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RECENT DEVELOPMENT IN SEISMIC ISOLATION IN THE UNITED STATES*

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ABSTRACT

The first seismically isolated building in the United States was completed in 1985. In the fourteen years since then, a total of not more than twenty-five new buildings and twenty-two retrofits of existing buildings has been completed. In contrast, the number of base-isolated building in Japan completed over the same time period is of the order of a few hundred, and in China, where the first isolated building was completed in 1995, there are now over seventy base-isolated buildings.

Currently there are several building codes that govern the design of base-isolated buildings in the United States. New regulations have been prepared for the year 2000 and beyond, which are both complex and conservative, discouraging the use of seismic isolation. These codes require the engineer to design isolators for very large displacements and mandate extensive prototype and production testing, thereby restricting isolation's application to special structures such as hospitals and emergency service centers where a requirement for operational functionality following large earthquake events justifies the cost premium and time delays associated with the use of seismic isolation.

Conversely, seismic isolation is widely used throughout the United States for highway bridges and is governed by a single design code that is simple to use and not overly conservative. Isolation systems are being used for the retrofit of several very large bridges in California. The isolators to be used for this projects are very large, and a test machine at the University of California, San Diego (UCSD), has just been completed to test these isolators at full-scale, real-time rates.

This paper will describe the current regulatory environment for seismic isolation and the testing requirements for isolators. A description of the new test facility at UCSD will be included.

INTRODUCTION

Although seismic isolation has been used in the United States for close to twenty years and is considered a mature technology, there are no indications that its use is increasing. In the United States, only a few projects each year are initiated, and these are generally state, county, or city projects, with not one housing project either completed or in the design stage to date. In contrast, Japan and China design and build many isolated projects each year, with a high proportion of these projects being for housing and commercial buildings.

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Seismic isolation is perceived in the United States as expensive, complicated, and time-consuming in both design and execution. While these criticisms are valid for many of the recent projects in which isolation has been used, the fault does not lie with the technology itself. The fault lies with the degree of over-regulation that is associated with the technology. The use of seismic isolation is constrained by a series of code documents that are conservative, complicated, and burdensome to the designer and the owner.

The benefits of using seismic isolation for earthquake-resistant design are many: isolation leads to a simpler structure with much less complicated seismic analysis as compared with conventional structures, isolated designs are less sensitive to uncertainties in ground motion; and, finally, the used components are much more reliable than conventional structural components. The drawbacks to using isolation stem directly from code documents that require the designer to use significantly larger factors of safety and, despite the availability of extensive test results on full-sized isolators of various types, testing of isolators has to be done for each new project.

CODE ISSUES FOR BASE-ISOLATED STRUCTURES

The first building in the United States to use a seismic isolation system was completed in 1985. Although this building was publicized in national engineering magazines and visited by a great many engineers and architects from the United States and around the world, it was several years before construction of the second base-isolated building was begun. The acceptance of isolation as an anti-seismic design approach for some classes of buildings was clearly hampered in the United States by lack of a code covering base-isolated structures. To address this issue the Structural Engineers Association of Northern California (SEAONC) created a working group to develop design guidelines for isolated buildings.

The Seismology Committee of the Structural Engineers Association of California (SEAOC) is responsible for developing provisions for earthquake-resistant design of structures. These provisions, published as "Recommended Lateral Design Requirements and Commentary" (SEAOC, 1985), generally known as the "Blue Book," have served as the basis for various editions of the Uniform Building Code (UBC). Published by the International Conference of Building Officials (ICBO), it is the most widely used code for earthquake design. In 1986 the SEAONC sub-committee produced a document entitled "Tentative Seismic Isolation Design Requirements" (SEAONC, 1986)–known as the "Yellow Book"–as a supplement to the fourth edition of the Blue Book.

The approach and layout of the Yellow Book parallels the Blue Book as closely 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 SEAOC Seismology Committee formed a subcommittee in 1988 to produce an isolation design document entitled "General Requirements for the Design and Construction of Seismic-Isolated Structures" (SEAOC, 1989). In 1990 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 (ICBO, 1991). This 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.

Another code document, developed for the design of base-isolated hospitals in California, has been adopted by the Building Safety Board (BSB) of the Office of State Architect. Entitled "An Acceptable Method for Design and Review of Hospital Buildings Utilizing Base Isolation" (OSHPD, 1989), these guidelines were developed in part by SEAONC for the BSB and are similar to both the SEAONC requirements and the UBC code. The version adopted by the BSB in 1989 was revised in January 1992 and includes additional requirements.

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 (DBE) is defined as the level of earthquake ground shaking that has a 10% probability of being exceeded in a 50-year period. The design provisions for this level of input require that the structure above the isolation system remains essentially elastic. The second level of input is defined as the Maximum Capable Earthquake (MCE), 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.

