(Robinson, W. H., 1998: 68–69)

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PASSIVE CONTROL OF STRUCTURES, THE NEW ZEALAND EXPERIENCE

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ABSTRACT

In New Zealand, Japan, Italy and the USA, seismic isolation, 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 broad categories – fragile structures of historic significance and new structures with contents which need to be protected or continue to operate during and immediately after the earthquake. Examples of these structures are hospitals and other emergency centres. The seismically isolated bridges include both new and old bridges in areas of seismic activity.

Seismic isolation systems developed and used in New Zealand include – sliding bearings or flexible piles with steel or lead dampers providing the damping and the lead rubber bearing which, in one unit, provides both the isolation and the damping. To date more than fifty bridges and ten buildings have been isolated with most structures being isolated with lead rubber bearing systems.

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

KEYWORDS: Earthquakes, Seismic Isolation, Damping, Lead Rubber Bearings, Engineering Seismology

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.

Our studies in NZ, in seismic isolation began in 1968 as the combination 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, Robinson & McVerry, 1993 (Japanese and Chinese, 1998)). Skinner led the research and development of the steel devices and the initial studies of the concept and principles of seismic isolation while Robinson was the first person to suggest that lead would be an excellent damping material. Robinson invented the Lead Extrusion Damper (LED) (Robinson & Greenbank, 1976), the Lead Rubber Bearing (LRB) (Robinson, 1982), and the Penguin Vibration Damper (PVD) (Monti & Robinson, 1996). He also led the team that developed these devices for practical applications.

Very strong support for the principles of seismic isolation is given by the results of the January 1994 Los Angeles earthquake. The fact that of the ten hospitals affected by the Los Angeles 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 criteria, suffered no structural damage but had to be closed temporally because the high acceleration caused a water pipe to burst on the top floor. One kilometre 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 Computer Centre 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 (see Figure 1):

- 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 mm – 400 mm) by the addition of an appropriate amount of damping (usually 5 % to 30 % of critical).
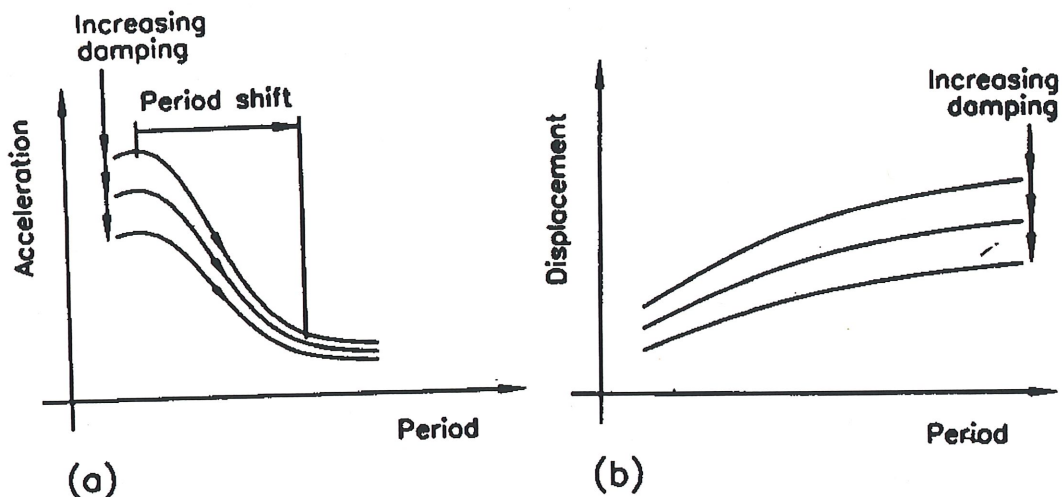

Fig. 1 Effect of period and damping on (a) acceleration, and
(b) total displacement for the isolated system

The increased period (> 1.5 sec, usually 2 sec to 3 sec) 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 %. 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 < 300 mm. Recently, 'inverted friction pendulums' have been used (Zayas, 1995).

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. The problem for designers of seismic isolation systems is to optimise the two conflicting requirements of maximising the period, thereby increasing the displacement, and at the same time maximising the damping, thereby controlling the displacement.

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 do 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.

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 surface (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 (e.g., PTFE) • Friction pendulum

The rubber bearing consists of layers of rubber, 5 mm to 20 mm 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 occurred 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 1974-76 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 something like 20 % of the design vertical load.

