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The implementation of base isolation in the United States

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ABSTRACT: The concept of base isolation as an innovative means of providing earthquake resistance to structural systems was met initially with a great deal of skepticism by the engineering community. Today, however, it is on the cutting edge of seismic resistance engineering, as evidenced by the rapidly increasing number of buildings, both new construction and retrofit, using this earthquake resistant technique. It is now generally accepted that a base-isolated building will perform better than a conventional fixed-base building in moderate or strong earthquakes. In the structures in which it has been used so far, the major benefit has been to reduce the effects of seismic forces on contents and internal equipment, more than justifying the increased cost of isolated construction. This review will mainly cover the development and application of base isolation to buildings in the United States. The acceptance of this approach has been slow, but as a result of the 1989 Loma Prieta earthquake there is an increasing interest in its use for repair of buildings damaged in that earthquake and for the retrofit of historic buildings that are considered vulnerable to earthquake loading.

1 INTRODUCTION

The application of base isolation to address the problem of providing earthquake resistance to structural systems is a radical departure from the traditional approaches used by structural engineers. In conventional fixed-base design, efforts to strengthen the structural system to provide superior seismic performance lead to a stiffer structure, and thus will attract more force to the structure and its contents. A fixed-base building tends to amplify the ground motion. In order to minimize this amplification, the structural system must be either extremely rigid or provided with high levels of damping. At best, rigidity leads to the contents of the building experiencing the accelerations of the ground motion which may be too high for sensitive internal equipment and contents. The alternative of providing high levels of damping into the system generally leads to damage of the structural system or to structural forms.

Isolation allows the engineer to design a system that can function without damping, yet protects the building and its contents with relatively simple and low-cost structural systems. The concept has been long in gestation, but is now being used enthusiastically in many countries. At the present time, there are several types of isolation systems in use, many variants of existing systems are being developed, and new systems are being proposed and tried.

When I first presented a review of seismic isolation at the 2nd U.S. National Conference on Earthquake Engineering at Stanford University in 1979 (Kelly 1979), it was the only paper on base isolation in the entire conference. Although a few papers on base isolation had been submitted, the organizers felt that there was not enough interest in the subject to justify accepting more than one paper and these were compressed into one. At the 8WCEE in San Francisco in 1984, there was only one session devoted to base isolation; in 1988 at the 9WCEE there were four sessions, were dominated by Japanese researchers who were, by then, the leaders in this area; at the 10th WCEE in 1992, there were four sessions each day with the lecture hall overflowing with people.

To press the point even further, in 1985, I collected all the papers on isolation (in English) that I could find; this totaled about 180. By mid-1990, the updated version totaled 390 publications, by mid-1992 I would estimate that the total would be in the thousands. In this year, 1992, there are more symposia, workshops, and specialist meetings on base isolation in the United States alone than there were published papers in 1982.

Obviously, the wealth of publications on base isolation indicate that to date, research is being widely conducted on a large variety applications. However, are the results of this research being transferred into general engineering practice? Since the use of base isolation is a radical change in the way engineers think of providing earthquake protection, the implementation is most visible in its application to buildings. Most research is transferred into practice in an incremental way and may not be very visible. The straightforward manner in which the eccentrically-braced frame design was accepted in seismic areas is a case in point.

The use of base isolation in buildings in the United States was very slow. In contrast, its acceptance in Japan was rapid and widespread. There are now at least 65 base-isolated buildings in Japan either completed, under construction, or licensed for construction.

This review will focus entirely on base isolation as applied to buildings, leaving aside seismic isolation for bridges. The number of bridges that have been designed and built using isolation concepts is very large, but when applied to bridges, energy dissipation predominates; whereas for buildings, the dominant mechanism is isolation and energy dissipation plays only a minor role. Also, the review will focus mainly on the development and implementation of base isolation in the United States. An adequate assessment of worldwide applications would exceed the restrictions on this review.

When a building is built on an isolation system, it should have a fundamental frequency that is lower than both its fixed-base frequency and the dominant frequencies of the ground motion. The first mode of the isolated structure then involves deformation only in the isolation system, the structure above being almost rigid. The higher modes which produce deformation in the structure are orthogonal to the first mode, and thus to the ground motion. These higher modes then have very low participation factors, so that if there is high energy in the ground motion at the higher mode frequencies, this energy cannot be imparted to the structure. In this way, the demand on the structural system is reduced and the accelerations transmitted to the internal non-structural components, contents, and equipment are also reduced.