A number of changes were incorporated into the 1994 version of the UBC (ICBO, 1994) regulations for isolated buildings that made these codes even more conservative in some aspects than the earlier version. The 1994 regulations restricted further the use of static analysis, although the code continued to require static analysis in all cases in order to provide various minimum levels below which design values obtained by dynamic analysis cannot fall. The design had to be based on two levels of earthquake input: the DBE–used to calculated the total design displacement of the isolation system and the forces in the superstructure–and the MCE–used to calculate what is referred to as the total maximum displacement of the isolation system for which the system must be shown to be safe. The vertical distribution of force was changed from a uniform one to a triangular one that is generally used for fixed-base structures. The superstructure was to be designed for forces produced by the isolation system at the design displacement reduced by certain reduction factors, that were now less than the previous factors (generally one-half of those for fixed-base structures). The results of these two changes for the design forces was that the superstructure will be elastic for the DBE.

The 1994 code specified an extensive, detailed series of prototype tests that must be carried out prior to construction of the isolators. These tests were not for determining quality control in the manufacturing of the isolators, but were intended to establish the design properties of the isolation system. Ironically, in many cases these tests could not be carried out on full-scale isolators due to the combination of forces, the magnitude of these forces, and the loading rates that would be needed to satisfy the requirements and reduced-scale prototypes would have to be used. In contrast, no specific tests for production bearings were required, although a quality control test program was mandatory.

Other requirements stipulated that there should be a design review of the isolation system and testing programs for prototypes and production bearings by a peer review panel. This review of the isolation system included the earthquake inputs used for the design, the design itself, and the presence of peer review panel at the prototype testing. The peer review panel was also required to review all supporting analysis for the design of the superstructure and review the quality-control testing program.

Further changes have been made in the 1997 version of the UBC regulations for isolated structures (ICBO, 1997), resulting in a code that is both more conservative and more complicated. A large number of new terms have been added. For example, there are now six different displacements that have to be computed. The number of soil profile types has been increased to six, of which three are hard rock, rock, and soft rock. There are four seismic coefficients to be calculated, but in zone 4, where most isolated buildings in the United States are located, it is necessary to calculate two factors: and , which depend on seismic source type and seismic source distance, another factor , which depends on , and two other factors, and , which depend on , , and . The result is that the simple static analysis computation of the earlier versions of the code has been replaced by a sequence of table definition and formulae.

All isolated projects are currently designed using dynamic analysis (based on time histories, as there are many computer programs now available for this purpose), but static analysis is still required to ensure that the design quantities do not fall below certain minimal levels from the static analysis.

In the fixed base code the reduction factor, *R* (now called response modification factor), varies widely with structural systems from a high of 8.5 through 7.5, 7.0, 6.5, 6.0, 5.5, 4.5, 4.2, 3.5, 2.8 to a low of 2.2. In the isolation regulations the reduction factor is almost everywhere 2.0, with a few systems having an *R* factor of 1.6. This is intended to ensure elastic behavior in the superstructure at the DBE, but is much too conservative.

One feature that has persisted through all versions of the UBC isolation regulations is the scaling of the time histories. In essence, the code requires an increase of 30% in the target spectra to account for bilateral ground motion. However, isolation systems are always isotropic, and the maximum isolator displacement can be in any direction. The basic static formula for maximum displacement is intended to be applied in any direction and why the dynamic analysis should include bilateral displacements is not clear.

The extensive testing requirements for prototype isolators remain from the earlier code versions. New requirements for inspection and replacement have been added, including requirements for periodic monitoring, requirements on repair or retrofit of an isolation system, and a requirement for a horizontal displacement monitoring device.

In total, the 1997 version of the UBC regulations for seismic-isolated structures have completed the process of turning the simple straightforward and rational code developed in the 1986 Yellow Book into a complicated and conservative set of requirements that will seriously undermine the use of isolation technology by the general engineering community. The whole impetus for developing isolation systems, by creating cost-effective, simple, strategies to create earthquake-resistant structures, has been lost.

The 1997 UBC will be replaced in 2000 by the International Building Code (IBC), which will also have provisions for seismically isolated structures. The requirements in the IBC are essentially the same as those in the 1997 UBC, with some changes in notation, but with the same conservatism in calculating design displacements and seismic forces. The irrational use of a triangular distribution of force persists. The reduction factor for seismic isolated superstructures is specified to be 3/8 that for conventional structures, with the maximum not to exceed 2.

It is interesting to compare the design requirements for conventional and isolated buildings from these codes. For example, a steel moment frame structure with a 2-sec period and 5% damping, at a soil site within 2 km (1.3 miles) of an active fault (such as the San Andreas or Hayward fault), can be designed for an ultimate strength of 7.5% of the structural weight. In contrast, a 2-sec period base-isolated building with 10% damping in the isolation system will have to be designed and tested for displacements of around 0.75 m (30 in.). If it should have a steel moment frame superstructure, the building will have to be designed for 28% of the weight of the structure. The premium for isolation is much too large to encourage use of the technology.

RECENT BASE ISOLATION PROJECTS

In the period since the Post-SMiRT in Taormina, the retrofit project for the San Francisco City Hall has been completed, and the building opened for business on 1 January 1999. The San Bernardino Medical Center was also dedicated in early 1999. Both of these projects are very large and very expensive, involving several hundred isolators, each project costing several hundred millions of dollars.