The high-damping rubber bearing has a damping in the range of 8 % to 15 % 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 markedly 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 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 (Skinner, Robinson & McVerry, 1993), the lead-extrusion damper (Robinson & Greenbank, 1976) and the lead-rubber bearing (Robinson, 1982; Cousins et al., 1991). 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 variable (Zayas, 1995).

The lead-rubber bearing (LRB) consists essentially of a laminated elastomeric bearing of the type commonly found in bridges (to accommodate 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. 1 ms) via the interrelated processes of recovery, recrystallisation and grain growth (Robinson & Greenbank, 1976; Robinson, 1982). 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 hysteresis loop typical of such dampers is shown schematically in Figure 2. 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 1.6 MN (160 tonnes) 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%.
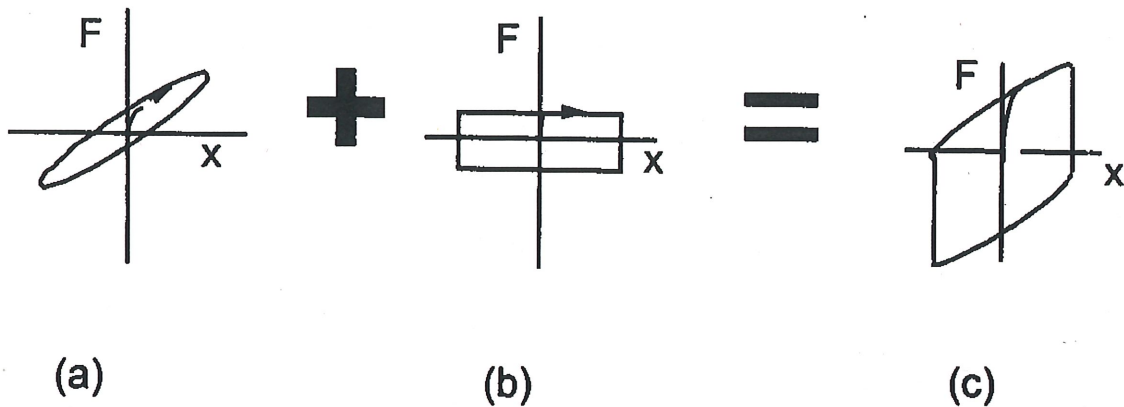

(a)   (b)   (c)

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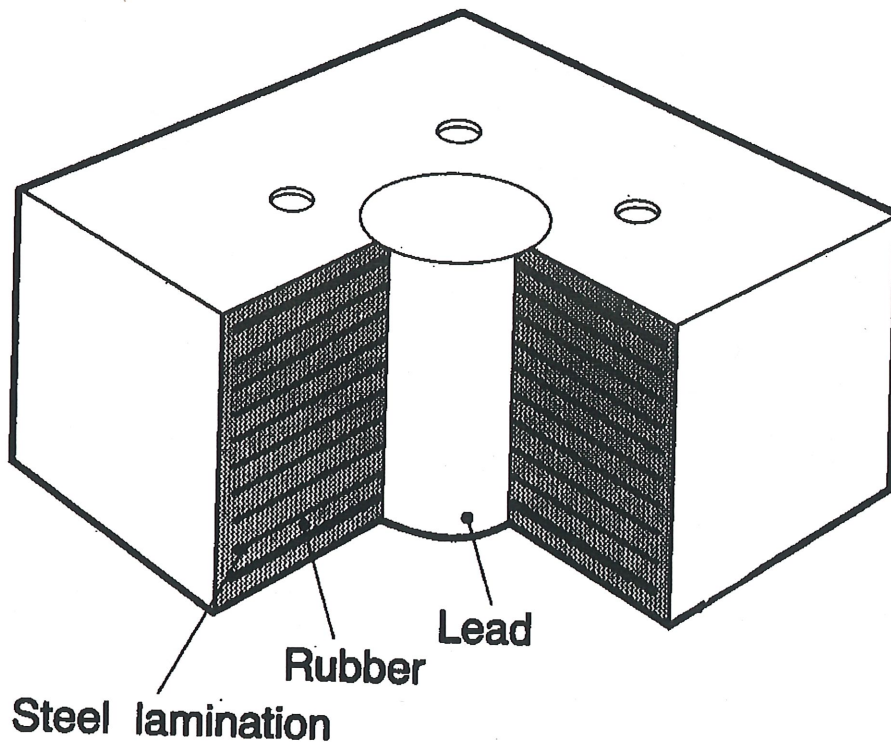F(rubber) + F(lead) = F(LRB)