This makes isolation a very attractive approach where protection of expensive sensitive equipment is needed and it is no surprise that this technology has been used for buildings such as hospitals, computer centers, and nuclear facilities. This action of the isolation system is independent of damping, although some damping is beneficial to suppress resonance due to long-period motion at the frequency of the isolation system, but high levels of damping are not needed in isolation systems for buildings where protection of internal equipment is the goal of the design. High levels of energy dissipation lead to smaller displacements at the isolation system but higher accelerations in the superstructure, and are thus advantageous for bridges where control of displacements is important and accelerations in the deck are not important.

The history of the development of base isolation has been covered in several review articles, for example, Kelly (1986), Mayes and Buckle (1990), and Kelly (1988). As mentioned earlier, the most widespread use of the approach is in Japan. There are several applications in New Zealand (Dowrick, Cousins, Robinson & Babor 1992); several in Italy (Giuliani 1989), including one project of five large buildings, and large number of applications in France, including two nuclear power plants (Postollec 1983) (Jolivet & Richli 1977). There are a few buildings using a simple method of isolation in China (Lee 1984), and several buildings in Russia (Eisenberg, Melentyev, Smirnov & Menykin 1992). In the United States, isolation is now being used for both new buildings, for the repair of buildings damaged by the Loma Prieta earthquake of 1989 and for the retrofit of historic buildings.

Research in the United States on isolation systems has increased exponentially in recent years, as attested by the number of symposia, workshops, and other meetings devoted entirely to seismic isolation topics. Some have been focused on civil structures, some on nuclear facilities, and others on the use of isolation for U.S. Government buildings. A number of cooperative research programs are under way, including one involving the Earthquake Engineering Research Center (EERC) and Shimizu Corporation of Japan with the participation of Malaysian Rubber Producers' Association (MRPRA) of the United Kingdom and Argonne National Laboratory (ANL) in the United States. In another, the National Center for Earthquake Engineering Research (NCEER) in Buffalo is working with the Taisei Corporation of Japan on the development of advanced sliding isolation systems. Numerous cooperative research programs on isolation for nuclear facilities are in place involving research workers from Japan, the United States, Italy, France and the United Kingdom.

The emphasis in most base isolation applications up to this time has been on large structures with sensitive or expensive contents, but there is increasing interest in the possibility of applying the technology to public housing and other buildings such as schools and local health centers in developing countries. Several projects are under way for such applications.

The challenge is to develop a low-cost isolation system that can be used in conjunction with vernacular methods of construction, such as masonry block and lightly reinforced concrete frames. Demonstration buildings for housing projects have been completed using natural rubber bearings as the isolation system in Santiago, Chile (Sarrazin & Moroni 1992)) and in Squillace in southern Italy (Vestroni, Capecchi, Meghella, Mazza & Pizzigalli 1992). Demonstration projects are being planned for housing projects in Shantou City, Guangdong Province in China (Zhou, Kelly, Fuller & Pan 1992). and in Indonesia, both with partial support from the United Nations Industrial Development Organization (UNIDO).

2 CODE REQUIREMENTS FOR ISOLATED BUILDINGS

The first building in the United States to use a seismic isolation system was completed in 1985 and was publicized in national engineering magazines and visited by a great many engineers and architects from the United States and around the world. However, it was several years before the second base-isolated building was begun. The acceptance of isolation as an anti-seismic design approach for some classes of buildings has clearly been slowed in the United States by lack of a code covering base-isolated structures.

The Structural Engineers Association of Northern California (SEAONC) created a working group in 1980 to develop design guidelines for isolated buildings. A brief document was produced and became the starting point for a sub-committee of the SEAONC Seismology Committee that was formed in early 1985. The Seismology Committee of the Structural Engineers Association of California (SEAOC) has been responsible for the development of provisions for the earthquake resistant design of structures, published as Recommended Lateral Design Requirements and Commentary, generally referred to as the "Blue Book" (SEAOC 1985). This has served as the basis for the various editions of the Uniform Building Code (UBC), published by the International Conference of Building Officials (ICBO), and which is the most widely used code for earthquake design. The SEAONC sub-committee produced a document entitled "Tentative Seismic Isolation Design Requirements" (SEAONC 1986) which was published by SEAONC in September 1986 as a supplement to the fourth edition of the Blue Book. The approach and layout of the 1986 document was chosen to parallel the Blue Book as far as possible. Emphasis was placed on equivalent lateral force procedures, and as in the Blue Book, the level of seismic input was that required for the design of fixed-base structures a level of ground motion that has a 10% change of being exceeded in a 50-year period. As in the Blue Book, dynamic methods of analysis are permitted, and for some types of structures required, but the simple statically equivalent formulas provide a minimum level for the design.