In California, another emergency services center was begun for the city of Long Beach. This 2-story, steel frame, 2700 m^2 (30,000 ft^2) structure was designed by Fluor-Daniel, Inc., of Irvine, California. It will have 24 elastomeric isolators, with an estimated cost of around $10-20 million.

Asian Art Museum

Construction is due to begin shortly on the retrofit of the former San Francisco library, the future home of the Asian Art Museum, whose collection is valued in the billions of dollars. The museum is currently housed at the De Young Museum in Golden Gate Park, a structure that is not seismically adequate and will be replaced. The former library will be retrofitted using around 200 lead-rubber isolators to be supplied by D.I.S., Inc. The estimated cost of this project is around $75 million, and the design engineers are Forell-Elsesser Engineers of San Francisco.

Hearst Mining Memorial Building

There are three base isolation projects under construction in the City of Berkeley. The Hearst Mining Memorial Mining Building of the University of California, Berkeley, is being retrofitted using base isolation. The building, designed by the famous architect John Galen Howard, was completed in 1903. The building is considered by many to be the most important building on the university campus, both historically and architecturally, therefore any retrofit would have to be sensitive to the architectural and structural aesthetic of the building. The building is a bearing wall structure, with some columns and very limited lateral strength. The bearing walls are unreinforced brick masonry, with a facing of 0.2 m (8 in.) thick Sierra granite on the exterior walls. The floors are concrete on steel joists and beams.

The building is located less than 1/2 km (1600 ft) from the Hayward fault, and in a campus-wide seismic hazard assessment was rate as very poor. The building had been occupied by the Department of Material Science and had laboratories, workshops, classrooms, and administration offices. In view of the seismic risk, the building has been vacant for a few years.

The retrofit has been designed to have almost no impact on the existing structure. The reduction in seismic load effected by the isolation system will allow the lateral load to be resisted by the existing brick walls. Some strengthening of the floor slabs will be done, and the roof system will be tied to the walls. The isolation system has 120 high-damping isolators supplied by Uni-Poly/Andre of the United Kingdom. The project has a cost estimate of around $50 million.

Civic Center Building, City of Berkeley

Another retrofit project in the city of Berkeley is the seismic upgrade of the city administration office building, known as the Civic Center building. Built in 1938, this 5-story, reinforced concrete, approximately 7900 m^2 (88,0000 ft^2) building houses the many city administration offices. The seismic resisting system is perimeter concrete shear walls. The city has requested that the building, which is about 2 km (1.3 miles) from the Hayward fault, be retrofitted to a performance level that will guarantee that it be fully operation following a major earthquake. The city also specified that the retrofit not affect the external appearance of the building. These requirements led to a seismic isolation retrofit. The structural engineers for the retrofit design were Forell-Elsesser Engineers, and the isolation system will use around 45 lead-plug isolators provided by Skellerup/Oiles. Construction costs are estimated to be around $27 million.

Public Safety Building, City of Berkeley

A new seismically isolated building for the city of Berkeley has been under construction for about one year and is due to be completed in mid-2000. The Public Safety Building, a 5940 m^2 (66,000 ft^2), 2-story, emergency services center, will house the administration of police, fire, and emergency services for the city. It is located less than 2 km (1.3 miles) from the Hayward fault and is designed to be fully operational following a major earthquake. Unlike most public buildings in the United States, this project was undertaken through a design-building process. The building is built on 27 lead-rubber isolators provided by D.I.S., Inc. The project cost is $15 million.

Pixar Center

One of the very few non-governmental isolation projects currently underway is the new studio building for Pixar Animation, Inc., which is nearing completion in Emeryville in the San Francisco Bay Area. The building is a 2-story braced steel frame structure of 22,500 m^2 (250,000 ft^2). The isolation consists of 122, 800 mm (32 in.) and 900 mm (36 in.) diameter, high-damping rubber isolators provided by Bridgestone Engineered Products, Co., Inc., of Yokohama, Japan. The design engineers were Rutherford and Chekene, San Francisco. The building was designed to the 1997 UBC base isolation requirements. The site is not near fault, but the MCE displacement requirements were around 0.68 m (27 in.). The estimated construction cost is $35 million, and the building is due to be completed in late- 1999.

Cathedral of Our Lady of the Angels

Another non-government base isolation project currently under construction is the Cathedral of Our Lady of the Angels in Los Angeles, California. The Roman Catholic Cathedral of Los Angeles was badly damaged in the 1994 Northridge, California, earthquake and rather than repairing and retrofitting the original cathedral, the Archdiocese decided to replace the old building. The new, 5200 m^2 (58,000 ft^2), base-isolated structure was designed by the Spanish architect Jose Rafael Moneo. It is expected to be completed in late 2001, at an estimated construction cost of $75 million. The isolation system comprises 149 high-damping, natural rubber isolator with sizes from 900 mm (36 in.) to 1.0 m (40 in.) in diameter, and 47 sliding bearings, all of which are supplied by Uni-Poly/Andre, United Kingdom.

