive testing places an unneccessary additional cost on the application of seismic isolation. Over the last four years more than four hundred high damping and lead-rubber bearings have been tested, with all of these bearings meeting the specifications. When the placement of the bearings is taken into consideration, the bearings act in parallel with the shear forces additive, this approach is seen to be overly conservative.

For isolation bearings, Penguin Engineering is convinced that the time has come for the various characteristics, such as; vertical stiffness, shear stiffness, damping, vertical load, maximum displacement etc, to be standardised. Thus the bearing manufacturers could concentrate on providing high quality bearings at a reasonable price. Penguin Engineering is convinced that such an approach would result in a greater range of bearings of high quality, delivered on time, with the required characteristics. This approach would encourage the application of seismic isolation with a marked reduction in the loss of life and destruction to property caused by earthquakes.

BRIDGES

The first bridge to be seismically isolated in New Zealand was the Motu Bridge, in 1973, which used steel in flexure for damping. Since 1973 more a total of 49 road and rail bridges in New Zealand have been seismically isolated, eight being retrofitted.

Since its invention in 1976 by far the most common system for seismically isolating bridges in NZ, Japan and USA has been the lead-rubber bearing. Usually the lead-rubber bearings are installed between the bridge superstructure and the supporting piers. One of the reasons for the popularity of this type of seismic isolation is the fact that it combines the functions of isolation and energy dissipation in a single compact unit, whilst supporting the weight of the superstructure and providing an inelastic restoring force. The lead plug in the centre of the elastomeric bearing is subject to shear deformation under horizontal loading, providing considerable energy dissipation when it yields under severe earthquake loading. The lead-rubber bearing provides an extremely economic solution for seismically isolating bridges.

RETROFIT OF SEISMIC ISOLATION IN TWO HISTORIC BUILDINGS

The first building in the world to be seismically isolated with lead-rubber bearings was the William Clayton Building in Wellington (completed 1981). For this building, sitting on 80 lead-rubber bearings, the natural period of the isolated building was estimated at 2.5 seconds with a yeild force to seismic weight ratio of ~ 5%. Several other new buildings have been isolated in this way in New Zealand, but the retrofit of seismic isolation to existing buildings in New Zealand has only just begun.

The retrofitting of seismic isolation in two seismically vulnerable masonry buildings of historic significance, namely the old Parliament Building and the Assembly Library (Figures 5 & 6) in central Wellington, is now under way. All of the 514 bearings for the lead-rubber seismic isolation system have been tested in our laboratory, and they have been installed by the contractors. The various associated engineering works, such as refurbishment, are expected to be completed in 1996. The retrofit involves re-piling the building with lead-rubber bearings and rubber bearings in the supports, as well as cutting a seismic gap in the 500mm thick concrete walls. During an earthquake the building will be able to move in any direction on a horizontal plane up to distances of 300mm. Figure 9 shows the new foundations and beams being installed under the floor and also shows a lead-rubber bearing at the top right of the photograph. The effect of the isolation is calculated as increasing of the fundamental period from a value of 0.45 seconds to 2.5 seconds (Poole and Clendon, 1992).

Figure 3 shows schematically a typical lead-rubber bearing and Figure 4 is a superposition of hysteresis loops obtained when testing the bearings manufactured by DIS Pacific Limited for the NZ Parliament Building. For these tests the axial load was 1.6MN (160tonnes), with a cycling rate of 0.1 Hz for six cycles. The inside loops are for a high-damping rubber bearing while the outside loops are for a lead-rubber bearing. The hysteresis loops shown in Figure 4 were obtained during tests on these bearings. All 514 bearings retrofitted to these two buildings perform within ±5% of the specifications as part of the total quality management.

SEISMIC ISOLATION OF THE MUSEUM OF NEW ZEALAND

The construction of a major new building, the Museum of New Zealand, on the waterfront in central Wellington, started in June 1993. This 190x104 m building with a triangular floor plan is being isolated by 142 lead-rubber bearings with teflon sliding bearings under the shear walls. The museum with five floor levels has a total floor area of 35,000 square metres and height of 23 metres. The building was not designed to a code but instead is required to suffer no damage in a 250 year return period earthquake and not collapse with a 2000 year earthquake (Boardman and Kelly 1993). The calculated maximum floor accelerations for the 250 year earthquake, for the fixed-base and isolated cases, are 1.02 and 0.33g respectively. For the 2000 year event these values rise to 1.69 and 0.48g clearly illustrating the advantages of seismic isolation. The associated displacements for the isolated case for the 250 and 2000year events are ~260mm and ~510mm respectively. Estimates for damage costs are included in Figure 7. These results illustrate the significant reduction to damage costs in the case of the isolated Museum. The estimated period of the isolated structure is high at 2.5 seconds to overcome problems with the site, an area which has been 'reclaimed' from the shoreline.

Figure 5 New Zealand Parliament and Assembly Library after retofit with lead-rubber bearing isolators.