The Seismology Committee of the state-wide association (SEAOC) formed a subcommittee in 1988 to produce a isolation design document entitled "General Requirements for the Design and Construction of Seismic-Isolated Structures" (SEAOC 1989). This was published as an appendix to the fifth edition of the Blue Book in 1990 and later adopted by ICBO as an appendix to the seismic provisions in the 1991 version of the UBC (UBC 1991). The version of the code includes the static method of analysis and retains a minimum level of design based on a factor of the static analysis values, but increases the number of situations where dynamic analysis is mandatory.

A further code document has been developed for the design of base-isolated hospitals in California. The Building Safety Board (BSB) of the Office of State Architect has adopted guidelines entitled, "An Acceptable Method for Design and Review of Hospital Buildings Utilizing Base Isolation" (OSHPD 1989). These guidelines are similar to both the SEAONC requirements and the UBC code, having been developed in part by SEAONC for the BSB. The version adopted by the BSB in 1989 has subsequently been revised with some additional requirements being included in a version that was adopted in January 1992.

The UBC code differs from the SEAONC guidelines in that it explicitly requires that the design must be based on two levels of seismic input. A design basis earthquake is defined as the level of earthquake ground shaking which has a 10% probability of being exceeded in a 50-year period. For this level of input the design provisions require the structure above the isolation system to remain essentially elastic. The second level of input is defined as the maximum credible earthquake which is the maximum level of earthquake ground shaking that may be expected at the site within the known geological framework. This is taken as that earthquake ground motion that has a 10% probability of being exceeded in 250 years. The isolation system should be designed and tested for this level of seismic input and all building separations and utilities that cross the isolation interface should be designed to accommodate the forces and displacements for this level of seismic input.

Although the SEAONC and the UBC documents are very similar in many ways there is a fundamental difference between them. The first puts a premium on using static analysis and tends to force the designer toward regular superstructures with braced frames. The second on the other hand, makes dynamic analysis necessary in more situations and creates an incentive to use dynamic analysis even where it is not mandatory in order to permit reductions in the design shear for the superstructure. The SEAONC 1986 document used reduction factors (R_w) for the design of the superstructure that were one half of those used for the corresponding fixed-base structural system. The 1991 UBC document uses even more conservative reduction factors. For example, a fixed-base braced frame design would have a reduction factor of 8, whereas, if it were base isolated, it would would be allowed a reduction factor of 4 in the SEAONC code and only 2.3 in the UBC code.

These requirements for isolated buildings represent a radical departure from the code for fixed-base structures. The UBC seismic requirements for fixed-base buildings are intended to provide reasonable protection for life safety but not intended to limit damage or to maintain functionality of the structure. The fixed-base code allows the structure to be designed for forces that are very much less than those that would be developed if the structure were to remain elastic. It is implicitly assumed that inherent overstrength and ductility will prevent collapse in a large earthquake and ensure life safety, but no check that this will be achieved is required. The requirements for isolated structures is such that the superstructure will be essentially elastic for the design basis earthquake and the isolation system will be tested and designed to be capable of sustaining the maximum credible earthquake. Since large inelastic deformations of the structure as permitted in the design of fixed-base structures can produce significant structural damage, and as a consequence, the possibility of loss of functionality, the more stringent requirements for isolated buildings will limit the level of damage that could occur and thus, these code requirements should lead to buildings which can survive severe earthquakes with little damage to structural elements, non-structural components, and with no loss of function.

In the UBC guidelines, a peer review of the design and construction of all base-isolated structures is mandatory under the code. This review is to be conducted by an independent engineering team experienced in seismic-analysis techniques and base-isolation practice whose responsibilities include reviewing both the site-specific seismic criteria and the preliminary design including design displacement and lateral forces, and overview and observation of the prototype testing and quality control program for the isolation system.

The major differences between the hospital guidelines and the UBC requirements are that no static analysis is permitted, dynamic analysis being essential. Also, site specific seismic input is required of two levels of ground motion corresponding to maximum probable and maximum credible earthquakes. Extensive testing requirements are specified and it is required that the isolation system should be monitored for the life of the building and a monitoring program must be submitted for approval with the design of the building.