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

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:

$$F(\text{rubber}) + F(\text{lead}) = F(\text{LRB})$$

$$\quad\ (a)\qquad\quad (b)\qquad\quad (c)$$

(1)

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, $k(r)\,x_{max}^2/2$. Thus $h = \Delta W/\left(\pi\, k(r)\, x_{max}^2\right)$, 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 Figure 2. The incorrect 'diagonal', from opposite corners of the force-displacement hysteresis loop, has been used by others 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.
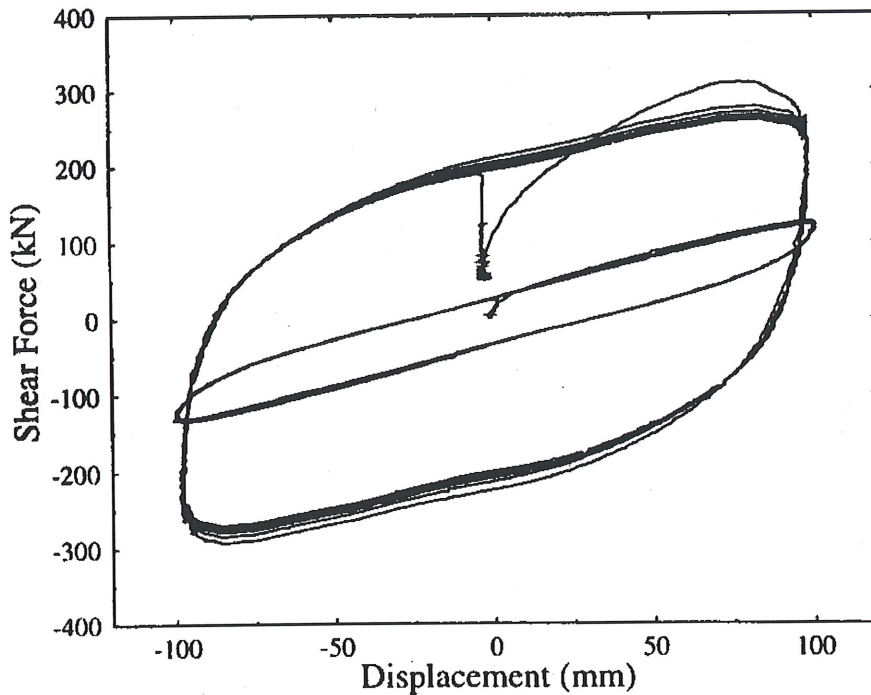

Fig. 4 Hysteresis loops for high-damping rubber bearing (inside loops) and lead-rubber bearing (outside loop)

The PVD, a lead-shear damper, is a device suitable for providing 'added damping', and is a very compact damper with a dynamic range of ~ four orders of magnitude. The PVD behaves as a 'coulomb damper' and can be used to provide additional damping for isolation systems or to increase the damping capacity of a tall structure (Monti & 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 unnecessary additional cost on the application of seismic isolation. Over the last four years more than four hundred high damping and lead-rubber bearings made in NZ have been tested by Penguin, with all of these bearings meeting the specifications. This approach is seen to be overly conservative, when the placement the bearings is taken into consideration because they act in parallel, thus the shear forces are additive.

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 believes 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 its invention by Robinson in 1976, the lead-rubber bearing has been by far the most common system for seismically isolating bridges in NZ, Japan and USA. Of the more than 50 bridges which have been isolated in New Zealand, more than 80% use the LRB. The remaining bridges have been fitted with either steel dampers or lead extrusion dampers.

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.

SEISMIC ISOLATION OF THE MUSEUM OF NEW ZEALAND

The first building in the world to be seismically isolated with 'lead-rubber bearings' or with a modern 'rubber elastomeric bearing' 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 sec with a yield force to seismic weight ratio of ~ 5%. Several other new buildings have been isolated in this way in New Zealand.

The construction of a major new building, the Museum of New Zealand, Te Papa, on the waterfront in central Wellington, started in June 1993 and opened in February 1998. Figures 5 and 6 illustrates Te Papa during construction, while Figure 7 shows the front of Te Papa after completion. The site for this building is reclaimed land and required major compaction, of the order of one metre, before construction. This 190 m × 104 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 m (Figure 8). 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 1.02g and 0.33g respectively. For the 2000 year event these values rise to 1.69g and 0.48g clearly illustrating the advantages of seismic isolation. The associated displacements for the isolated case for the 250 and 2000 year events are ~260 mm and ~510 mm respectively. Estimates for damage costs are included in Figure 9. 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 sec to overcome problems with the site, an area which has been 'reclaimed' from the shoreline.