Figure 6 Lead-rubber bearings being retrofitted under New Zealand Parliament

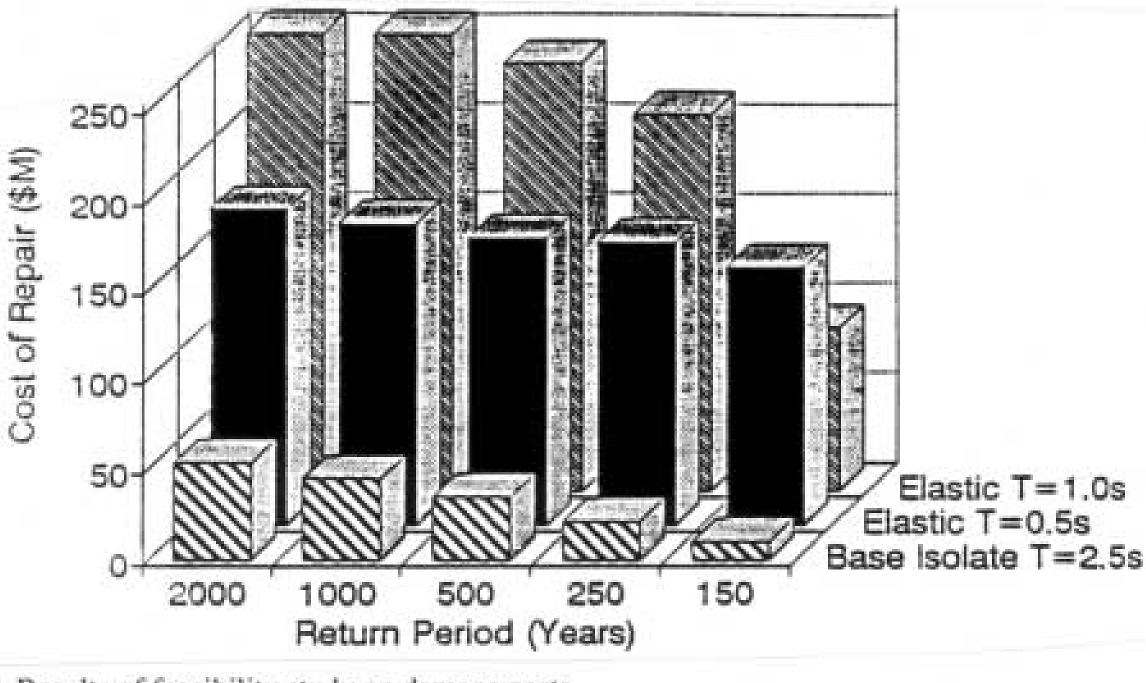

Figure 7 Results of feasibility study on damage costs

To ensure adequate performance of the isolation system all of the lead-rubber bearings have been tested by PEL. All of these bearings were within 6% of the specifacations. For the prototype lead-rubber bearings the test vertical loads were as high as 13.4MN (1340tonnes) and displacements up to 487mm.

CONCLUSIONS

The experience in seismic isolation in Japan, Italy, USA and New Zealand can be summarised as follows:

• *Bridges*: Over 200 bridges have been seismically isolated with about one half of the applications being in new bridges. In Japan, USA and New Zealand the lead-rubber bearing is the favoured device while in Italy viscous and steel hysteretic dampers are used. Typically for hysteretic dampers the yield force to weight ratio ~ 10% resulting in a damping ~10 to 20%. Six bridges isolated (LRB) in the area of the Kobe Earthquake suffered no damage while unisolated bridges nearby were destroyed.

• *Buildings*: Both new and old buildings have been seismically isolated. In Japan seismically isolation has been applied to new buildings the largest being the C-1 building (an office building in Tokyo (LRB)), the T-1 building (a computer centre in Tokyo (LRB)), and the Matumura Research Insitute (a small laboratory (HDRB)). In the USA the applications have been mainly with the retrofit of seismic isolation to existing buildings including the city halls of Oakland (LRB), Los Angeles (HDRB), San Francisco (LRB), US Court of Appeals in San Francisco (Friction Pendulum). As mentioned previously in New Zealand there are two large seismic isolation projects in progress at present, the retrofitting of isolation to the NZ Parliament Building and the associated Assembly Library and the new Museum of NZ. Both of these use LRB systems.

Three isolated buildings performed extremely well in earthquakes; the USC Teaching Hospital in Los Angeles (LRB) in 1994, the Computor Center of the Ministry of Post and Telecommunications (LRB) in 1995, and in 1995 the Matumura Research Insitute building in Kobe. The performance of these three buildings in real earthquakes illustrates the huge advantages of seismical isolation with these structures being able to continue to operate during and immediately after an earthquake with no break in its utilisation.

• *Future*: The technology of seismic isolation has now reached a mature stage, where, having been proven in practice, it is to be strongly recommended as an option to be included in the design of structures or buildings in regions of seismic risk, particularly where the building or its contents are of significant value to owner or to the community.

Consideration should be given to standardising isolation systems thereby enabling manufacturers to both improve their products and to reduce costs.

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