3 ISOLATION SYSTEMS USED OR PROPOSED IN THE UNITED STATES

Most new or retrofit base isolation projects have made use of elastomeric isolation bearings and of these, most are in the form of lead plug bearings (LRB). The first type of bearing used for a building in the United States was the high-damping rubber bearing (HDR). Elastomeric systems are also widely used in other countries. In Japan, they are often used in conjunction with some type of steel dampers or other energy-dissipating devices. In New Zealand, there have been several buildings with LRB's and two buildings using a system based on sleeved piles (Boardman, Wood & Carr 1983) (McKay, Chapman & Kirkcaldie 1990). Aspects of elastomer technology pertinent to isolation systems have been reviewed by Taylor et al. (1992).

Sliding systems have been the subject of much recent research at NCEER, both for buildings and bridges. Additionally, the frictional characteristics of PTFE (Teflon) surfaces have been studied (Mokha, Constantinou & Reinhorn 1988) (Mokha, Constantinou & Reinhorn 1990) (Constantinou, Mokha & Reinhorn 1990). One of the systems being studied is the Frictional Pendulum System (FPS) (Zayas, Low & Mahin 1990). In this system the structure is supported on spherically shaped bearings with the load being applied through a small area covered by a high-strength composite material. The FPS has been used to retrofit an apartment building in San Francisco damaged by the Loma Prieta earthquake and will be used for the retrofit of a large U.S. Government building in San Francisco.

Many other new systems have been proposed. One example is the R-FBI (Mostaghel 1986) which uses many Teflon sliding surfaces. It has been tested on the shake table at EERC (Mostaghel, Kelly & Clark 1992). Systems that combine sliders and elastomeric bearings have been proposed and have been tested (Chalhoub & Kelly 1990) and at least one system has been used for retrofit of an historic building.

At the present time, the development of new isolation systems is extremely active and many new mechanisms are being explored. Table 1 lists only a few of the systems currently used or proposed in the United States.

Table 1. Isolation systems used/proposed in the United States

Elastomeric Systems
High-Damping Rubber Bearings (HDR), Non-Proprietary
Lead Rubber Bearings (LRB), DIS

Sliding Systems
Earthquake Barrier (EBS), M.S. Caspe
Friction-Pendulum System (FPS), EPS
Resilient Frictional Base Isolation (RFBI) N. Mostaghel

Hybrid Systems
Combined Rubber-Slider-Restrainer Systems, Fyfe Associates
Zoltan Isolator, Lorant Group
GERB Steel Springs, GERB, Gesellschaft fur Isolierung mbH & Co KG

Other Systems
Cable Suspension System, F. Garza-Tamez
Anti-Friction Isolation System, V. Shustov
Rocking Columns System, L. Li

4 BASE-ISOLATED BUILDINGS IN THE UNITED STATES

The first building in the United States to use base isolation was the Foothills Community Law and Justice Center which was begun in 1982 and completed in 1985. Further use of this approach was slow, with a few projects reaching the stage of feasibility assessment but not proceeding to construction. The next building projects using base isolation were not in California but in Salt Lake City, Utah. One was a new building for a computer manufacturing company and the purpose of the isolation system was to protect the computers and not the building. The other was the first use, in the United States and perhaps the world, of isolation as a seismic rehabilitation method for a historic building.

After this slow start, interest in the use of isolation has increased dramatically and at the present time, mid-1992, there are now many base isolation building projects in the United States either completed, under construction or in the design phase. Some of these projects are for new building, but a very large number are seismic retrofit projects. These have been stimulated by the damage to several historic buildings in San Francisco, Oakland, and the surrounding area from the 1989 Loma Prieta earthquake. It is interesting to note that the use of isolation for new buildings is, at the present time, mainly in southern California, whereas most isolation projects in northern California are for retrofits.

Tables 2, 3, and 4 list completed projects and projects that are reasonably likely to go forward to construction, both for new buildings and for retrofit. Further details on the type of isolator and the design philosophy of the completed buildings can be found in several papers and reports of which Tarics, Way and Kelly (1988), Reaveley, Mayes and Sveinsson (1988), Allen and Bailey (1988), Anderson (1989), Way and Howard (1990), Hart et al. (1991), and Asher et al. (1990) are a representative sample.

5 DEVELOPMENT OF ISOLATION SYSTEMS FOR NUCLEAR APPLICATIONS

Nuclear power plants are examples of buildings where the reduction of response of internal equipment is the primary goal. The analysis of equipment and piping systems for seismic loading is one of the most expensive parts of the design process and it is complicated by the fact that for fixed-base construction, different levels of a plant have different seismic response. Thus, it is generally necessary to use multiple support response spectrum analysis. The use of base isolation could reduce the amplification of acceleration at higher levels of a plant and would permit the use of simple design methods for equipment and piping, as well as eliminate the need for seismic restraints such as snubbers.