Tables 1 and 2 list completed projects and projects that are reasonably likely to go forward to construction, both for new buildings and for retrofit.

THE CALTRANS BEARING TEST MACHINE

The latest development in seismic isolation research in the United States is the completion of an extremely large seismic isolation bearing test machine at the University of California, San Diego. This machine was commissioned by the State of California Department of Transportation (Caltrans) to enable testing of the extremely large seismic isolators planned for the retrofit of the toll bridges in California. The use of isolation to limit seismic force input to the superstructure of several very large toll bridges requires bearings and energy dissipators of unprecedented size. This testing facility has been planned to provide the capacity to allow full-scale, real-time testing to determine the dynamic mechanical characteristics of very large isolation components.

The isolators for which the machine was designed are friction-pendulum bearings for the Benicia- Martinez bridge in Contra Costa County and elastomeric bearings for the Coronado bridge in San Diego County, California, as well as for several types of dampers.The FPS bearing is around 3.5 m · 3.75 m (140 in. · 150 in.) in plan dimension and will carry vertical loads of the order of a few thousand tons. The seismic displacements are around 1.2 m (48 in.). The elastomeric devices have similar requirements, but smaller plan dimensions. The technical specifications for the machine are given in Table 3. The significant quantities are a maximum vertical load of 53 MN (6000 tons), a horizontal longitudinal load of 8.9 MN (1000 tons), and a lateral load of 4.45 MN (500 tons). The machine has a horizontal longitudinal displacement capacity of ±1.2 m (48 in.), a lateral displacement of ±0.6 m (24 in.), and a maximum longitudinal and lateral velocities of 1.75 m/sec (70 in./sec) and 0.75 m/sec (30 in./ sec).

The large loads, displacements, and velocities required for the machine place an exceptional demand for hydraulic power, which is met by the use of 100 nitrogen-charged accumulators, with 19,000 liters (5000 gallons) of hydraulic fluid operating at 34 MPa (5000 psi).

Table 1: Base-Isolated Buildings and Projects in the United States

Foothill Communities Law & Justice Center		**Aircraft Simulator Manufacturing Facility**	
Location:	Rancho Cucamonga, Calif.	Location:	Salt Lake City, Utah
Owner:	County of San Bernardino	Owner:	Evans&Sutherland Corp.
Size:	230,0800 sq.ft.	Size:	190,000 sq.ft.
Total cost:	$36 million	Total cost:	$8 million
Completed:	1985	Completed:	1988
Engineers:	Taylor&Gaines; Reid&Tarics	Engineers:	Reaveley Engrs.&Assoc; DIS
System:	HDR	System:	LRB
Supplier:	Oil States Ind. (now LTV)	Supplier:	DIS; Furon
University of Southern California Hospital		**Fire Command and Control Facility**	
Location:	Los Angeles, California	Location:	East Los Angeles, Calif.
Owner:	USC&Nat. Med. Enterprises	Owner:	County of Los Angeles
Size:	350,000 sq.ft.	Size:	32,000 sq.ft.
Total cost:	$50 million	Total cost:	$6.3 million (excl. equip.)
Completed:	1991	Completed:	1990
Engineers:	KPFF	Engineers:	Fluor-Daniel Engrs., Inc.
System:	LRB	System:	HDR
Supplier:	DIS; Furon	Supplier:	Fyfe Assoc.; Dynamic Rubber
Kaiser Regional Data Center		**Titan Solid Rocket Motor Storage**	
Location:	Corona, Calif.	Location:	Vandenburg Air Force Base
Owner:	Kaiser Foundation Health Plan	Owner:	U.S. Air Force
Size:	120,000 sq.ft.	Size:	N.A.
Total cost:	$32 million	Total cost:	N.A.
Completed:	1992	Completed:	1992
Engineers:	Taylor&Gaines	Engineers:	Bechtel National, Inc.
System:	LRB	System:	HDR
Supplier:	DIS; Furon	Supplier:	LTV
Water Quality Laboratory		**Two Residences**	
Location:	Portland, Oregon	Location:	West Los Angeles, Calif.
Owner:	Portland Water Bureau	Owner:	David Lowe
Size:	28,000 sq.ft.	Size:	4,700 sq.ft. ea.
Total cost:	$12 million	Total cost:	$20,000 per each base
Completed:	1993	Completed:	1992
Engineers:	Harris Group; DIS	Engineers:	David Lowe
System:	LRB	System:	GERB Resistant Base
Supplier:	DIS; Furon	Supplier:	GERB
AutoZone Headquarters		**Emergency Operations Center**	
Location:	Memphis, Tenn.	Location:	Los Angeles, Calif.
Owner:	AutoZone Corp.	Owner:	County of Los Angeles
Size:	210,000 sq.ft.	Size:	33,000 sq.ft.
Total cost:	$26 million	Total cost:	$6 million
Completed:	1995	Completed:	1994
Engineers:	JMGR Inc.	Engineers:	DMJM