To ensure adequate performance of the isolation system all of the lead-rubber bearings have been tested by Pel in a test-rig shown schematically in Figure 10. All of these bearings were within 6% of the specifications. For the prototype lead-rubber bearings the test vertical loads were as high as 13.4 MN (1340 tonnes) and displacements up to 487 mm.

This museum, Te Papa or 'our place', is a great success with more than one million visitors in a period of less than six months. It is possible for visitors to view the lead-rubber bearings.

RETROFIT OF SEISMIC ISOLATION IN TWO HISTORIC BUILDINGS

The retrofitting of seismic isolation in two seismically vulnerable masonry buildings of historic significance, namely the old Parliament Building and the Assembly Library in central Wellington, was completed in 1996 (Figure 11). All of the 514 bearings for the lead-rubber seismic isolation system have been tested in our laboratory. This retrofit involved re-piling the building with lead-rubber bearings and rubber bearings in the supports, as well as cutting a seismic gap in the 500 mm thick concrete walls. During an earthquake the building will be able to move in any direction on a horizontal plane up to distances of 300 mm. Figure 12 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 sec to 2.5 sec (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 Ltd, for the NZ Parliament Building. For these tests the axial load was 1.6 MN (160 tonnes), 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.

The retrofit of seismic isolation and the refurbishment to the Parliamentary Buildings is such a success that each day a number of tours of the buildings are available. These tours include a viewing of an isolation bearing.

SEISMIC RETROFIT IN PROGRESS

The retrofit of seismic isolation to existing buildings in New Zealand is continuing at present with the application to the BNZ building and the Maritime Museum, both in Wellington. These two masonary building were found to be earthquake risks and the most economical method of upgrading was to retrofit with a 'lead-rubber bearings' seismic isolation system.

1. Maritime Museum

The former Head Office building of the Wellington Harbour Board has great historic value to the city, being the focus of harbour management from 1892 until the dissolution of the Board in 1989. The first reason for the settlement of Wellington was the harbour, and shipping has been an important reason for its commercial prominence ever since. This masonry building is now the Wellington Maritime Museum and is being upgraded to present earthquake codes by seismically isolating it with a lead-rubber bearing system.

2. BNZ Building

The former BNZ building No. 3, built in 1885, of the BNZ complex and one of Wellington's oldest masonry buildings. This buildings has a classical Victorian style and facade and is richly decorated with fine plasterwork. This building is currently being retrofitted with a lead-rubber bearing seismic isolation system.

All bearings were tested prior to installation by Penguin Engineering Limited.

FUTURE

The technology of seismic isolation has now reached a mature stage, where, having been proven in practice, in the Los Angeles 1994 earthquake and the 1995 Great Hanshin earthquake, 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 the owner or the community.

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

CONCLUSIONS

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

1. 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.