There are several large research programs directed toward the use of isolation for nuclear facilities. In the United States, a program funded by the Department of Energy and conducted by Argonne National Laboratory, was carried out over 1988-92. This program has covered shake table tests (Kelly 1991) and testing of a variety of potential elastomeric isolators under a wide range of loadings to determine dynamic characteristics, failure modes, fatigue resistance, and to establish failure modes. Isolators at a scale factor of two were tested under this program at EERC and full-size isolators in a large isolator test facility at the Energy Technology Engineering Center (ETEC) near Los Angeles, California. The results of these tests are detailed in Tajirian & Kelly (1988). and in conference proceedings (IAEA 1992). Under this DOE program, four different sets of isolators were obtained from four manufacturers.

The four test programs confirmed the high quality of high-damping elastomeric bearings. They were shown to be capable to extremely large shear strains before failure even under high levels of vertical pressure. It was shown that the failure mechanism is only slightly affected by pressure and that the stiffness is unaffected by pressure, while the damping is increased by pressure. The tests demonstrated that the entire search to find damping mechanisms to accompany isolation systems has been a misplaced effort. Much more important for the design of practical isolation systems is that fact that the elastomer hardens very strongly after a level of shear strain has been exceeded. If the isolators are much wider than their height, buckling is not a factor in their response and the stiffness increases by a factor of six beyond 250% shear strain. Thus, if 200% shear strain is taken as the nominal design level, at which level of base shear the superstructure is just at the yield point, then the base shear must increase by at least a factor of six before the isolation system fails. This means that the failure mechanism for the entire structure will be in the superstructure and not in the isolators. This means that conceptually , collapse of an isolated structure is no different from that of a conventional structure with, however, the proviso that the level of earthquake impact that produces the failure must be much greater for the isolated structure due to the large displacement capacity of the isolation system. The strong hardening response of the system beyond the design level means that if the system exceeds this level, the period shortens significantly and the system becomes non-resonant.

The results of these tests confirm that base-isolated nuclear facilities can be designed and built and that their performance in moderate and strong earthquakes will be superior to conventional design and that the isolation system will provide damage control to the structure and to internal equipments and contents. The performance in very strong earthquakes much beyond those assumed for design will also be superior to conventional structures, but will have the same type of collapse mechanisms in the structure. These results should lead to increased confidence in the use of the technology for nuclear facilities and also for buildings housing sensitive internal equipment such as data centers, computer manufacturing facilities, telephone exchanges, and buildings that must be able to continue operation after strong earthquakes such as emergency control centers and hospitals.

5.1 General Electric Corp. PRISM Reactor

Interest in applying seismic isolation to nuclear plants has existed in the U.S. ever since its use by the French (Kunar & Maine 1979) (Vaidya & Eggenberger 1984). In recent years, the DOE has supported the development of two compact advanced LMR concepts, the Power Reactor Inherently Safe Module (PRISM) designed by General Electric Corp., and the Sodium Advanced Fast Reactor (SAFR) designed by Rockwell International Corp. Both concepts incorporate seismic isolation in the reference design to support plant standardization, enhance plant safety margins, permit siting in zones with higher seismicity, and thus reduce plant costs.

The selected isolation system for both concepts consists of steel-laminated elastomeric bearings. For PRISM, high-damping bearings are used to provide horizontal protection for the reactor module only, while for SAFR, the entire building is supported on bearings which provide both horizontal and vertical isolation (Tajirian, Kelly & Aiken 1990) (Aiken, Kelly & Tajirian 1989). The PRISM concept was selected by DOE for further development and has been reviewed and approved by NRC. PRISM employs a 155 MWe compact standardized LMR (Berglund, Tippets & Salerno 1988). in which the reactor module with its key safety functions of reactor shutdown, shutdown heat removal, and containment systems are isolated in the horizontal direction from potentially damaging ground motions. The reactor vessel has a diameter of 20 ft. and a height of 62 ft., and is supported from the top. The relatively small diameter of the vessel provides sufficient intrinsic resistance in the vertical direction to minimize amplifications in vertical ground motions making vertical isolation unnecessary. The entire isolated structure, which weighs approximately 5,000 tons, is supported on 20 large diameter steel-laminated elastomeric bearings, and is housed in an underground silo. The elastomeric compound used consisted of a highly filled natural rubber with high-damping (Derham, Kelly & Thomas 1985).