System:	LRB	System:	HDR
Supplier:	DIS	Supplier:	Bridgestone
San Bernardino Medical Center		**M.L. King, Jr.-C.R. Drew Diagnostics Trauma Center**	
Location:	Colton, Calif.	Location:	Willowbrook, Calif.
Owner:	County of San Bernardino	Owner:	County of Los Angeles
Size:	900,000 sq.ft.	Size:	140,000 sq.ft.
Total cost:	$350 million	Total cost:	$40 million
Completed:	1997	Completed:	1995
Engineers:	KPFF; Taylor&Gaines	Engineers:	John Martin Assoc.; BIC
System:	HDR	System:	HDR
Supplier:	DIS Pacific	Supplier:	DIS; Furon
Traffic Management Center		**San Francisco Public Library**	
Location:	Kearny Mesa, Calif.	Location:	San Francisco, California
Owner:	CalTrans/CHP	Owner:	City&County San Francisco
Size:	45,000 sq.ft.	Size:	377,000 sq.ft.
Total cost:	N.A.	Total cost:	$87 million
Completed:	Late 1994	Completed:	1995
Engineers:	Forell/Elsesser Engrs.	Engineers:	OLMM Structural Design; Forell/Elsesser Engrs.
System:	HDR	System:	LRB
Supplier:	Bridgestone	Supplier:	DIS; Furon
LAC + USC Medical Center (Replacement)		**911 Emergency Communications Center**	
Location:	East Los Angeles, Calif.	Location:	San Francisco, Calif.
Owner:	Los Angeles County	Owner:	City&County of San Francisco
Size:	350,000 sq.ft.	Size:	55,000 sq.ft.
Total cost:	N.A.	Total cost:	$12 million (constr. costs)
Completed:	OSHPD Review 1994-95	Completed:	Under construction (1998)
Engineers:	KPFF	Engineers:	Forell/Elsesser Engrs.
System:	HDR	System:	HDR
Supplier:	BTR/Andre	Supplier:	BTR/Andre
Public Safety Building		**Emergency Communications Center**	
Location:	Berkeley, Calif.	Location:	San Diego, Calif.
Owner:	City of Berkeley	Owner:	City&County San Diego
Size:	66,000 sq.ft.	Size:	38,000 sq.ft.
Total cost:	$15 million	Total cost:	$6 million
Completed:	Construction begins 1998	Completed:	early 1998
Engineers:	SOHA Engrs.,	Engineers:	Fluor-Daniel Engrs., Inc.
System:	LRB	System:	LRB
Supplier:	DIS Sparks	Supplier:	DIS Sparks
Washington State Emergency Operations Center		**Insurance Co. Data Center**	
Location:	Camp Murray, Wash.	Location:	Near Seattle
Owner:	State of Washington	Owner:	Major insurance co.
Size:	29,700 sq.ft.	Size:	62,700 sq.ft.

Total cost:	N.A.	Total cost:	N.A.
Completed:	Under construction	Completed:	under design development
Engineers:	KPFF	Engineers:	KPFF
System:	FPS	System:	N.A.
Supplier:	EPS	Supplier:	N.A.
San Francisco Airport		**Hayward City Hall**	
Location:	San Bruno, Calif.	Location:	Hayward, Calif.
Owner:	City&County of San Francisco	Owner:	City of Hayward
Size:	N.A.	Size:	135,000 sq.ft.
Total cost:	N.A.	Total cost:	$27 million
Completed:	N.A.	Completed:	Completed 12/97
Engineers:	SOM San Francisco	Engineers:	KPFF San Francisco
System:	FPS	System:	FPS+Dampers
Supplier:	EPS	Supplier:	EPS; Taylor Devices
Pixar Center		**Cathedral of Our Lady of the Angels**	
Location:	Emeryville, Calif.	Location:	Los Angeles, Calif.
Owner:	Pixar Animation Studios	Owner:	Catholic Archdiocese
Size:	250,000 sq.ft.	Size:	58,000 sq.ft.
Total cost:	$35 million	Total cost:	$75 million
Completed:	1999/2000	Completed:	2001
Engineers:	Rutherford& Chekene	Engineers:	N. Youssef&Assoc.
System:	HDR	System:	HDR
Supplier:	Bridgestone	Supplier:	Uni-Poly/Andre
Microchip Fabrication Facility			
Location:	Mexicali, Mexico		
Owner:	Rockwell International		
Size:	50,000 sq.ft.		
Total cost:	N.A.		
Completed:	N.A.		
Engineers:	KPFF		
System:	LRB		
Supplier:	DIS Sparks		

Table 2: Retrofit Base-Isolated Buildings and Projects in the United States

Salt Lake City and County Building		**Rockwell International Corp. Headquarters**	
Location:	Salt Lake City, Utah	Location:	Seal Beach, Calif.
Owner:	Salt Lake City Corp.	Owner:	Rockwell International
Size:	170,000 sq.ft.	Size:	260,000 sq.ft.
Total cost:	$30 million (inc. nonseismic	Total cost:	$14 million
Completed:	rehab).	Completed:	1991
Engineers:	1989	Engineers:	Englekirk&Sabol, Inc.
	E.W. Allen&Assoc.;	System:	LRB