2. 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 Institute (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 that have recently been completed. These were 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 Computer Centre of the Ministry of Post and Telecommunications (LRB) in 1995, and in 1995 the Matumura Research Institute 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 utilisation.
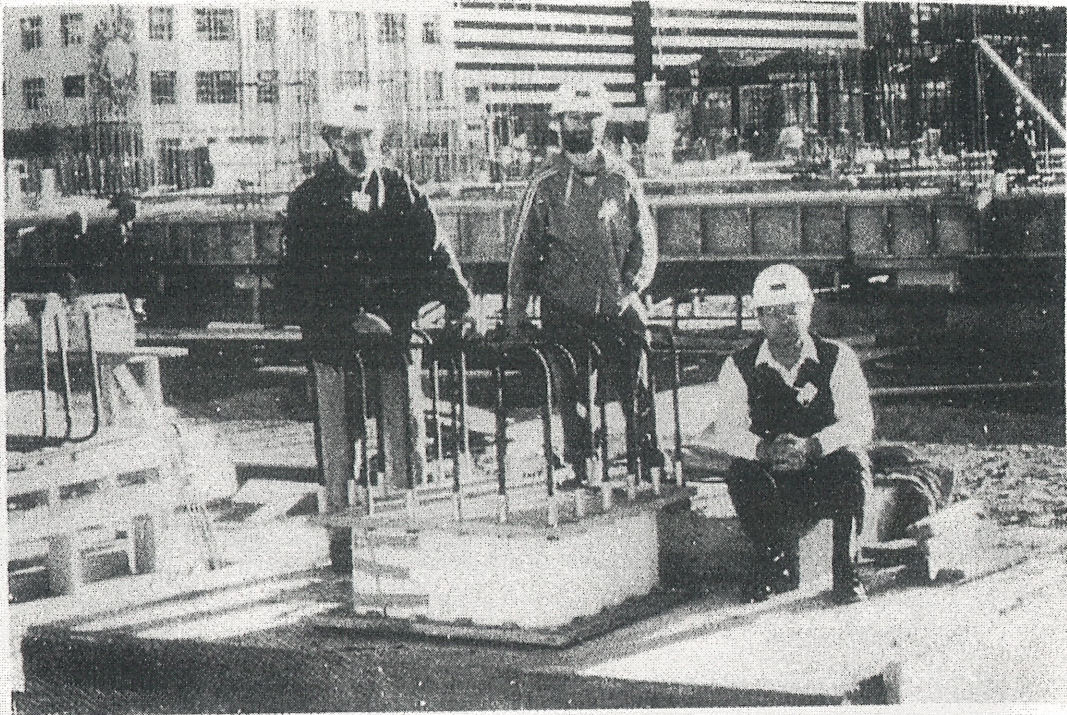
Fig. 5 Illustrates the lead-rubber bearing in place,
ready for a concrete column and beam to be cast above it
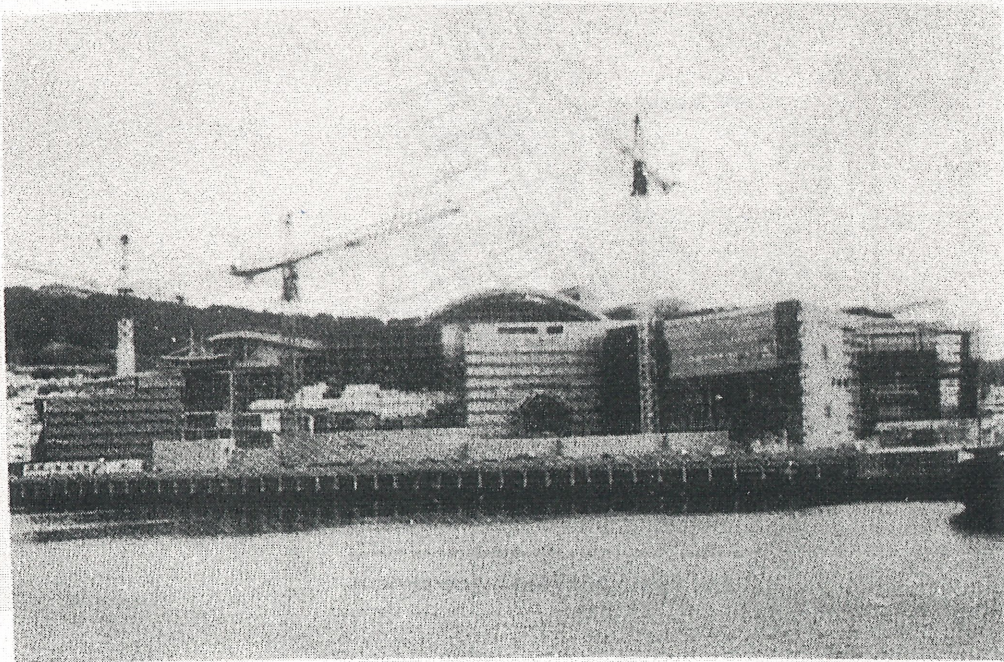