This particular system was selected for PRISM following a review of available hardware because it is a simple design and its dynamic response, especially at extreme loadings, is easier to characterize than some of the more nonlinear systems. Furthermore, it has sufficient inherent damping to eliminate the need for additional energy-absorbing devices which can complicate the design and the system response. Shake table tests and numerical analysis have shown that equipment response in isolated buildings is minimized when high-damping elastomeric bearings with no add-on damping elements are used, and that when frictional or elasto-plastic dampers are incorporated, they inevitably cause high-frequency response and increased accelerations in equipment (Kelly 1982) (Kelly & Tsai 1984) (Fujita et al. 1988) (Tajirian and Kelly 1987) (Skinner, Robinson & McVerry 1989) (Fan & Ahmadi 1992).

5.2 International Cooperation Programs

A cooperative program to develop design guidelines for nuclear plants using high-damping elastomeric isolators was begun in 1988 at the initiative of the Italian Agency for New Technologies, Energy and Ambient (ENEA) and General Electric Nuclear Energy and with the cooperation of ISMES in Italy and Bechtel National in the U.S. The resulting guidelines were outline at the IAEA Specialists Meeting on Seismic Isolation Technology in San Jose, California in 1992 (Martelli & Bettinali 1992).

The United Kingdom nuclear power industry has considered the application of seismic isolation to future LMR plants to potentially reduce costs, to increase margins of safety, and to facilitate standardization (Austin et al. 1989). The U.K. has been participating in a joint program with the Electric Power Research Institute (EPRI) and the Central Research Institute of Electric Power Industry (CRIEPI) of Japan to evaluate the technical feasibility of selected seismic isolation systems and their applicability in the design of large LMR plants (Gray, Rodwell & Hattori 1988) such as the European Fast Reactor (EFR). Available seismic isolation devices have been evaluated and candidate systems have been selected.

A joint U.S./Japanese program to study isolation systems for nuclear facilities has been conducted by ANL and Shimizu Corp. of Japan. As part of this program, two types of isolation systems based on high-damping rubber have been installed at the Shimizu demonstration isolation building at Tohoku University in Sendai, Japan. The first system installed at the demonstration building was closely based on the high-shape factor isolator designed for the PRISM reactor at a scale factor of approximately three. This system was monitored in the building from October 1989 to November 1990, when it was replaced by a system using a newly developed low-modulus high-damping rubber developed for application to nuclear facilities at soft-soil sites. This system is still in place at the present time. The results of the monitoring program for the two systems is given in Chang and Seidensticker (1991).

6 FUTURE DIRECTIONS IN BASE ISOLATION

It seems clear that the increasing acceptance of base isolation throughout the world will lead to many more applications of this technology. It is also clear that while elastomeric systems will continue to be used, there is a willingness to try other systems. The initial scepticism that was so prevalent when elastomeric systems were initially proposed is no longer evident, and the newer approaches which are currently being developed will benefit from this more receptive climate and lead to the development of systems based on different mechanisms and materials.

For all systems, the most important area of future research is that of the long-term stability of the mechanical characteristics of the isolator and its constituent materials. The long-term performance of isolators can best be developed from inspection and retesting of examples that have been in service for many years. Elastomeric systems in the form of non-seismic bridge bearings have been used for upwards of thirty years and a record of satisfactory performance has been established (Stevenson 1985).

Many of the completed base-isolated buildings have experienced earthquakes and so far their performance has been as predicted. The earthquakes, if close, have been small or have been moderate and distant so that the accelerations experienced have not been large. As more isolated buildings are built in earthquake-prone regions of the world, we can anticipate learning more about the behavior of such structures and it will be possible to reduce the degree of conservatism that is currently present in the design of these structures. It should be possible to bring about an alignment of the codes for fixed-base and isolated structures and have a common code based on the specified level of seismic hazard and structural performance and in this way allow the economic use of this new technology for those building types for which it is appropriate.

It is clear that the use of seismic isolation has finally achieved a level of acceptance that will ensure its continued use and its further development and that this new and radical approach to seismic design will be able to provide safer buildings at little additional cost as compared to conventional design. Additionally, base isolation will play a major role in the future in projects as diverse as advanced nuclear reactors and public housing in developing countries.