System:	Forell/Elsesser Engrs.	Supplier:	DIS; Furon
Supplier:	LRB		
	DIS; LTV		
Mackay School of Mines		**Marina Apartments**	
Location:	Reno, Nevada	Location:	San Francisco, Calif.
Owner:	University of Nevada, Reno	Owner:	Dr. Hawley
Size:	27,000 sq.ft.	Size:	20,000 sq.ft.
Total cost:	$7 million	Total cost:	N.A.
Completed:	1993	Completed:	1991
Engineers:	Jack Howard&Assoc.; BIC	Engineers:	EPS
System:	HDR+PTEF sliders	System:	FPS
Supplier:	Furon	Supplier:	EPS
Channing House Retirement Home		**Long Beach Hospital**	
Location:	Palo Alto, Calif.	Location:	Long Beach, Calif.
Owner:	Nonprofit corporation	Owner:	Veterans Administration
Size:	260,000 sq.ft.	Size:	350,000 sq.ft.
Total cost:	$9 million (est.)	Total cost:	$18 million
Completed:	In design phase	Completed:	1995
Engineers:	Rinnie&Peterson; DIS	Engineers:	N. Youssef&Assoc.; DIS
System:	LRB	System:	LRB
Supplier:	DIS; Furon	Supplier:	DIS; DIS Pacific
U.S. Court of Appeals		**Seattle Standpipe & Water Tank**	
Location:	San Francisco, Calif.	Location:	Seattle, Wash.
Owner:	U.S. General Services Admin.	Owner:	Seattle Water Department
Size:	350,000 sq.ft.	Size:	N.A.
Total cost:	N.A.	Total cost:	N.A.
Completed:	1994	Completed:	N.A.
Engineers:	Skidmore, Owings&Merrill	Engineers:	Cygna Group Inc.
System:	FPS	System:	HDR
Supplier:	EPS	Supplier:	N.A.
San Francisco City Hall		**Los Angeles City Hall**	
Location:	San Francisco, Calif.	Location:	Los Angeles, Calif.
Owner:	City&County of San Francisco	Owner:	City of Los Angeles
Size:	550,000 sq.ft.	Size:	912,000 sq.ft.
Total cost:	$292 million ($184 million for seis mic retrofit	Total cost:	$250 million (est.)
Completed:	75% completed 6/98	Completed:	Detailed design in progress
Engineers:	Forell/Elsesser Engrs	Engineers:	N. Youssef&Assoc.; S.I.E.
System:	LRB	System:	HDR
Supplier:	DIS; DIS Pacific	Supplier:	Bridgestone
Oakland City Hall		**State of California Justice Building**	
Location:	Oakland, Calif.	Location:	San Francisco, Calif.
Owner:	City of Oakland	Owner:	State of California
Size:	153,000 sq.ft.	Size:	250,000 sq.ft.
Total cost:	$47 million	Total cost:	$40 million (inc. nonseismic renov.)
Completed:	1994		

Engineers:	Forell/Elsesser Engrs.; DIS
System:	LRB
Supplier:	DIS Pacific

Completed:	Conceptual design 1992
Engineers:	Rutherford&Chekene;
System:	C. Kircher Assoc.
Supplier:	LRB
	DIS; Furon

U.S. Court of Appeals

Location:	San Francisco, Calif.
Owner:	U.S. General Services Admin.
Size:	350,000 sq.ft.
Total cost:	N.A.
Completed:	1994
Engineers:	Skidmore, Owings&Merrill
System:	FPS
Supplier:	EPS

Seattle Standpipe & Water Tank

Location:	Seattle, Wash.
Owner:	Seattle Water Department
Size:	N.A.
Total cost:	N.A.
Completed:	N.A.
Engineers:	Cygna Group Inc.
System:	HDR
Supplier:	N.A.

Hughes Bldg. S-12

Location:	El Segundo, Calif.
Owner:	Hughes Aircraft Co.
Size:	240,000 sq.ft.
Total cost:	$8 million
Completed:	1995
Engineers:	Brian L. Cochran Assoc.
System:	LRB
Supplier:	DIS

Kerkhoff Hall, UCLA

Location:	Los Angeles, Calif.
Owner:	Regents, University of Calif.
Size:	100,000 sq.ft.
Total cost:	$15.3 million
Completed:	1996
Engineers:	Brandow&Johnston; The Hart
System:	Group
Supplier:	LRB
	DIS Pacific

Campbell Hall

Location:	Monmouth, Oregon
Owner:	Western Oregon State College
Size:	30,000 sq.ft.
Total cost:	$2.5 million
Completed:	1994
Engineers:	Van Domelen/Looijena; McGarrigle/ Knauf
System:	LRB
Supplier:	DIS Pacific