Fig. 6 Te Papa during construction as seen from the waterfront

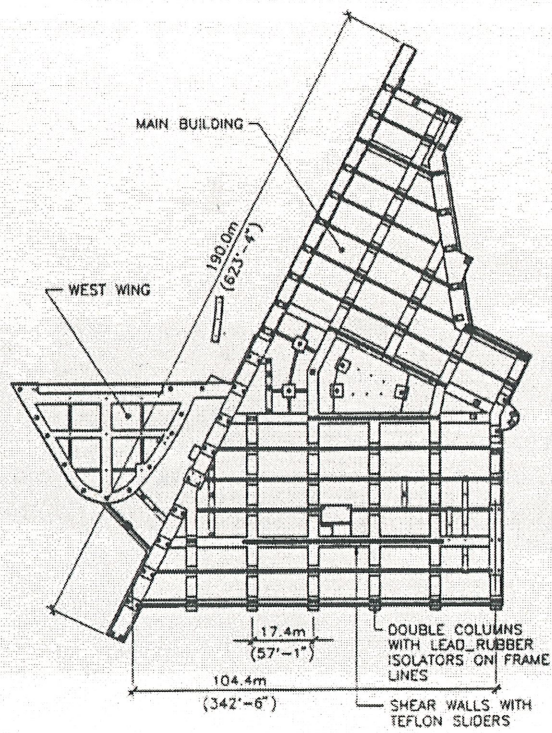Fig. 7 Main entrance view of Te Papa on completion
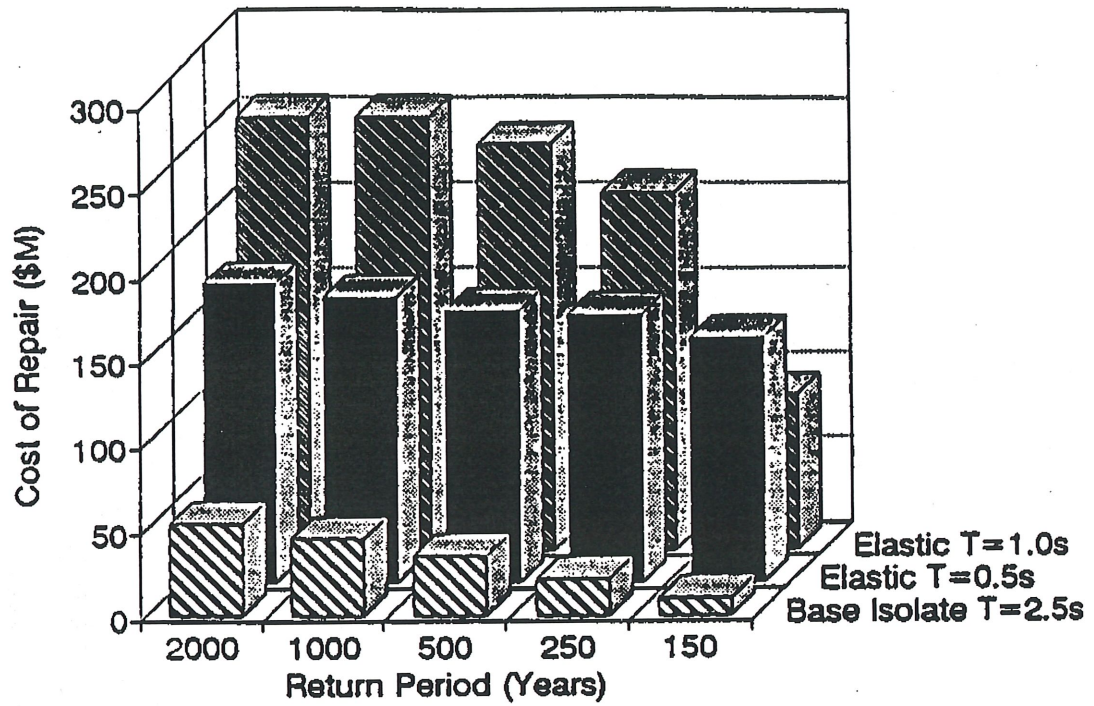