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Table 2 Completed base isolation building projects in the United States - new construction

Fire Command and Control Facility

Location:	East Los Angeles, California
Status:	New
Owner:	County of Los Angeles
Size:	32,000 sq. ft.
Cost:	$6.3 million (excl. installed equipment)
Completed:	April 1990
Engineers:	Fluor-Daniel Engineers, Inc.
System:	HDR
Supplier:	Fyfe Assoc./Dynamic Rubber

Aircraft Simulator Manufacturing Facility

Location:	Salt Lake City, Utah
Status:	New
Owner:	Evans and Sutherland, Corp.
Size:	140,000 sq. ft.
Cost:	$8 million
Completed:	1988
Engineers:	Reavely Engineers and Assoc.; DIS
System:	LRB
Supplier:	DIS/Furon

University of Southern California Hospital

Location:	Los Angeles, California
Status:	New
Owner:	USC and National Medical Enterprises
Size:	250,000 sq. ft.
Cost:	$50 million
Completed:	1988
Engineers:	KPFF
System:	LRB
Supplier:	DIS/Furon

Foothills Communities Law and Justice Center

Location:	Rancho Cucamonga, California
Status:	New
Owner:	County of San Bernardino
Size:	230,000 sq. ft.
Total Cost:	$36 million
Completed:	1985
Engineers:	Taylor & Gaines; Reid & Tarics Assoc.
System:	HDR
Supplier:	Oil States Industries (now LTV)

Two Residences

Location:	West Los Angeles, California
Status:	New
Owner:	David Lowe
Size:	4,700 sq. ft. each
Cost:	$20,000 for each base
Completion:	1992
Engineers:	David Lowe
System:	GERB Resistant Base
Supplier:	GERB

Kaiser Computer Center

Location:	Corona, California
Status	New
Owner:	Kaiser Foundation Health Plan
Size:	120,000 sq. ft.
Cost:	$32 million
Completion:	Under construction 1992
Engineers:	Taylor & Gaines
System:	LRB & HDR
Supplier:	DIS/Furon

Titan Solid Rocket Motor Storage

Location:	Vandenburg Air Force Base, California
Status	New
Owner:	U.S. Air Force
Size:	N.A.
tab (	);
Cost:	N.A.
Completion:	1992
Engineers:	Bechtel Corp.
System:	HDR
Supplier:	LTV

San Bernardino Medical Center

Location:	Colton, California
Status	New
Owner:	County of San Bernardino
Size:	Five buildings, totaling 900,000 sq. ft.
Cost:	N.A.
Completion:	Design & review 1992
Engineers:	KPFF; Taylor & Gaines
System:	HDR
Supplier:	DIS

M.L. King Jr.-C.R. Drew Diagnostics Trauma Center

Location:	Watts, California
Status	New
Owner:	County of Los Angeles
Size:	140,000 sq. ft.
Cost:	$40 million
Completion:	Final design OSHPD review 1992
Engineers:	John Martin Assoc.; BIC
System:	HDR & Bronze Alloy Sliders
Supplier:	Not selected

Emergency Operations Center

Location:	East Los Angeles, California
Status	New
Owner:	County of Los Angeles
Size:	33,000 sq. ft.
Cost:	$6 million
Completion:	Construction starts 1992
Engineers:	DMJM
System:	HDR
Supplier:	Not selected

San Francisco Main Public Library

Location:	San Francisco, California
Status:	New
Owner:	City & County of San Francisco
Completed:	Design in progress 1992
Cost:	N.A.
Completion:	N.A.
Engineers:	Olmm Structural Design; Forell/Elsesser Eng.
System:	Not selected
Supplier:	N.A.

Water Control Center-Water Quality Laboratory

Location:	Portland, Oregon
Status:	New
Owner:	Portland Water Bureau
Size:	28,000 sq. ft.
Cost:	N.A.
Completion:	Design phase 1992
Engineers:	Harris Group; DIS
System:	LRB
Supplier:	DIS

Table 3 Completed base isolation building projects in the United States - retrofit

Salt Lake City and County Building

Location:	Salt Lake City, Utah
Status:	Retrofit
Owner:	Salt Lake City Corp.
Size:	170,000 sq. ft.
Cost:	$30 million (inc. non-seismic rehab.)
Completed:	1988
Engineers:	E.W. Allen and Assoc.; Forell/Elsesser Eng.
System:	LRB
Supplier:	DIS/LTV

Rockwell Seal Beach Facility

Location:	Seal Beach, California
Status:	Retrofit
Owner:	Rockwell International
Size:	300,000 sq. ft.
Cost:	$14 million
Completed:	1991
Engineers:	Englekirk & Hart
System:	LRB
Supplier:	DIS/Furon