Hoag Memorial Hospital Nursing Tower

Location:	Newport Beach, Calif.
Owner:	Hoag Memorial Presbyterian
Size:	120,000 sq.ft.
Total cost:	$14 million (est.)
Completed:	2001
Engineers:	Taylor&Assocs.; BIC
System:	HDR+Lead bronze sliders
Supplier:	Uni-POLY/Andre

Hearst Mining Building

Location:	Berkeley, Calif.
Owner:	Regents, Univ. of California
Size:	50,000 sq.ft.
Total cost:	$47 million
Completed:	Construction begins 7/98
Engineers:	Rutherford&Chekene
System:	HDR
Supplier:	Uni-POLY/Andre

Asian Art Museum

Location:	San Francisco, Calif.
Owner:	Asian Art Museum
Size:	190,000 sq.ft.
Total cost:	$75 million
Completed:	October 2000
Engineers:	Forell/Elsesser Engrs., OLMM, Tanenbaum Manheim
System:	LRB
Supplier:	D.I.S.

Microchip Fabrication Facility

Location:	Newport Beach, Calif.

Civic Center Building

Location:	Berkeley, California

Owner:	Rockwell International	Owner:	City of Berkeley
Size:	240,000 sq.ft.	Size:	88,000 sq.ft.
Total cost:	N.A.	Total cost:	$27 million
Completed:	N.A.	Completed:	early 2000
Engineers:	KPFF	Engineers:	Forell/Elsesser Engrs.
System:	LRB	System:	LRB
Supplier:	DIS Sparks	Supplier:	Skellerup/Oiles

The design of the test machine was developed jointly by the University of California, San Diego, and the MTS Corporation of Minnesota. The machine is located in a pre-stressed concrete reaction frame (a concrete box), with a concrete base to which four horizontal actuators are attached. These actuators drive a moving horizontal platen on which the test article is located. The horizontal forces generated are equilibrated by the concrete box. The platen slides over four hydrostatic low friction bearings attached to the floor of the concrete structure, and the platen has four outrigger arms that react against overturning forces on the platen. These outrigger arms have sliding bearings that move in pockets in the sides of the concrete box. Table 4 shows the various actuators and their technical specifications.

The vertical loads are reacted by a removable cross-beam attached to the concrete box. The cross- beam comprises three steel box beams, each just less than 178 kN (20 tons), the capacity of the overhead crane, and are connected to the concrete box by 24 high-strength steel rods. In use, the rods will be pre-stressed by hydraulic jacks to a tension that will ensure the maintenance of full connection and friction at the cross-beam/concrete box interface.

Table 3: Technical Specifications

		Accuracy of application	**Accuracy of readout**
Vertical force	53,400 kN (12,000 kips)	±5%	0.5% full range
Vertical movement	8136 kN/m (72,000 kips/in.)		±1.35 kN/m (12 kips/in.)
Longitudinal force	8900 kN (2000 kips)		1.0% full range
Lateral force	4450 kN (1000 kips)		1.0% full range
Vertical displacement	±0.127 m (5 in.)	±2%	1.0% full range
Longitudinal displacement	±1.22 m (48 in.)	±2%	1.0% full range
Lateral displacement	±0.61 m (24 in.)	±2%	1.0% full range
Vertical velocity	±254 mm/sec (10 in./sec)	±10%	
Longitudinal velocity	±1778 mm/sec. (70 in./sec)	±10%	
Lateral velocity	±762 mm/sec (30 in./sec)	±10%	
Height of specimen	Up to 1.52 m (5 ft)		
Relative platen rotation	±2°		

The design of the system began in June 1997; excavation of the pit for the box began shortly after. The accumulator building and the installation of the accumulators were completed in the middle of 1998, and the concrete box and most of the major components were installed by the end of 1998. Shake-down tests were carried out in the first half of 1999, and the first test is scheduled for August 1999. The total cost of the test facility is estimated to be $15 million, which has been provided by Caltrans.

Table 4. MTS Actuators Technical Specifications

Function	Horizontal actuator	Vertical actuator-bearing	Vertical (outrigger) actuator-bearing
Quantity	4	4	4
Max. force (tension)	4500 kN (1000 kips)	NA	NA
Max. force (compression)	7000 kN (1600 kips)	18,000 kN (4000 kips)	534 kN (120 kips)
Stroke	2.5 m (100 in.)	0.25 m (10 in.)	0.5 m (20 in.)
Rod diameter	0.3 m (12 in.)	NA	NA
Bore	0.5 m (20 in.)	0.81 m (32 in.)	0.19 m (7.5 in.)
Max. velocity	1.8 m/sec (70 in./sec)	0.4 m/sec (15 in./sec)	0.5 m/sec (18 in./sec)
Swivels	±20° both ends	±2°	±2°
Servovalves	19 m^3/min (5000 gpm)	11 m^3/min (3000 gpm)	0.7 m^3/min (180 gpm)
Pressure	35 MPa (5000 psi)	35 MPa (5000 psi)	21 MPa (3000 psi)
Weight	13 tons (28 kips)	4.4 tons (9.7 kips)	0.4 tons (1 kips)

RECENT TRENDS IN BASE ISOLATION

Seismic isolation technology in the United States today is applied almost entirely to large, expensive buildings housing sensitive internal equipment, for example, computer centers, chip fabrication factories, emergency operation centers, and hospitals. The isolators used in these applications are large, expensive, and heavy. An individual isolator can weight one ton and often more. To extend this valuable earthquake-resistant strategy to housing and commercial buildings, it is necessary to reduce the cost and weight of the isolators.