Fig. 8 Te Papa floor plan

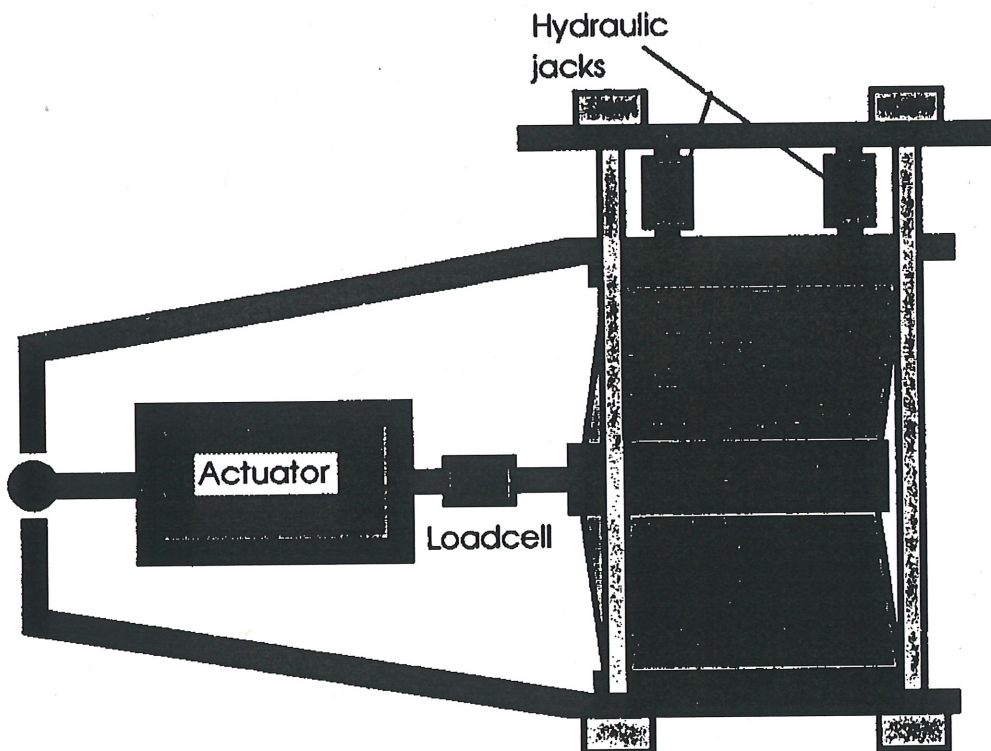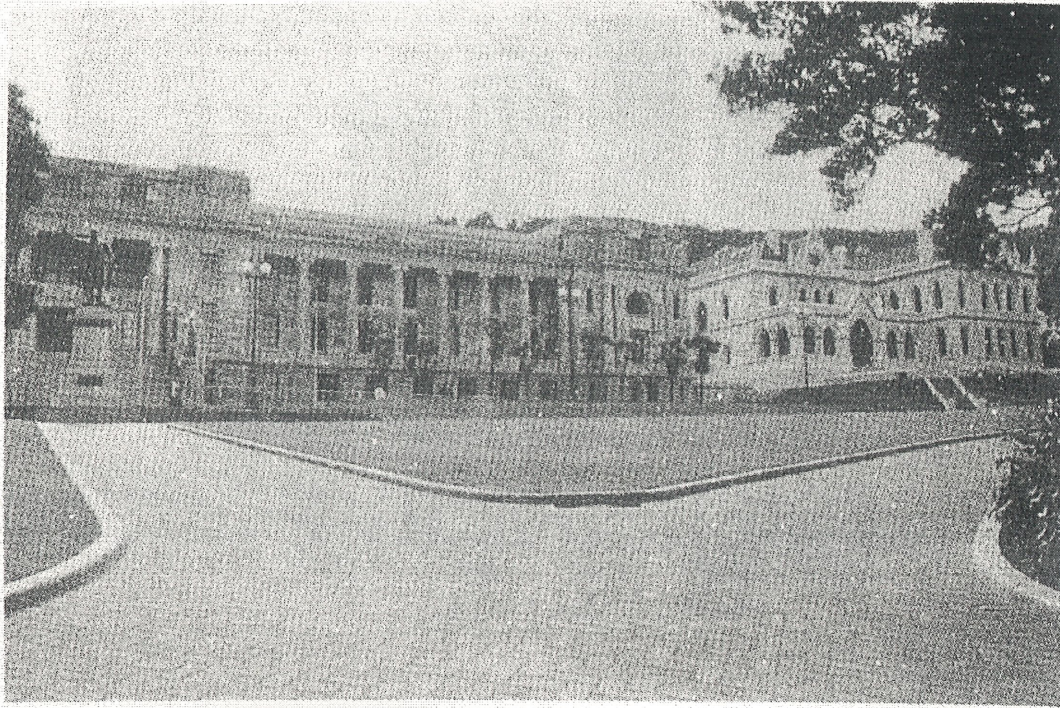Fig. 9 Results of feasibility study on damage costs

Fig. 10 Schematic drawing of Test Rig

Fig. 11 New Zealand Parliament and Assembly Library after retrofitting
with lead-rubber bearing isolators

Fig. 12 Lead-rubber bearings being retrofitted under New Zealand Parliament

ACKNOWLEDGEMENTS

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