Mackay School of Mines

Location:	Reno, Nevada
Status	Retrofit
Owner:	University of Nevada, Reno
Size:	27,000 sq. ft.
Cost:	$7 million
Completion:	Under construction 1992
Engineers:	Jack Howard and Assoc.; BIC
System:	HDR & PTEF sliders
Supplier:	Furon

Marina Apartments

Location:	San Francisco, California
Status	Retrofit
Owner:	Dr. Hawley
Size:	20,000 sq. ft.
Cost:	N.A.
Completion:	1991
Engineers:	EPS
System:	FPS
Supplier:	EPS

Table 4 Potential base isolation building projects in the United States - retrofit

Channing House Retirement Home

Location:	Palo Alto, California
Status	Retrofit
Owner:	Non-profit corporation
Size:	260,000 sq. ft.
Cost:	N.A.
Completion:	In design phase 1992
Engineers:	Renne & Peterson; DIS
System:	LRB
Supplier:	DIS

Long Beach Hospital

Location:	Long Beach, California
Status	Retrofit
Owner:	Veteran's Administration
Size:	350,000 sq. ft.
Cost:	N.A.
Completion:	Final Design 1992
Engineers:	A.C. Martin & Assoc.
System:	Not selected
Supplier:	N.A.

Hayward City Center

Location:	Hayward, California
Status	Retrofit
Owner:	City of Hayward
Size:	145,000 sq. ft.
Cost:	$7 million
Completion:	Final design 1992
Engineers:	EQE, San Francisco; C. Kircher Assoc.
System:	FPS & HDR
Supplier:	EPS & Bridgestone

U.S. Customs House

Location:	San Francisco, California
Status	Retrofit
Owner:	U.S. General Services Administration
Size:	142,000 sq. ft.
Cost:	$14 million (estimate)
Completion:	Conceptual design in progress
Engineers:	URS Blume
System:	Not selected
Supplier:	N.A.

Asian Art Museum

Location:	San Francisco, California
Status	Retrofit
Owner:	City and County of San Francisco
Size:	170,000 sq. ft.
Cost:	N.A.
Completion:	Conceptual design in progress
Engineers:	Rutherford & Chekene; C. Kircher Assoc.
System:	Not selected
Supplier:	N.A.

San Francisco City Hall

Location:	San Francisco, California
Status	Retrofit
Owner:	City and County of San Francisco
Size:	N.A.
Cost:	N.A.
Completion:	Conceptual design in progress
Engineers:	Forell/Elsesser Eng.
System:	Not selected
Supplier:	N.A.

50 United Nations Plaza

Location:	San Francisco, California
Status	Retrofit
Owner:	U.S. General Services Administration
Size:	345,000 sq. ft.
Cost:	N.A.
Completion:	Architect/Engineer selection 1992
Engineers:	N.A.
System:	N.A.
Supplier:	N.A.

Oakland City Hall

Location:	Oakland, California
Status	Retrofit
Owner:	City of Oakland
Size:	153,000 sq. ft.
Cost:	$47 million (estimate)
Completion:	Final design 1992
Engineers:	Forell/Elsesser Engineers; DIS
System:	LRB
Supplier:	DIS

State of California Justice Building

Location:	San Francisco, California
Status	Retrofit
Owner:	State of California
Size:	250,000 sq. ft.
Cost:	$40 million (est., incl. non-seismic renovation)
Completion:	Conceptual Design 1992
Engineers:	Rutherford & Chekene; C. Kircher Assoc.
System:	Not selected
Supplier:	N.A.

U.S. Court of Appeals

Location:	San Francisco, California
Status	Retrofit
Owner:	U.S. General Services Administration
Size:	350,000 sq. ft.
Cost:	N.A.
Completion:	Conceptual Design 1992
Engineers:	Skidmore, Owings & Merrill
System:	FPS
Supplier:	EPS

Kerckhoff Hall, UCLA

Location:	Los Angeles, California
Status	Retrofit
Owner:	Regents, Univ. of Calif.
Size:	100,000 sq. ft.
Cost:	$15.3 million
Completion:	December, 1994
Engineers:	Brandow & Johnston
System:	Not selected
Supplier:	N.A.

Educational Services Center

Location:	Los Angeles, California
Status	Retrofit
Owner:	L.A. Community College District
Size:	90,000 sq. ft.
Cost:	$450,000
Completion:	August 1992
Engineers:	Fleming Corp.
System:	Earthquake Barrier
Supplier:	N.A.