The primary weight in an isolator is due to the reinforcing steel plates, which are used to provide the vertical stiffness of the rubber-steel composite element. A typical rubber isolator has two large end- plates [around 25 mm (1 in.) thick] and 20 thin reinforcing plates 3 mm (1/8 in.) thick). The high cost of producing the isolators results from the labor involved in preparing the steel plates and laying-up of the rubber sheets and steel plates for vulcanization bonding in a mold. The steel plates are cut, sand- blasted, acid cleaned, and then coated with bonding compound. Next, the compounded rubber sheets with the interleaved steel plates are put into a mold and heated under pressure for several hours to complete the manufacturing process. It is possible that both the weight and the cost of isolators can be reduced by eliminating the steel reinforcing plates and replacing them with a fiber reinforcement.

The weight reduction is possible as fiber materials are available with an elastic stiffness that is of the same order as steel. Thus the reinforcement needed to provide the vertical stiffness may be obtained by using a similar volume of very much lighter material. The cost savings may be possible if the use of fiber allows a simpler, less labor-intensive manufacturing process. It is also possible that the current approach of vulcanization under pressure in a mold with steam heating can be replaced by microwave heating in an autoclave.

Another benefit to using fiber reinforcement is that it would then be possible to build isolators in long rectangular strips, whereby individual isolators could be cut to the required size. All isolators are currently manufactured as either circular or square in the mistaken belief that if the isolation system for a building is to be isotropic, it needs to be made of symmetrically shaped isolators. Rectangular isolators in the form of long strips would have distinct advantages over square or circular isolators when applied to buildings where the lateral resisting system is constituted of walls. When isolation is applied to buildings with structural walls, additional wall beams are needed to carry the wall from isolator to isolator. A strip isolator would have a distinct advantage for retrofitting masonry structures and for isolating residential housing constructed from concrete or masonry blocks.

In modeling the isolator reinforced with steel plates, the plates are assumed to be inextensional and rigid in flexure. The fiber reinforcement is made up of many individual fibers grouped in strands and coiled into a cord of submillimeter diameter. The cords are more flexible in tension than the individual fibers, therefore, they may stretch when the bearing is loaded by the weight of a building. On the other hand, they are completely flexible in bending, so the assumption made when modeling current isolators–that plane sections remain plane–no longer holds. In fact, when a fiber-reinforced isolator is loaded in shear, a plane cross section becomes curved. This leads to an unexpected advantage in the use of fiber reinforcement. When the bearing is displaced in shear, the tension in the fiber bundle (which acts on the curvature of the reinforcing sheet caused by the shear) produces a frictional damping that is due to individual strands in the fiber bundle slipping against each other. This energy dissipation in the reinforcement adds to that of the elastomer. Recent tests show that this energy dissipation is larger than that of the elastomer. Therefore, when designing a fiber-reinforced isolator for which a specified level of damping is required, it is not necessary to use elaborate compounding to provide the damping, but to use the additional damping from the fiber.

To calculate the vertical stiffness of a steel-reinforced bearing, an approximate analysis is used that assumes that each individual pad in the bearing deforms in such as way that horizontal planes remain horizontal and points on a vertical line lie on a parabola after loading. The plates are assumed to constrain the displacement at the top and bottom of the pad. Linear elastic behavior with incompressibility is assumed, with the additional assumption that the normal stress components are approximated by the pressure. This leads to the well-known "pressure solution", which is generally accepted as an adequate approximate approach for calculating the vertical stiffness. Extensional flexibility of the fiber reinforcement can be incorporated into this approach, and that predictions of the resulting vertical stiffness can be made.

Theoretical analyses of vertical and horizontal stiffnesses and the buckling of the fiber-reinforced isolator have been supplemented by experimental work, and while the tests are only preliminary, they indicate that the concept is viable. The vertical stiffness of the model isolators is in the range of stiffnesses of practical designs of steel-reinforced bearings, with the same diameter and the same thickness of rubber. The hysteresis loops generated under combined compression and shear have effective stiffnesses that are somewhat (~20%) less than the equivalent steel-reinforced bearing, but have the same general characteristics and show stable behavior up to a peak shear strain of 150% (the limit of the testing machine).

Much recent discussion has focused on "smart" rubber bearings and "intelligent" base isolation systems as the new thrust in seismic isolation research. While there may be a role for these adaptive systems for large expensive buildings in highly seismic areas, the development of lightweight, low-cost isolators is crucial if this method of seismic protection is to be applied to a wide range of buildings, such as housing, schools, and medical centers, in earthquake-prone areas of the world.

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